Software Security

Building Security in

CMSC330 Summer 2021

Security breaches

- **TJX** (2007) - 94 million records*
- **Adobe** (2013) - 150 million records, 38 million users
- **eBay** (2014) - 145 million records
- **Equifax** (2017) – 148 millions consumers
- **Yahoo** (2013) – 3 billion user accounts
- **Twitter** (2018) – 330 million users
- **First American Financial Corp** (2019) – 885 million users
- **Anthem** (2014) - Records of 80 million customers
- **Target** (2013) - 110 million records
- **Heartland** (2008) - 160 million records

**containing SSNs, credit card nums, other private info*

https://www.oneid.com/7-biggest-security-breaches-of-the-past-decade-2/

2017 Equifax Data Breach

- 148 million consumers’ personal information stolen
- They collect every details of your personal life
  - Your SSN, Credit Card Numbers, Late Payments…
- You did not sign up for it
- You cannot ask them to stop collecting your data
- You have to pay to credit freeze/unfreeze

Vulnerabilities: Security-relevant Defects

- The causes of security breaches are varied, but many of them owe to a **defect** (or ***bug***) or **design flaw** in a targeted computer system's software.

- **Software defect** (bug) or **design flaw** can be **exploited** to affect an undesired behavior

Defects and Vulnerabilities

- The **use of software is growing**
  - So: more bugs and flaws

- Software is large (lines of code)
  - **Boeing** 787: 14 million
  - **Chevy volt**: 10 million
  - Google: 2 billion
  - Windows: 50 million
  - Mac OS: 80 million
  - **F35 fighter** Jet: 24 million

Quiz 1

Program testing can show that a program has no bugs.

A. True
B. False

Quiz 1

Program testing can show that a program has no bugs.

A. True
B. False

Program testing can be used to show the presence of bugs, but never to show their absence!

--Edsger Dijkstra

In this Lecture

- The basics of threat modeling.
- Two kinds of *exploits*: **buffer overflows** and **command injection**.
- Two kinds of *defense*: **type-safe programming languages**, and **input validation**.

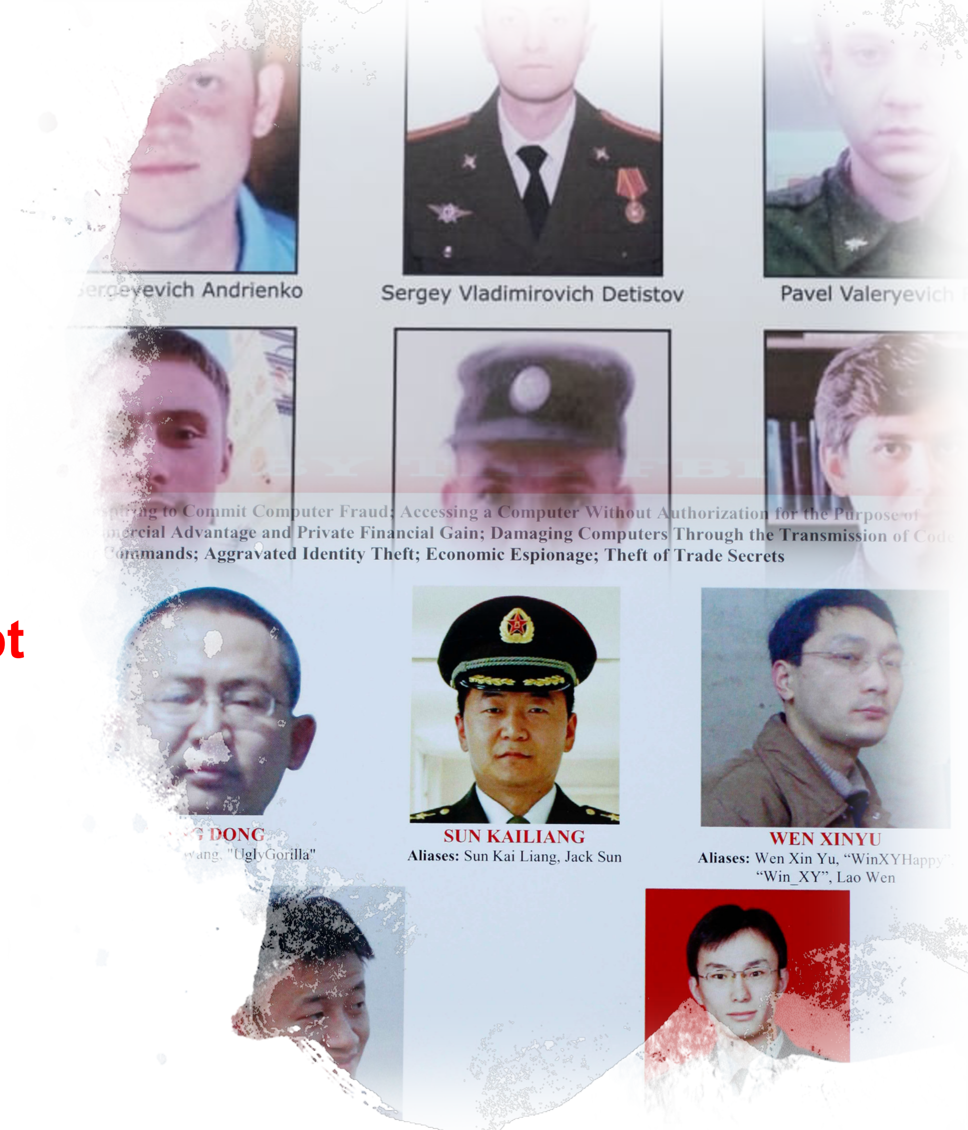
You will learn more in CMSC414, CMSC417, CMSC456

Considering Correctness

- **All software is buggy**, isn't it? Haven't we been dealing with this for a long time?
- A **normal user** **never sees most bugs**, or figures out how to **work around** them
- Therefore, **companies fix the most likely bugs**, to save **money**

Exploit the Bug

- A typical interaction with a bug results in a **crash**
- An **attacker** is not a normal user!
  - The attacker **will actively attempt to find defects**, using unusual interactions and features
- An attacker will work to **exploit** the bug to do **much worse**, to achieve his goals



Exploitable Bugs

- **Many kinds of exploits** have been developed over time, with technical names like
  - Buffer overflow
  - Use after free
  - Command injection
  - SQL injection
  - Privilege escalation
  - Cross-site scripting
  - Path traversal
  - …

Buffer Overflow

- A buffer overflow describes a family of possible exploits of a vulnerability in which a program may incorrectly access a buffer outside its allotted bounds.

  - A buffer overwrite occurs when the out-of-bounds access is a write.
  - A buffer overread occurs when the access is a read.

Example: Out-of-Bounds Read/write in C

```c
#include <stdio.h>

void incr_arr(int *x, int len, int i) {
  if (i >= 0 && i < len) {
    x[i] = x[i] + 1;
    incr_arr(x,len,i+1);
  }
}

int y[10] = {1,1,1,1,1,1,1,1,1,1};
int z = 20;

int main(int argc, char **argv) {
  incr_arr(y,11,0);
  printf("%d =? 20\n",z);
  return 0;
}
```

Output:

```
21 =? 20
```

The value of z changed from 20 to 21. Why?

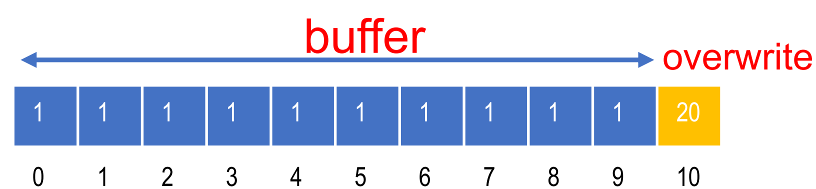
Example: Out-of-Bounds Read/write in C

```c
1  #include <stdio.h>
2
3  void incr_arr(int *x, int len, int i) {
4    if (i >= 0 && i < len) {
5      x[i] = x[i] + 1;
6      incr_arr(x,len,i+1);
7    }
8  }
9
10 int y[10] = {1,1,1,1,1,1,1,1,1,1};
11 int z = 20;
12
13 int main(int argc, char **argv) {
14   incr_arr(y,11,0);
15   printf("%d =? 20\n",z);
16   return 0;
17 }
```

Output:

```
21 =? 20
```

- array y has length 10
- but the second argument of `incr_arr` is 11, which is one more than it should be.
- As a result, line 5 will be allowed to read/write past the end of the array.



Example: Out-of-Bounds Read/write in OCaml

Consider the same program, written in OCaml

```
let rec incr_arr x i len =
  if i >= 0 && i < len then
    (x.(i) <- x.(i) + 1;
    incr_arr x (i+1) len)
;;

let y = Array.make 10 1;;
incr_arr y 0 (1 + Array.length y);;
```

Exception: `Invalid_argument "index out of bounds".`

- OCaml detects the attempt to write one past the end of the array and signals by throwing an exception.

Exploiting a Vulnerability

```c
#include <stdlib.h>
int main(int argc, char **argv) {
  int len = 10;
  if (argc == 2) len = atoi(argv[1]);
  incr_arr(y,len,0);
  printf("%d =? 20\n",z);
  return 0;
}
```

`a.out` 

`a.out 11` 

If an attacker can force the argument to be 11 (or more), then he can trigger the bug.

Quiz 2

If you declare an array as int a[100]; in C and you try to write 5 to a[i], where i happens to be 200, what will happen?

A. Nothing
B. The C compiler will give you an error and won't compile
C. There will always be a runtime error
D. Whatever is at a[200] will be overwritten

Quiz 2

If you declare an array as `int a[100];` in C and you try to write 5 to `a[i]`, where `i` happens to be 200, what will happen?

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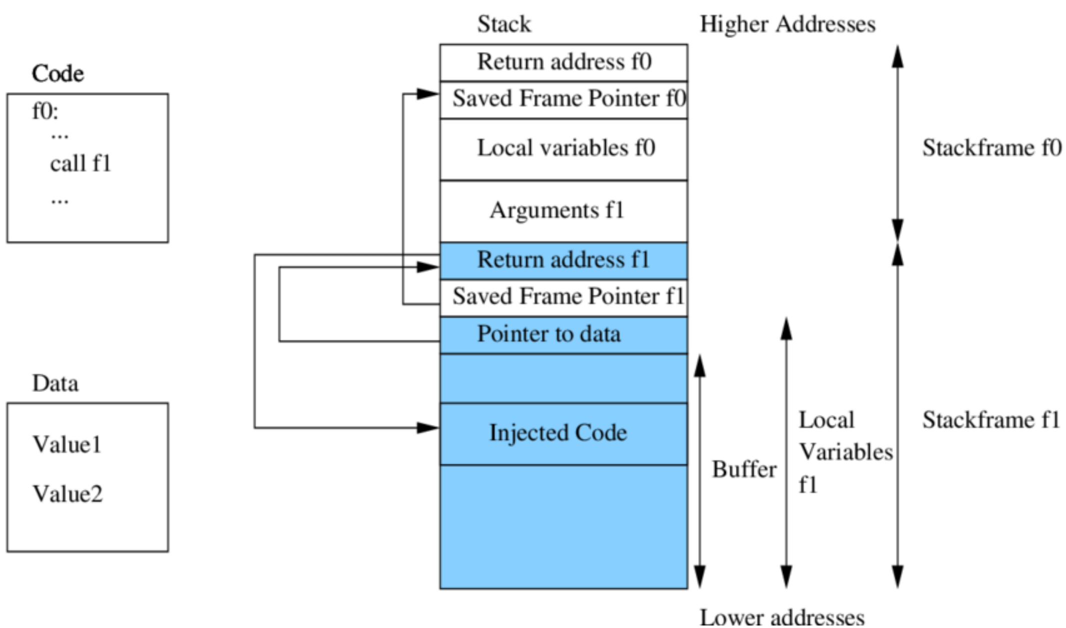
What Can Exploitation Achieve?

- **Buffer Overread: Heartbleed**
  - Heartbleed is a bug in the popular, open-source OpenSSL codebase, part of the HTTPS protocol.
  - The attacker can read the memory beyond the buffer, which could contain secret keys or passwords, perhaps provided by previous clients

What Can Exploitation Achieve?

- **Buffer Overwrite: Morris Worm**



What happened?

- For C/C++ programs
  - A buffer with the password could be a local variable

- Therefore
  - The attacker's input (includes machine instructions) is too long, and overruns the buffer

  - The overrun rewrites the return address to point into the buffer, at the machine instructions

  - When the call "returns" it executes the attacker's code

Quiz 3

Which kinds of operation is most likely to *not* lead to a buffer overflow in C?

A. Floating point addition
B. Indexing of arrays
C. Dereferencing a pointer
D. Pointer arithmetic

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Code Injection

- Attacker tricks an application to treat attacker-provided data as code

- This feature appears in many other exploits too

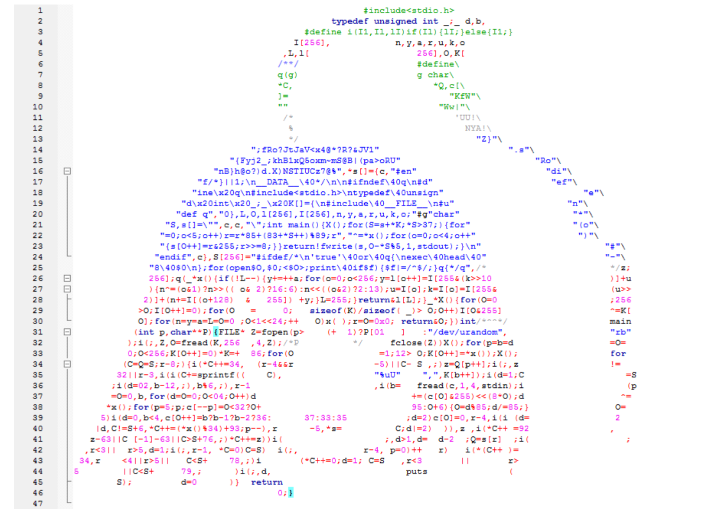
  - SQL injection treats data as database queries
  - Cross-site scripting treats data as Javascript commands
  - Command injection treats data as operating system commands
  - Use-after-free can cause stale data to be treated as code
  - Etc.

Use After Free (bug, no exploit)

```c
#include <stdlib.h>
struct list {
  int v;
  struct list *next;
};
int main() {
  struct list *p = malloc(sizeof(struct list));
  p->v = 0;
  p->next = 0;
  free(p); // deallocates p
  int *x = malloc(sizeof(int)*2); // reuses p's old memory
  x[0] = 5; // overwrites p->v
  x[1] = 5; // overwrites p->next
  p = p->next; // p is now bogus
  p->v = 2; // CRASH!
  return 0;
}
```

Trusting the Programmer?

- Buffer overflows rely on the ability to read or write outside the bounds of a buffer
- Use-after-free relies on the ability to keep using freed memory once it's been reallocated
- C and C++ programs expect the programmer to ensure this never happens
  - But humans (regularly) make mistakes!



Jim Hague's IOCCC winner program

Defense: Type-safe Languages

- Type-safe Languages (like Python, OCaml, Java, etc.) ensure buffer sizes are respected
  - Compiler **inserts checks** at reads/writes. Such checks can halt the program. But will prevent a bug from being exploited
  - **Garbage collection** avoids the use-after-free bugs. No object will be freed if it could be used again in the future.

Why Is Type Safety Helpful?

- Type safety ensures two useful properties that preclude buffer overflows and other memory corruption-based exploits.
  - Preservation: memory in use by the program at a particular type T always has that type T.
  - Progress: values deemed to have type T will be usable by code expecting to receive a value of that type
- To ensure preservation and progress implies that only non-freed buffers can only be accessed within their allotted bounds, precluding buffer overflows.
  - Overwrites breaks preservation
  - Overreads could break progress
  - Uses-after-free could break both

Quiz 4

Applications developed in the programming languages ___________ are susceptible to buffer overflows and uses-after-free.

A. Ruby, Python
B. Ocaml, Haskell
C. C, C++
D. Rust, C#

Quiz 4

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Costs of Ensuring Type Safety

- Performance
  - Array Bounds Checks and Garbage Collection add overhead to a program's running time.
- Expressiveness
  - C casts between different sorts of objects, e.g., a struct and an array.
    - Need casting in System programming
  - This sort of operation -- cast from integer to pointer -- is not permitted in a type safe language.

Command Injection

- A type-safe language will rule out the possibility of buffer overflow exploits.

- Unfortunately, type safety will not rule out all forms of attack
  - Command Injection: (also known as shell injection) is a security vulnerability that allows an attacker to execute arbitrary operating system (OS) commands on the server that is running an application.

What’s wrong with this Ruby code?

catwrapper.rb:

```
if ARGV.length < 1 then
  puts "required argument: textfile path"
  exit 1
end

# call cat command on given argument
system(“cat ”+ARGV[0])

exit 0
```

Possible Interaction

```
> ls
catwrapper.rb
hello.txt

> ruby catwrapper.rb hello.txt
Hello world!

> ruby catwrapper.rb catwrapper.rb
if ARGV.length < 1 then
  puts "required argument: textfile path"
…

> ruby catwrapper.rb "hello.txt; rm hello.txt"
Hello world!

> ls
catwrapper.rb
```

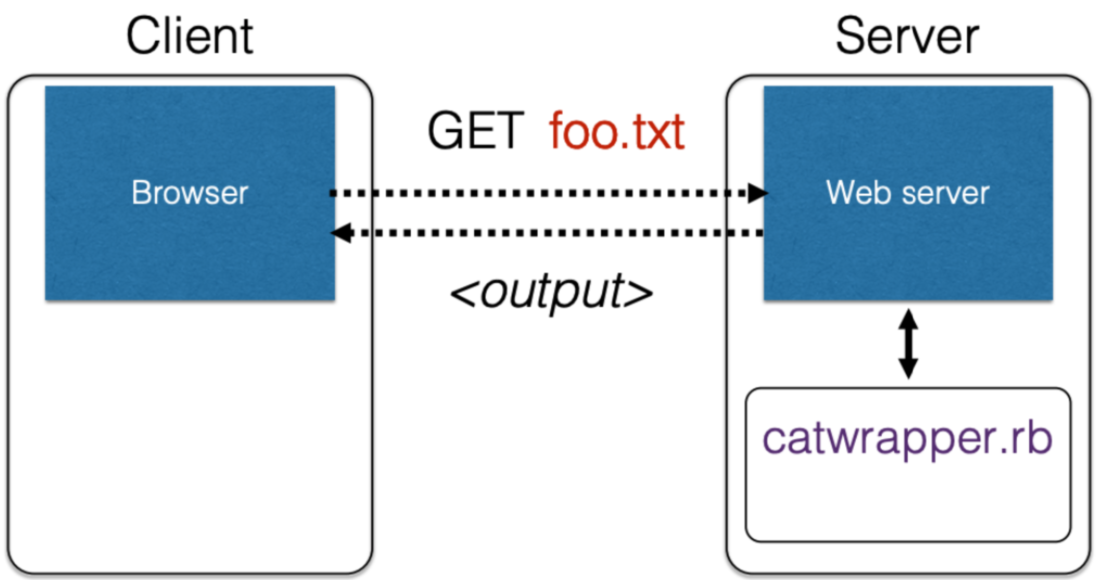
What Happened?

catwrapper.rb:

```
if ARGV.length < 1 then
  puts "required argument: textfile path"
  exit 1
end

# call cat command on given argument
system("cat "+ARGV[0])

exit 0
```

`system()` interpreted the string as having two commands, and executed them both

When could this be bad?



catwrapper.rb as a web service

Consequences

- If `catwrapper.rb` is part of a web service
  - **Input is untrusted** — could be anything
  - But we only want requestors to read (see) the contents of the files, not to do anything else
  - Current code is too powerful: vulnerable to

command injection

- How to fix it?

Need to validate inputs

https://www.owasp.org/index.php/Command_Injection

Defense: Input Validation

- Inputs that could cause our program to do something illegal
- Such atypical inputs are more likely when an untrusted adversary is providing them

We must validate the client inputs before we trust it

- ***Making input trustworthy***
  - ***Sanitize it*** by modifying it or using it it in such a way that the result is correctly formed by construction
  - ***Check it*** has the expected form, and reject it if not

Checking: Blacklisting

- ***Reject* strings with possibly bad chars: ' ; --**

```
if ARGV[0] =~ /;/ then
  puts "illegal argument"
  exit 1
else
  system("cat "+ARGV[0])
end
```

reject inputs *that have ; in them*

```
> ruby catwrapper.rb "hello.txt; rm hello.txt"
```

illegal argument

Sanitization: Blocklisting

- **Delete the characters you don't want:** `'` `;` `--`

```
system("cat "+ARGV[0].tr(";",""))
```

delete occurrences of ; from input string

```
> ruby catwrapper.rb "hello.txt; rm hello.txt"
Hello world!
cat: rm: No such file or directory
Hello world!
> ls hello.txt
hello.txt
```

Sanitization: Escaping

- **Replace problematic characters with safe ones**
  - change `'` to `\'`
  - change `;` to `\;`
  - change `-` to `\-`
  - change `\` to `\\`

- Which characters are problematic depends on the interpreter the string will be handed to
  - Web browser/server for URIs
    - `URI::escape(str,unsafe_chars)`
  - Program delegated to by web server
    - `CGI::escape(str)`

Sanitization: Escaping

```
def escape_chars(string)
  pat = /(\'|\"|\.|\*|\/|\-|\\|;|\||\s)/
  string.gsub(pat){|match|"\\" + match}
end
```

escape occurrences
of ', "", ; etc. in input string

```
system("cat "+escape_chars(ARGV[0]))
```

```
> ruby catwrapper.rb "hello.txt; rm hello.txt"
cat: hello.txt; rm hello.txt: No such file or directory
> ls hello.txt
hello.txt
```

Checking: Safelisting

- **Check that the user input is known to be safe**
  - E.g., only those files that exactly match a filename in the current directory

- **Rationale**: Given an invalid input, **safer to reject than to fix**
  - "Fixes" may result in wrong output, or vulnerabilities
  - ***Principle*** *of fail-safe defaults*

Checking: Safelisting

```
files = Dir.entries(".").reject{|f| File.directory?(f)}

if not (files.member? ARGV[0]) then
  puts "illegal argument"
  exit 1
else
  system("cat "+ARGV[0])
end
```

***reject inputs** that do not mention a legal file name*

```
> ruby catwrapper.rb "hello.txt; rm hello.txt"
illegal argument
```

Validation Challenges

- ***Cannot always delete or sanitize problematic characters***
  - You may want dangerous chars, e.g., “Peter O’Connor”
  - How do you know if/when the characters are bad?
  - Hard to think of all of the possible characters to eliminate
- ***Cannot always identify safelist cheaply or completely***
  - May be expensive to compute at runtime
  - May be hard to describe (e.g., “all possible proper names”)

Software Security

Part II: Web Security

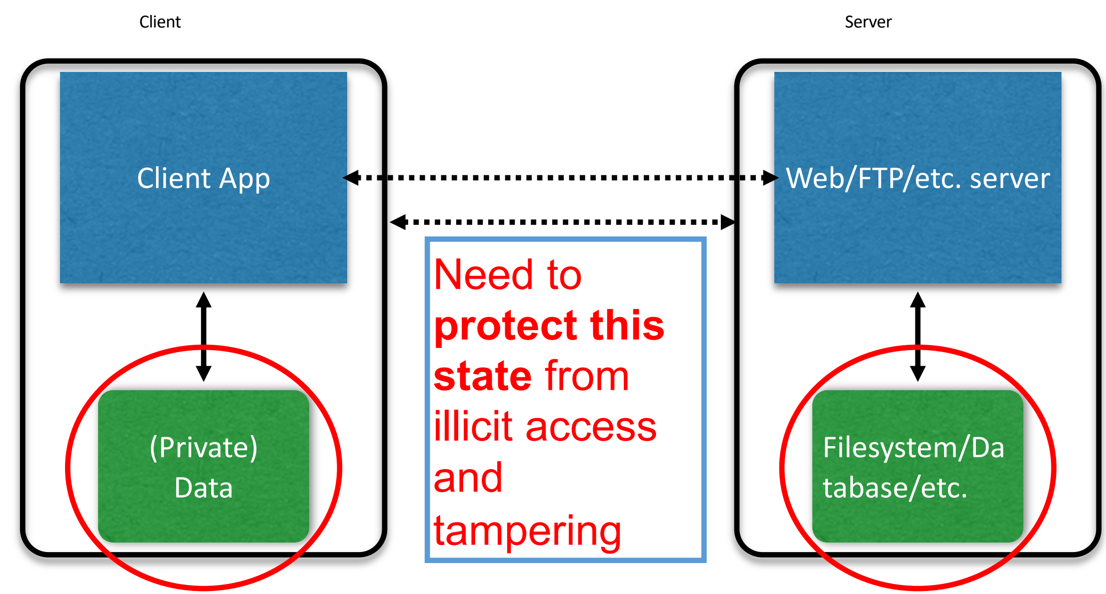
CMSC330 Spring 2021

WWW Security

- **Security for the World-Wide Web** (**WWW**) presents new vulnerabilities to consider:
  - **SQL injection**
  - Cross-site Scripting (**XSS**)
  -
- These share some common causes with memory safety vulnerabilities; like **confusion of code and data**
  - **Defense** also similar: **validate untrusted input**

- New wrinkle: **Web 2.0's use of mobile code**
  - How to protect your applications and other web resources?

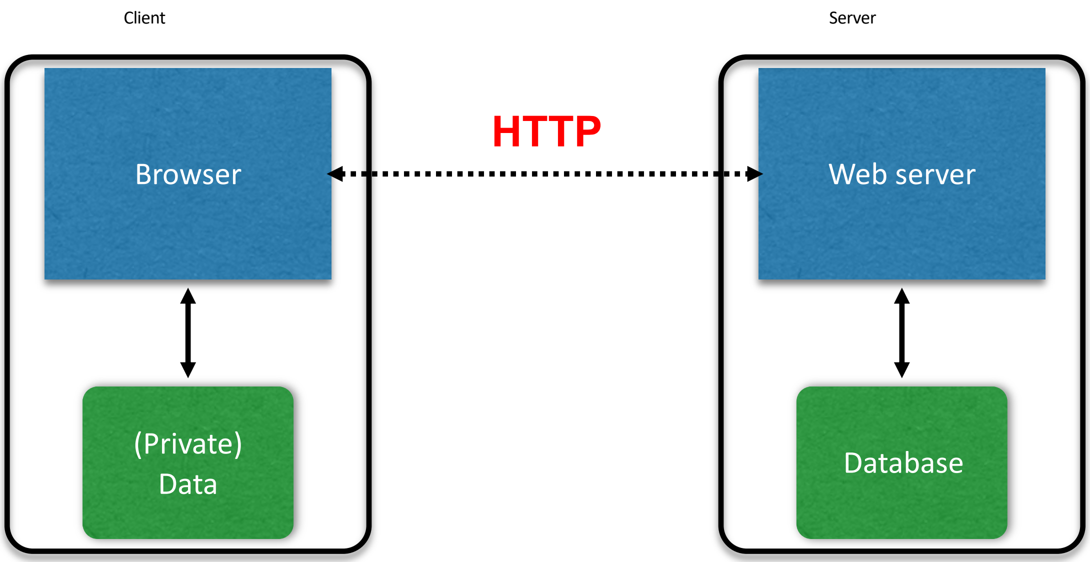
The Internet



(Much) user data is part of the browser

FS/DB is a separate entity, logically (and often physically)

The World Wide Web (WWW)



Interacting with web servers

Resources which are identified by a URL
(Universal Resource Locator)

`http://www.cs.umd.edu/~mwh/index.html`

Protocol — **Hostname/server** — **Path to a resource**

Protocol	Hostname/server	Path to a resource

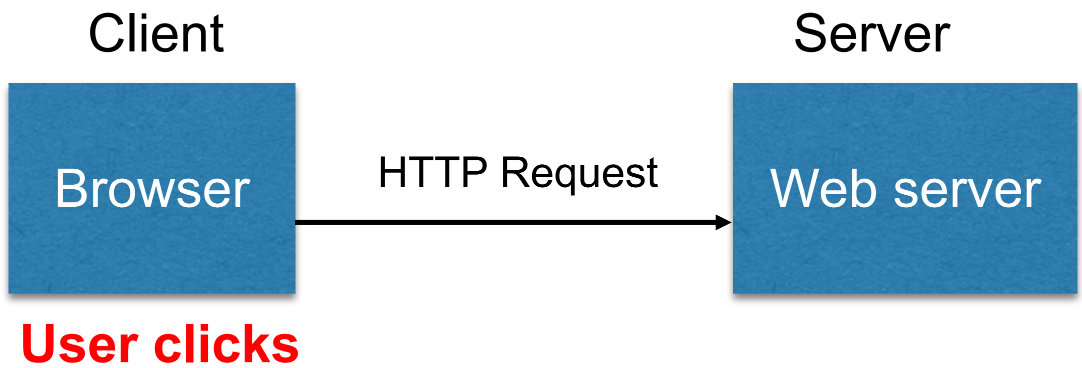
`ftp`
`https`
`tor`
	Translated to an IP address by DNS (e.g., `128.8.127.3`)	`index.html` is static content i.e., a fixed file returned by the server

`http://facebook.com/delete.php?f=joe123&w=16`

Path to a resource (`delete.php`) — ***Arguments*** (`f=joe123&w=16`)

Here, the file delete.php is dynamic content. i.e., the server generates the content on the fly

HyperText Transfer Protocol (HTTP)



- **Requests contain**:
  - The **URL** of the resource the client wishes to obtain
  - **Headers** describing what the browser can do
- **Request types** can be **GET** or **POST**
  - **GET**: retrieves data, most of it in URL itself (no server side effects)
  - **POST**: provides data as separate fields (can have side effects)

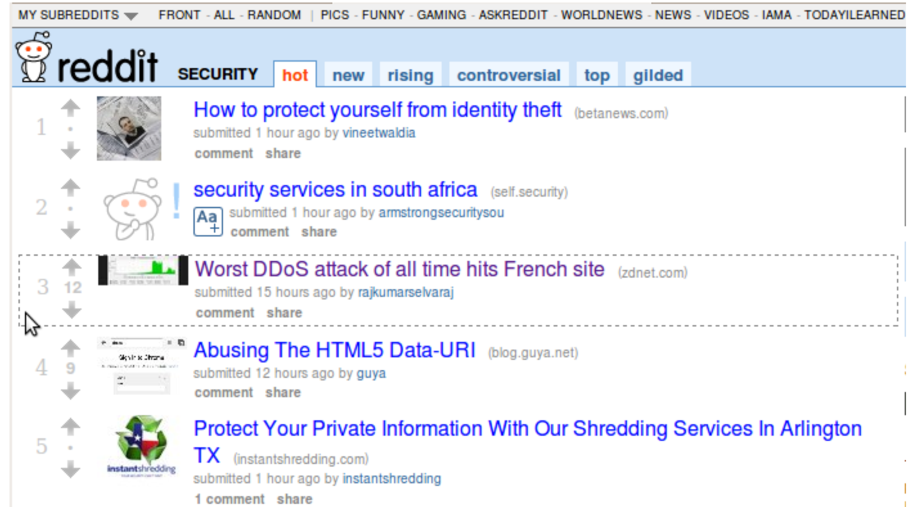
HTTP GET Requests

http://www.reddit.com/r/security

```
HTTP Headers
http://www.reddit.com/r/security

GET /r/security HTTP/1.1
Host: www.reddit.com
User-Agent Mozilla/5.0 (X11; U; Linux i686; en-US; rv:1.9.2.11) Gecko/20101013 Ubuntu/9.04 (jaunty) Firefox/3.6.11
Accept: text/html,application/xhtml+xml,application/xml;q=0.9,*/*;q=0.8
Accept-Language: en-us,en;q=0.5
Accept-Encoding: gzip,deflate
Accept-Charset: ISO-8859-1,utf-8;q=0.7,*;q=0.7
Keep-Alive: 115
Connection: keep-alive
Cookie: __utma=55650728.562667657.1392711472.1392711472.1392711472.1; __utmb=55650728.1.10.1392711472; __utmc=55650...
```

User-Agent is typically a ***browser,*** but it can be `wget`, JDK, etc.

Referrer



HTTP Headers

```
http://www.zdnet.com/worst-ddos-attack-of-all-time-hits-french-site-7000026330/

GET /worst-ddos-attack-of-all-time-hits-french-site-7000026330/ HTTP/1.1
Host: www.zdnet.com
User-Agent: Mozilla/5.0 (X11; U; Linux i686; en-US; rv:1.9.2.11) Gecko/20101013 Ubuntu/9.04 (jaunty) Firefox/3.6.11
Accept: text/html,application/xhtml+xml,application/xml;q=0.9,*/*;q=0.8
Accept-Language: en-us,en;q=0.5
Accept-Encoding: gzip,deflate
Accept-Charset: ISO-8859-1,utf-8;q=0.7,*;q=0.7
Keep-Alive: 115
Connection: keep-alive
Referer: http://www.reddit.com/r/security
```

Referrer URL: the site from which this request was issued.

HTTP POST Requests

Posting on Piazza

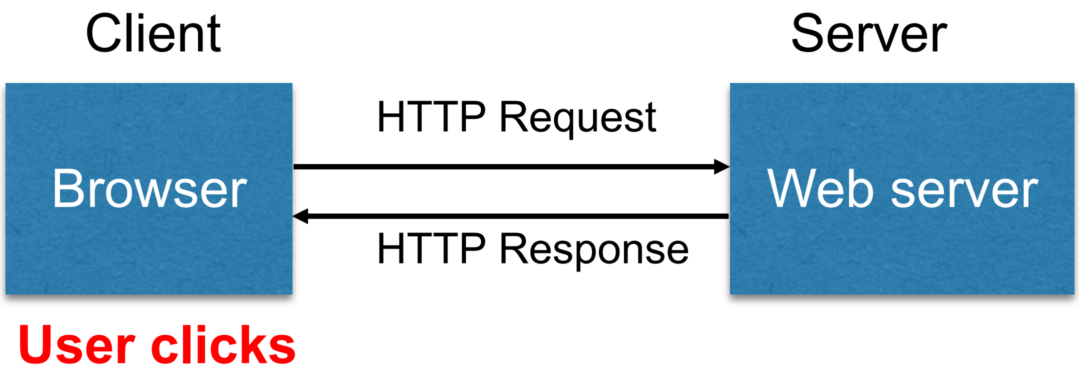
HTTP Headers

```
https://piazza.com/logic/api?method=content.create&aid=hrteve7t83et

POST /logic/api?method=content.create&aid=hrteve7t83et HTTP/1.1
Host: piazza.com
User-Agent: Mozilla/5.0 (X11; U; Linux i686; en-US; rv:1.9.2.11) Gecko/20101013 Ubuntu/9.04 (jaunty) Firefox/3.6.11
Accept: application/json, text/javascript, */*; q=0.01
Accept-Language: en-us,en;q=0.5
Accept-Encoding: gzip,deflate
Accept-Charset: ISO-8859-1,utf-8;q=0.7,*;q=0.7
Keep-Alive: 115
Connection: keep-alive
Content-Type: application/x-www-form-urlencoded; charset=UTF-8
X-Requested-With: XMLHttpRequest
Referer: https://piazza.com/class
Content-Length: 339
Cookie: piazza_session="DFwuCEFIGvEGwwHLJyuCvHIGtHKECCKL.5%25x+x+ux%255M5%22%215%3F5%26x%26%26%7C%22%21r...
Pragma: no-cache
Cache-Control: no-cache
 {"method":"content.create","params":{"cid":"hrpng9q2nndos","subject":"<p>Interesting.. perhaps it has to do with a change to the ...
```

Implicitly includes data as a part of the URL

Explicitly includes data as a part of the request's content

HyperText Transfer Protocol (HTTP)



- ***Responses*** contain:
  - ***Status*** code
  - ***Headers*** describing what the server provides
  - ***Data***
  - ***Cookies*** (much more on these later)
    - Represent *state* the server would like the browser to store on its behalf

HTTP Responses

HTTP version

Status code

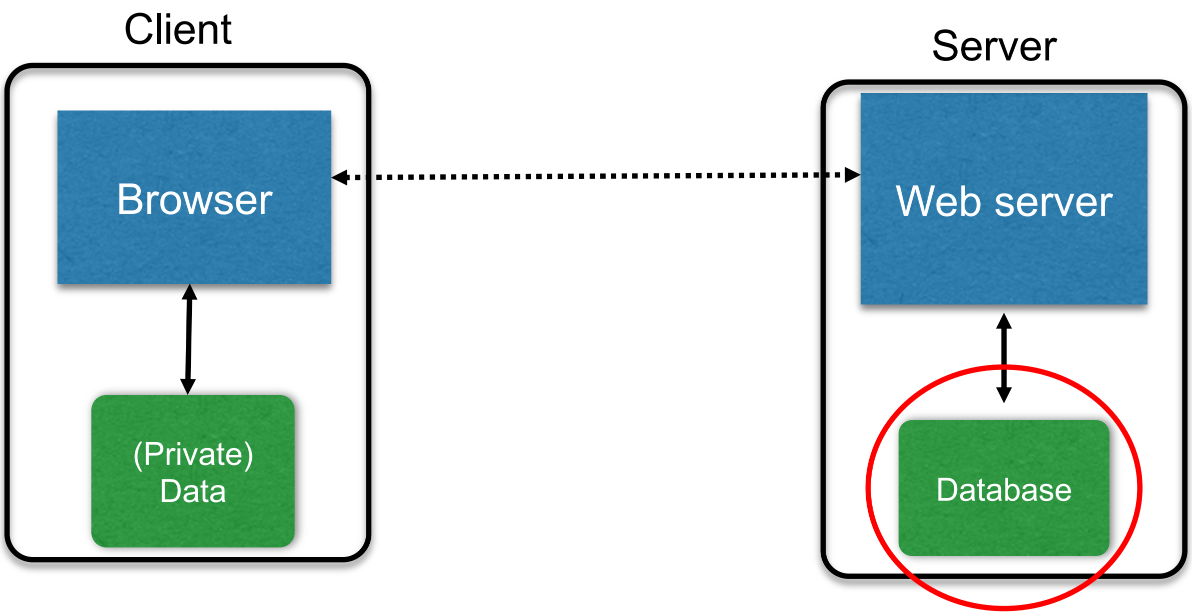
Reason phrase

```
HTTP/1.1 200 OK
Date: Tue, 18 Feb 2014 08:20:34 GMT
Server: Apache
Set-Cookie: session-zdnet-production=6bhqca1i0cbciagu11sisac2p3; path=/; domain=zdnet.com
Set-Cookie: zdregion=MTI5LjIuMTI5LjE1Mzp1czp1czpjZDJmNWY5YTdkODU1N2Q2YzM5NGU3M2Y1ZTRmN
Set-Cookie: zdregion=MTI5LjIuMTI5LjE1Mzp1czp1czpjZDJmNWY5YTdkODU1N2Q2YzM5NGU3M2Y1ZTRmN
Set-Cookie: edition=us; expires=Wed, 18-Feb-2015 08:20:34 GMT; path=/; domain=.zdnet.com
Set-Cookie: session-zdnet-production=59ob97fpinqe4bg6lde4dvvq11; path=/; domain=zdnet.com
Set-Cookie: user_agent=desktop
Set-Cookie: zdnet_ad_session=f
Set-Cookie: firstpg=0
Expires: Thu, 19 Nov 1981 08:52:00 GMT
Cache-Control: no-store, no-cache, must-revalidate, post-check=0, pre-check=0
Pragma: no-cache
X-UA-Compatible: IE=edge,chrome=1
Vary: Accept-Encoding
Content-Encoding: gzip
Content-Length: 18922
Keep-Alive: timeout=70, max=146
Connection: Keep-Alive
Content-Type: text/html; charset=UTF-8

<html> …… </html>
```

Headers

Data

Relational Databases & Stable Storage



Need to **protect this state** from illicit access and tampering

SQL Injection

- SQL injection is a code injection attack that aims to steal or corrupt information kept in a server-side database.

Data as Tables

- A relational database organizes information as tables of records.

Table Name

Column

Users

Row (Record)

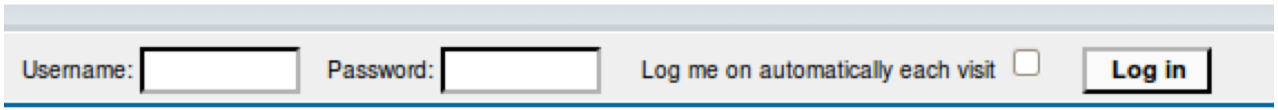
Name	Gender	Age	Email	Password
Dee	F	28	dee@pp.com	j3i8g8ha
Mac	M	7	bouncer@pp.com	a0u23bt
Charlie	M	32	aneifjask@pp.com	0aergja
Dennis	M	28	imagod@pp.com	1bjb9a93
Frank	M	57	armed@pp.com	ziog9gga

SQL (Standard Query Language)

```
SELECT Age FROM Users WHERE Name='Dee';     28

UPDATE Users SET email='readgood@pp.com'
   WHERE Age=32; -- this is a comment

INSERT INTO Users Values('Frank', 'M', 57, ...);

DROP TABLE Users;
```

Web Server SQL Queries

Website



“Login code” (Ruby)

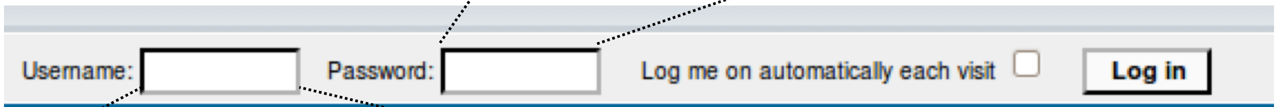
```
result = db.execute “SELECT * FROM Users
       WHERE Name=‘#{user}’ AND Password=‘#{pass}’;”
```

Suppose you successfully log in as user if this returns any results

How could you exploit this?

SQL injection

whocares



frank' OR 1=1; --

```
result = db.execute “SELECT * FROM Users
         WHERE Name=‘#{user}’ AND Password=‘#{pass}’;”
```

```
result = db.execute “SELECT * FROM Users
         WHERE Name=‘frank’ OR 1=1; --’ AND Password=‘whocares’;”
```

Always true
(so: dumps whole user DB)

Commented out

SQL injection

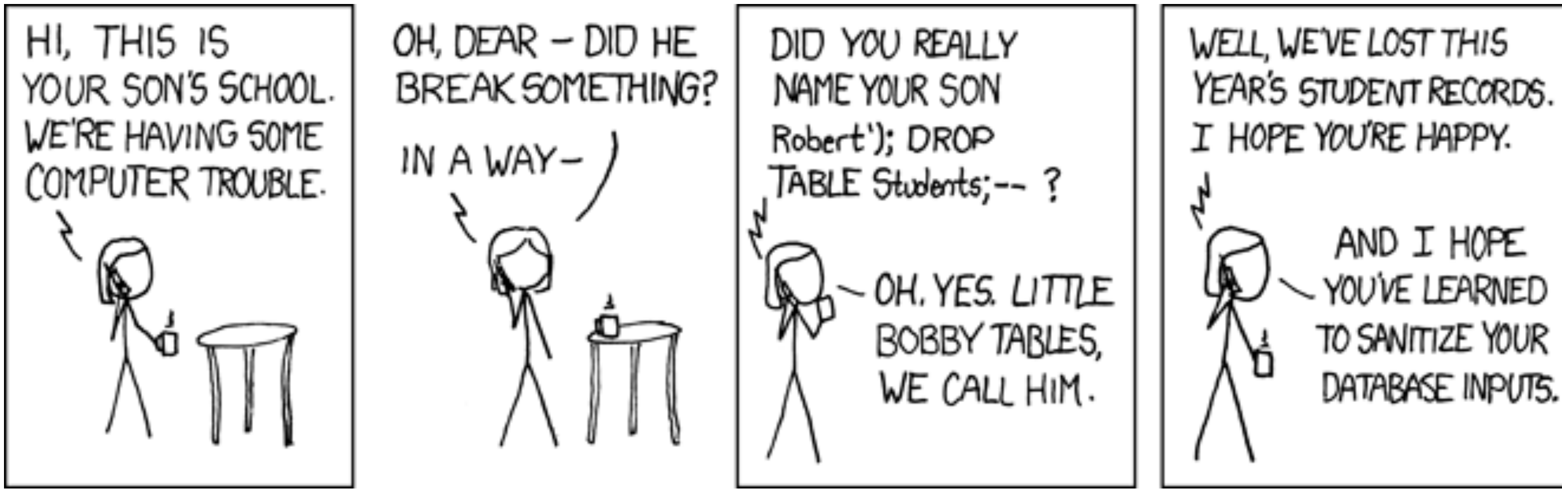

```
frank' OR 1=1); DROP TABLE Users; --
```

```
result = db.execute "SELECT * FROM Users
      WHERE Name='#{user}' AND Password='#{pass}';"
```

```
result = db.execute "SELECT * FROM Users
      WHERE Name='frank' OR 1=1;
      DROP TABLE Users; --' AND Password='whocares';";
```

Can chain together statements with semicolon:
STATEMENT 1 ; STATEMENT 2

SQL injection



http://xkcd.com/327/


ZU 0666',0,0); DROP DATABASE TABLICE; --

The Underlying Issue

```
result = db.execute “SELECT * FROM Users
       WHERE Name=‘#{user}’ AND Password=‘#{pass}’;”
```

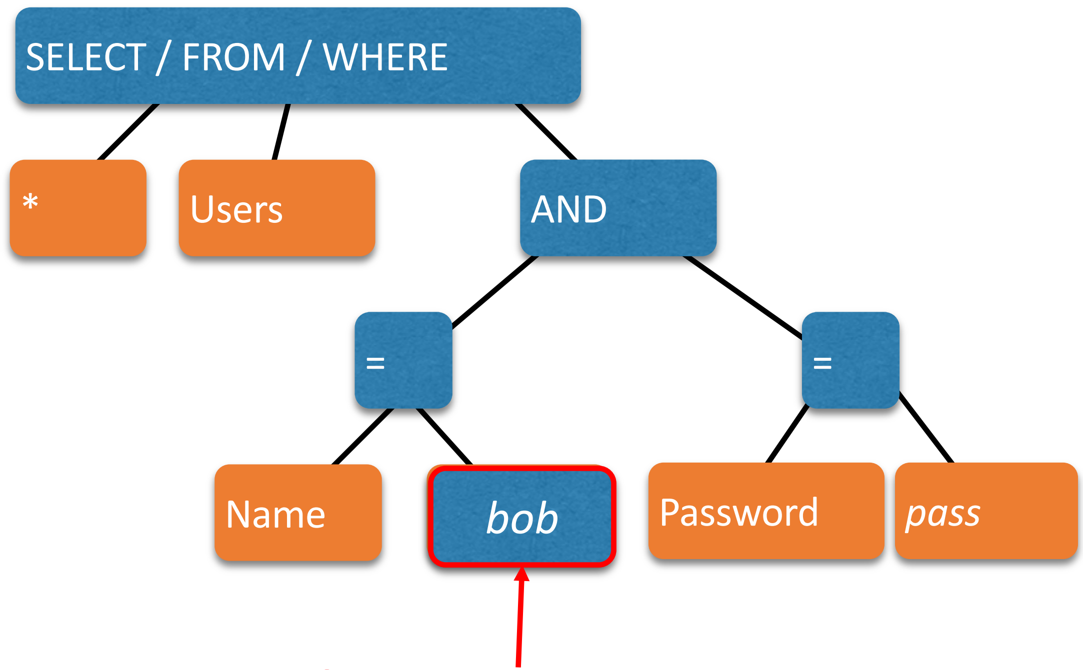
- This one string combines the **code** and the **data**
  - Similar to buffer overflows
  - and command injection

When the boundary between code and data blurs, we open ourselves up to vulnerabilities

The Underlying Issue

```
result = db.execute "SELECT * FROM Users
       WHERE Name='#{user}' AND Password='#{pass}';"
```

Intended AST for parsed SQL query



Should be ***data***, not ***code***

Defense: Input Validation

Just as with command injection, we can defend by **validating input**, e.g.,

- **Reject** inputs with bad characters (e.g.,; or --)
- **Remove** those characters from input
- **Escape** those characters (in an SQL-specific manner)

These can be effective, but the best option is to **avoid constructing programs from strings** in the first place

Sanitization: Prepared Statements

- **Treat user data according to its *type***
  - Decouple the code and the data

```
result = db.execute “SELECT * FROM Users
         WHERE Name=‘#{user}’ AND Password=‘#{pass}’;”
```

```
stmt = db.prepare("SELECT * FROM Users WHERE
                        Name = ? AND Password = ?”)
```

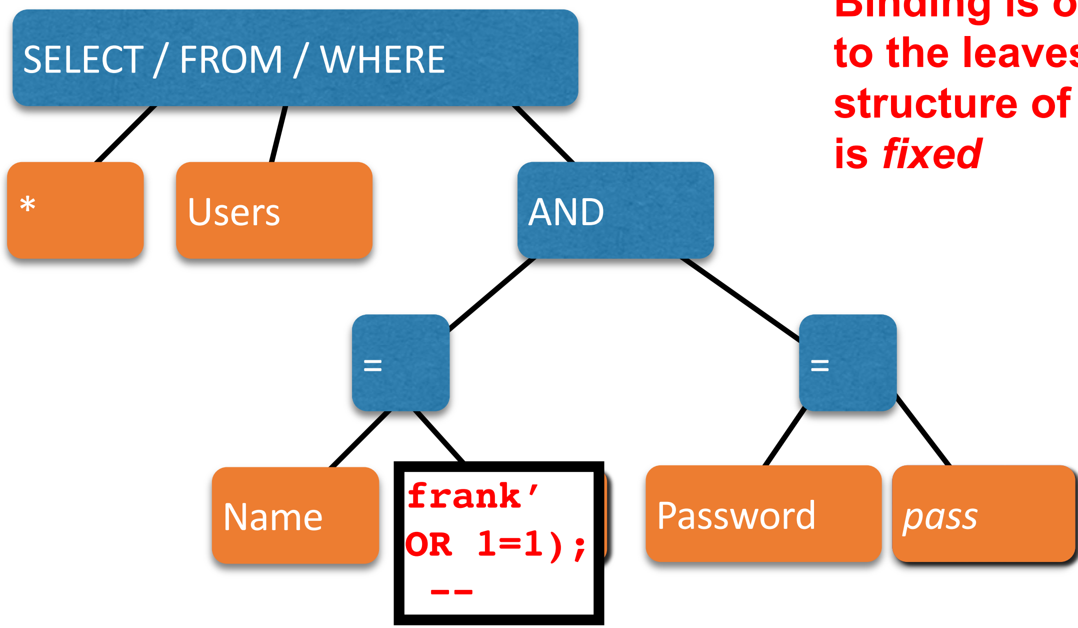
Variable binders parsed as strings

```
result = stmt.execute (user, pass)
```

Arguments

Using Prepared Statements

```
stmt = db.prepare("SELECT * FROM Users WHERE Name = ? AND Password = ?”)
result = stmt.execute(user, pass)
```



Binding is only applied to the leaves, so the structure of the AST is *fixed*