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Version Detection

For Software and Libraries

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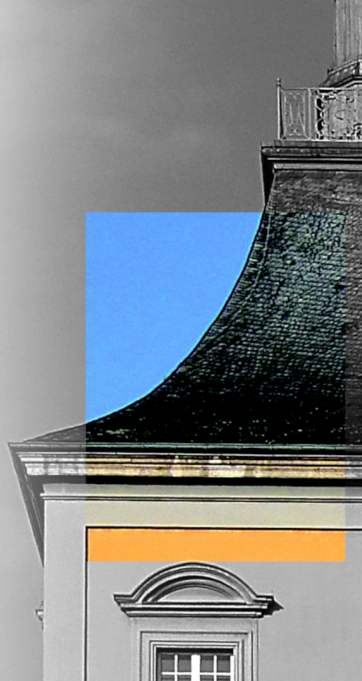
Lecture IT Security | Uni Bonn | WT 2024/25



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- Why should you want to detect versions?
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- Structural Analysis
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  - Dynamic Analysis

What is Version Detection?

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Definition

A definition for Version Detection:

> Version Detection refers to the process of identifying software or library versions given a static artifact or dynamic system. It operates from a position where the target has no explicit interest in announcing its versions.

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Software Versions

A software version is a unique identifier which maps to a unique state of a software. It usually consists of numbers or letters which are often assigned in ascending order to generate an order.

Examples:

- Linux 6.10.6
- Firefox 129.0.2
- intel-ucode 20240813-2
- pdfTeX 3.141592653-2.6-1.40.26
- Flavius 32501e228e1e865e397ccb437712066bae9ccdef

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Semantic Versioning

Systematic software versioning helps your dependency management.

Version X.Y.Z

X Major Version
increment when you make incompatible API changes

Y Minor Version
increment when you add functionality in a backward compatible manner

Z Patch Version
increment when you make backward compatible bug fixes

Why should you want to detect versions?

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Motivation: CVE & CVSS

CVE Description Components

- Software
- Version range
- Vulnerability

CVSS

- Measures CVE severity
- Multiple categories form a score between 0 and 10
- Multiple versions with different categories

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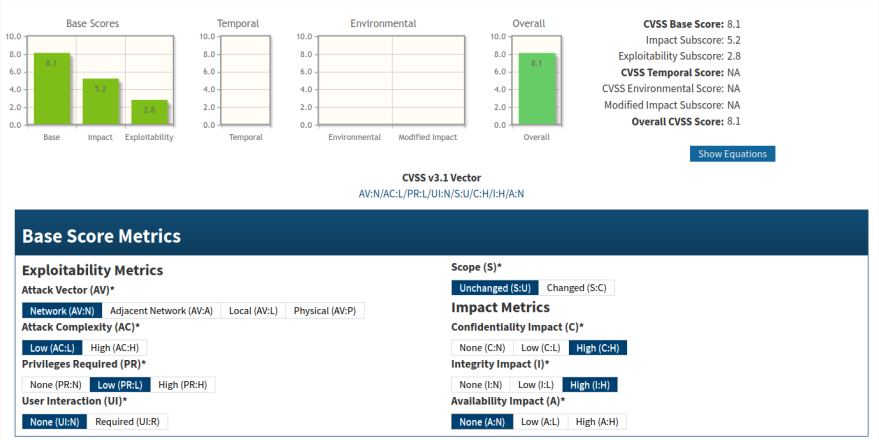
Motivation: CVE & CVSS



https://nvd.nist.gov/vuln-metrics/cvss/v3-calculator

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Be careful with CVEs

CVE: CVE-2020-19909 Integer Overflow in Curl

First CVSSv3 Scoring:
`AV:N/AC:L/PR:N/UI:N/S:U/C:H/I:H/A:H - 9.8`

Problematic parameter:

```
curl --retry-delay 18446744073709552
```

Issue:
Few actors control the CVE ecosystem (Mitre, NVD) and have policies with implications that many do not consider.

https://daniel.haxx.se/blog/2023/08/26/cve-2020-19909-is-everything-that-is-wrong-with-cves/

Types of Version Detection

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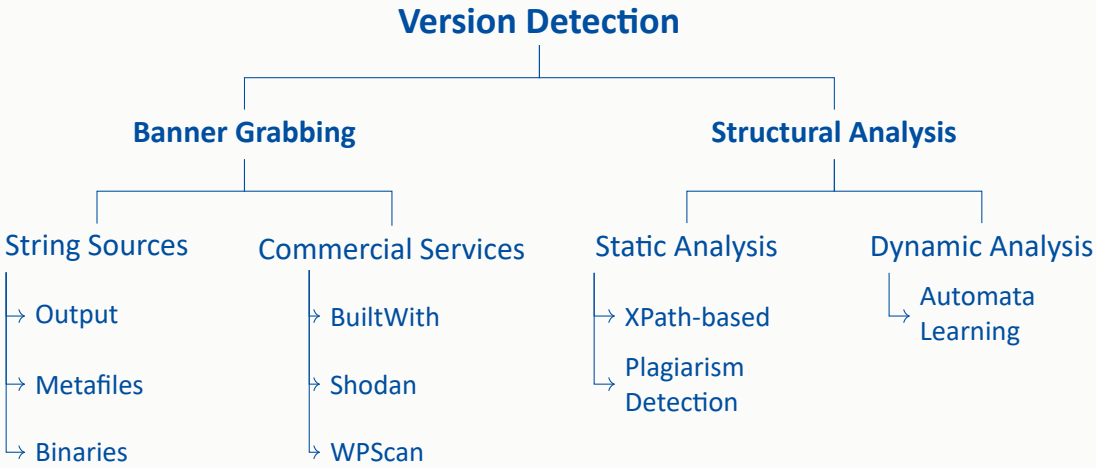
Taxonomy



Banner Grabbing

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Banner Grabbing

Most systems include functionality to announce their version.

For this, systems include a special string called **banner**.

Banner grabbing denotes the process of reading this banner.

Banners are usually unstructured and their location varies.

Main advantages: Easy to fetch, able to identify unknown versions

Main disadvantages: Easy to hide and spoof

Banner Grabbing

Lots of Strings

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Lots of strings

We will look at different sources for banners.

- **Output**
  Banners contained in the direct output of a system
- **Metafiles**
  Accidental files containing version information
- **Binaries**
  Banners in BLOBs and ELFs

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Banners from Output

If you have local access and the system and you analyze a locally installed package, the task is easy.

Example for Ubuntu:

```
$ apt-cache policy gcc
gcc:
  Installed: 4:13.2.0-7ubuntu1
  Candidate: 4:13.2.0-7ubuntu1
  Version table:
*** 4:13.2.0-7ubuntu1 500
    500 http://archive.ubuntu.com/ubuntu noble/main amd64 Packages
    100 /var/lib/dpkg/status
```

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Banners from Output

Most command line utilities offer an option similar to `--version`.

```
$ gcc --version
gcc (GCC) 14.2.1 20240805
Copyright (C) 2023 Free Software Foundation, Inc.
This is free software; see the source for copying conditions. There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
```

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Banners from Output

Most GUI Tools offer version information through their menu, often at `Help > About`.

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Banners from Output

Most web servers announce their version in the `Server` HTTP Header:

```
$ curl -I https://itsec.cs.uni-bonn.de/feedback/
HTTP/2 200
strict-transport-security: max-age=63072000; includeSubdomains; preload
accept-ranges: bytes
content-length: 509
content-type: text/html
etag: 66a26059-1fd
server: nginx/1.27.0
```

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Banners from Output

Many web applications announce their version in <meta> tags:

```
<!DOCTYPE html>
<html>
  <head>
    <meta name="generator" content="WordPress 6.4.1" />
    [...]
```

... and we can find even more version information in HTML.

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Metadata in the Output

The HTML output usually contains many more versions. They are most often classified as **metadata** and not strictly as banners.

- **CDN script URLs**

```
<script src="//cdnjs.cloudflare.com/ajax/libs/cookieconsent2/3.1.0/cookieconsent.min.js">
```

- **Web App Plugins**

```
<link rel='stylesheet' href='https://wordpress.org/wp-content/plugins/gutenberg/.../style.css?ver=18.8.0' />
```

- **Inline Data**

```
window._wpemojiSettings = {baseUrl:"https://s.w.org/images/core/emoji/15.0.3/72x72/"}
```

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Metafiles

Metafiles are served on a web server, but not required for functionality.
Usually, they are accessible through misconfiguration or accidentally copied.

Some types of metafiles include

- Readmes
- Files from package managers
- Files from version control
- Artifacts from the build process

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Metafiles

Readme files are often used to detect versions of WordPress extensions.

```
$ curl https://wordpress.org/wp-content/plugins/gutenberg/readme.txt | head
=== Gutenberg ===
Contributors: matveb, joen, karmatosed
Tested up to: 6.5
Stable tag: 18.8.0
License: GPLv2 or later
License URI: http://www.gnu.org/licenses/gpl-2.0.html

The Gutenberg plugin adds editing, customization, and site building to WordPre
Use it to test beta features before their official release.
```

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Metafiles

Files from package manager exist if a project is served directly. In the web, we can find many metafiles from composer (PHP) and npm (JavaScript).

```
$ curl https://wordpress.org/composer.json
{
 "name": "wordpress/wordpress.org",
 "description": "wordpress.org multi-network install",
 "license": "GPLv2+",

 "require-dev": {
  "dealerdirect/phpcodesniffer-composer-installer": "^0.7.0",
  "phpunit/phpunit": "^9.4",
  "spatie/phpunit-watcher": "^1.23.2",
  "wp-coding-standards/wpcs": "2.*"
 },

 "scripts": {
  "format": "phpcbf -p",
  "lint": "phpcs",
  "test": "php -d xdebug.mode=off ./vendor/bin/phpunit",
  "test:watch": "phpunit-watcher watch"
 }
}
```

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Metafiles

Files from package manager exist if a project is served directly. In the web, we can find many metafiles from composer (PHP) and npm (JavaScript).

```
$ curl http://149.202.74.137/package.json
{
    "private": true,
    "devDependencies": {
        "autoprefixer": "^10.3.7",
        "axios": "^0.21",
        "browser-sync": "^2.27.7",
        "browser-sync-webpack-plugin": "2.3.0",
        "laravel-mix": "^6.0.6",
        "lodash": "^4.17.19",
        "postcss": "^8.3.11",
        "tailwindcss": "^2.2.17"
    },
    "dependencies": {
        "@rateyo/jquery": "^3.0.0-alpha.2",
        "jquery": "^3.6.0",
        "rateyo": "^3.0.0-alpha.2",
        "slick-carousel": "^1.8.1"
    }
}
```

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Metafiles

Files from **version control systems** can be very sensitive as they may contain the complete history of the repository. Besides allowing **access to source files**, these can include **credentials** that have been pushed into the repository at any point in time.

```
$ curl https://flux-cdn.com/.git/HEAD
ref: refs/heads/masters
```

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Metafiles

Source maps are artifacts from JavaScript bundling process and can reveal file system paths of the source code.The package manager `pnpm` writes the package versions into directory names for symlinking.

```
$ curl https://assets-cdn.getbento.com/static/analytics/js/snowplow-3.1.6.js.map | jq .sources | grep .pnpm
"../../../common/temp/node_modules/.pnpm/tslib@2.3.0/node_modules/tslib/tslib.es6.js",
"../../../common/temp/node_modules/.pnpm/uuid@3.4.0/node_modules/uuid/lib/bytesToUuid.js",
"../../../common/temp/node_modules/.pnpm/uuid@3.4.0/node_modules/uuid/lib/rng-browser.js",
"../../../common/temp/node_modules/.pnpm/uuid@3.4.0/node_modules/uuid/v1.js",
"../../../common/temp/node_modules/.pnpm/uuid@3.4.0/node_modules/uuid/v4.js",
"../../../common/temp/node_modules/.pnpm/uuid@3.4.0/node_modules/uuid/index.js",
"../../../common/temp/node_modules/.pnpm/crypt@0.0.2/node_modules/crypt/crypt.js",
"../../../common/temp/node_modules/.pnpm/charenc@0.0.2/node_modules/charenc/charenc.js",
"../../../common/temp/node_modules/.pnpm/sha1@1.1.1/node_modules/sha1/sha1.js",
"../../../common/temp/node_modules/.pnpm/jstimezonedetect@1.0.7/node_modules/jstimezonedetect/dist/jstz.min.js",
```

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Binaries

Banners are usually stored directly in the binary. If we know how versions look, we can obtain them quite easily.

```
$ strings /boot/vmlinuz-linux | grep -E '[0-9]+\.[0-9]+\.[0-9]+'
6.10.7-arch1-1 (linux@archlinux) #1 SMP PREEMPT_DYNAMIC Thu, 29 Aug 2024 16:48:57 +0000
6.10.7-arch1-1 (linux@archlinux) (gcc (GCC) 14.2.1 20240805, GNU ld (GNU Binutils) 2.43.0) #1 SMP PREEMPT_DYNAMIC Thu, 29 Aug 2024
      16:48:57 +0000
1.5.2
```

```
$ strings /usr/bin/gcc | grep -E '[0-9]+\.[0-9]+\.[0-9]+'
GLIBC_2.3.2
GLIBC_2.3.4
GLIBC_2.2.5
14.2.1
14.2.1 20240805
[...]
```

Banner Grabbing

Commercial Services

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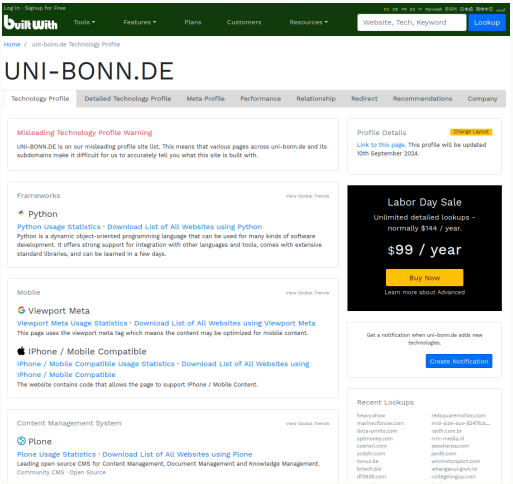
builtwith.com

Builtwith is a closed source product analyzing **technologies on the web**.



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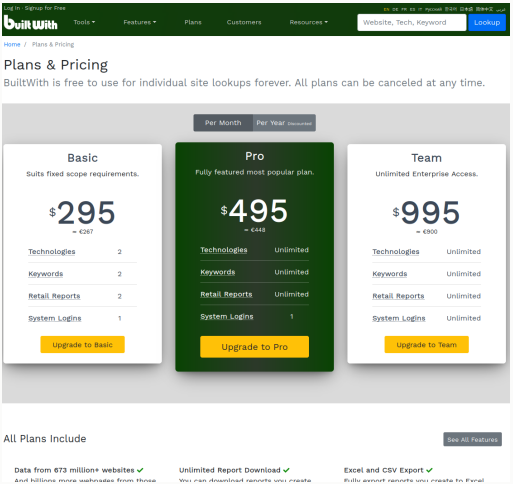

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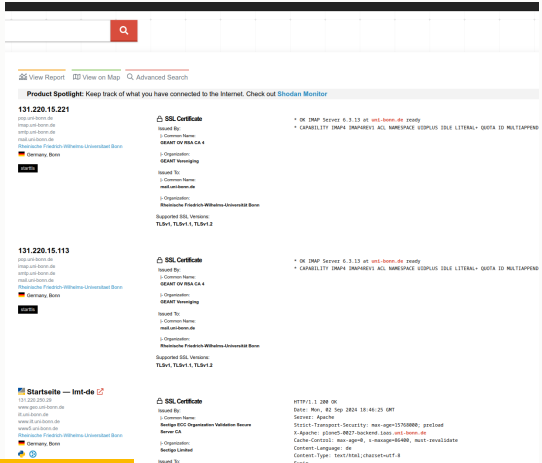
shodan.io

Shodan offers a closed-source **search engine for servers**. Thus, it is suitable to find IoT devices or many other interesting services.



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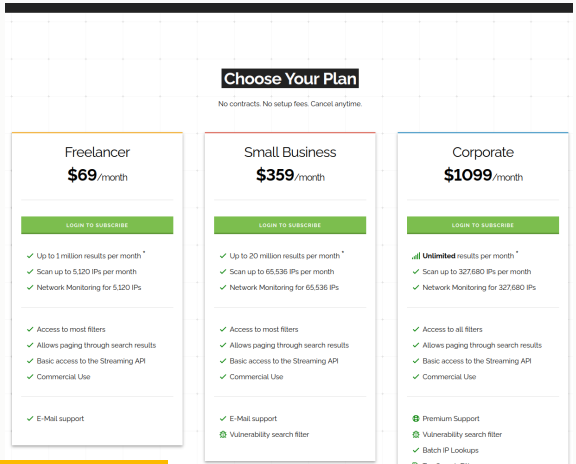

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Wappalyzer

Wappalyzer is an open source SaaS **web technology scanner**. It works with an extensive set of regular expressions.

wappalyzer / src / technologies / **p.json**

Code | Blame | 3105 lines (3105 loc) · 78.9 KB

```
1723        "website": "http://pligg.com"
1724      },
1725      "Plone": {
1726        "cats": [
1727          1
1728        ],
1729        "cpe": "cpe:2.3:a:plone:plone:*:*:*:*:*:*:*:*",
1730        "icon": "Plone.svg",
1731        "implies": "Python",
1732        "meta": {
1733          "generator": "Plone"
1734        },
1735        "website": "http://plone.org"
1736      },
1737      "Plotly": {
1738        "cats": [
1739          25
1740        ],
1741        "icon": "Plotly.png",
1742        "implies": "D3",
1743        "js": {
1744          "Plotly.version": "([\\d.])\\;version:\\1"
1745        },
1746        "scriptSrc": "https?://cdn\\.plot\\.ly/plotly",
1747        "website": "https://plot.ly/javascript/"
```

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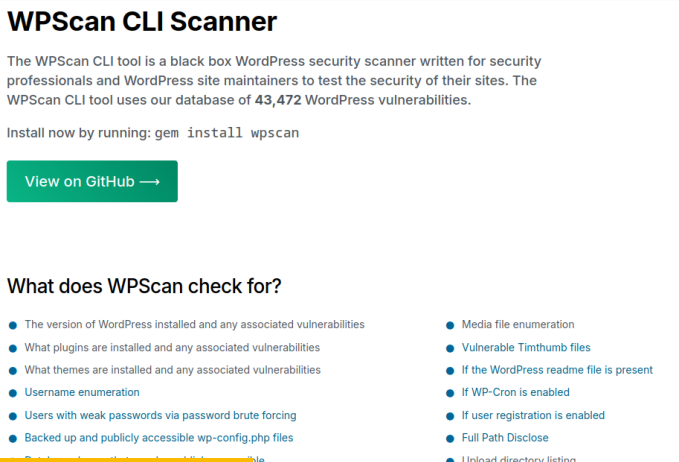
WPScan

WPScan is an open source **WordPress security scanner**. It retrieves versions through banner grabbing to search for known vulnerabilities.



Structural Analysis

Structural Analysis

Static Analysis

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Static Analysis

Structural static analysis compares features from statically analyzed assets to those supplied by a reference system.

We consider two use cases with different solutions:

1 Web Application Version Detection with XPath-based detection

2 Detection of library versions in JavaScript Bundle using plagiarism detection

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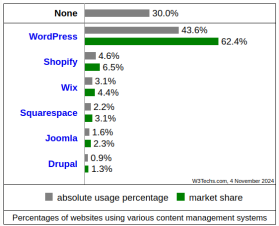
XPath-based detection

Web Applications power are an important foundation of the modern world wide web infrastructure. The following analysis technique focuses on the special class of **Content Management Systems (CMS)**.



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XPath-based detection

Web Applications power are an important foundation of the modern world wide web infrastructure. The following analysis technique focuses on the special class of **Content Management Systems (CMS)**.

Version Detection is highly useful for web applications for several reasons

- Internet exposure
- Widely deployed
- High risk of attacks

F. Marquardt and L. Buhl, “Déjà Vu? Client-Side Fingerprinting and Version Detection of Web Application Software,” 2021 IEEE 46th Conference on Local Computer Networks

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XPath-based detection

Banner grabbing has several disadvantages:

- Application specific
- Often relies on aggressive scanning
- Banners can be disabled

XPath-based detection improves these by being

- Generic
- Robust
- Passive

XPath-based detection

Foundations: XPath Basics

```
1  <html>
2    <head>
3      <title>Example</title>
4    </head>
5    <body>
6      <h1 class="example">
7        Hello World!
8      </h1>
9    </body>
10 </html>
```

- `//title`
  `<title>Example</title>`
- `/html/body/h1/text()`
  `Hello World!`
- `//h1[@class='example']`
  `<h1 ...> ... </h1>`
- `//body[1]`
  `<body> ... </body>`

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XPath-based detection

The main features in this scenario are derived from HTML files.

```
1  <html>
2    <head>
3      <title>Example</title>
4    </head>
5    <body>
6      <h1 class="example">
7        Hello World!
8      </h1>
9    </body>
10 </html>
```

- /html
- /html/head
- /html/head/title
- /html/body
- /html/body/h1
- /html/body/h1[@class=example]

XPath-based detection

Asset Hashing

Additional features are derived from hashing (static) assets (CSS, JS) with SHA256.

Main advantages: Performance increase, no equivalents for other formats

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XPath-based detection

Feature Extraction Process

1. Generate reference instances
2. Extract features
3. Store fingerprints
4. Feature pruning (take only fingerprints with highest feature cardinality)

Version Detection Process

1. Extract features
2. Compare with fingerprint database
3. Select version(s) with highest amount of matching features

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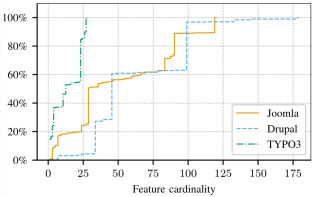
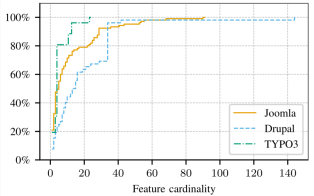
XPath-based detection: Results

CDF of feature cardinality

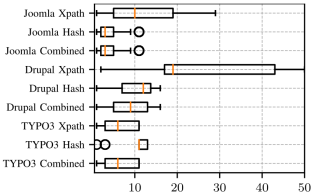


(a) XPath

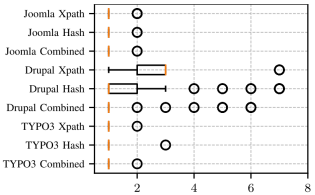


(b) Hash

Amount of candidates



(a) Counting all versions



(b) Counting only distinct minor versions

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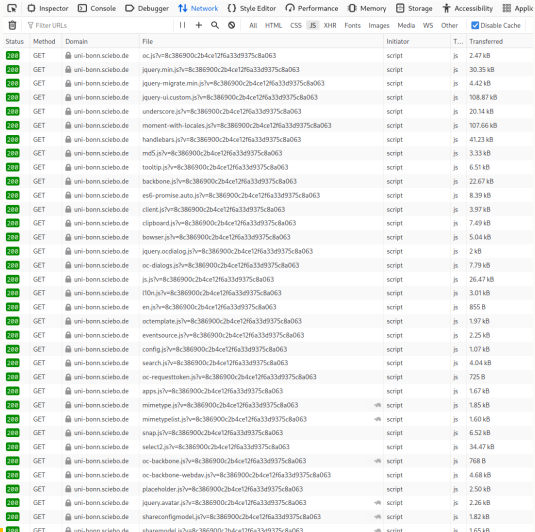
Plagiarism Detection

Why JavaScript Bundling

- Less HTTP requests
- Dependency ordering
- Scoping through IIFEs



Plagiarism Detection

Foundations: JavaScript Bundling

The bundling process consists of multiple steps:

🌳 **Tree Shaking**
Select source files to be bundled

✂️ **Code Split**
Detect logical boundaries through dynamic imports between modules

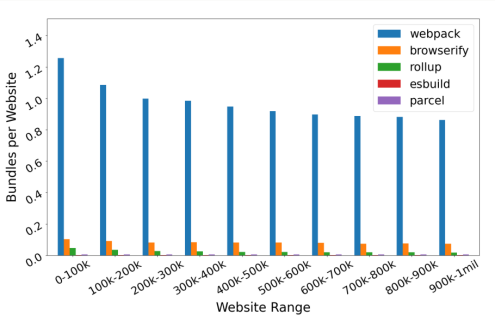
📦 **Packaging**
Wrap all components together

🔨 **Minification**
Shrink source code size

Plagiarism Detection

Foundations: JavaScript Bundlers in practice

Several JavaScript bundlers are used in practice. They employ different algorithms and architectures but **share the same approach**.



J. Rack and C. Staicu, "Jack-in-the-box: An Empirical Study of JavaScript Bundling on the Web and its Security Implications," CCS 2023

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Plagiarism Detection

Foundations: JavaScript Bundles with Webpack

```
1 (window.webpackJsonp=window.webpackJsonp||[]).push([[80],{
2 maj8:function(e,t,n){"use strict";/* object-assign, (c) Sindre Sorhus, @license MIT */ var r=Object.
    getOwnPropertySymbols,i=Object.prototype.hasOwnProperty,o=Object.prototype.propertyIsEnumerable;function a(e){if(
    null==e)throw new TypeError("Object.assign cannot be called with null or undefined");return Object(e)}...},
3 ZK3j:function(e,t,n){"use strict";var r=n("Y4pH"),i=n("qWlw");function o(e,t){return 55296==(64512&e.charCodeAt(t))&&(!(
    t<0||t+1>=e.length)&&56320==(64512&e.charCodeAt(t+1)))}function a(e){return(e>>>24|e>>>8&65280|e<<8&16711680|(255&e
    )<<24)>>>0}function s(e){return 1===e.length?"0"+e:e}t.toHex=function(e){for(var t="",n=0;n<e.length;n++)t+=s(e[n].
    toString(16));return t},t.rotr32=function(e,t){return e>>>t|e<<32-t}},
4 xy6B:function(e,t,n){"use strict";var r=n("ZK3j"),rotr32;function i(e,t,n){return e&t^~e&n}function o(e,t,n){return e&t^
    e&n^t&n}function a(e,t,n){return e^t^n}t.ft_1=function(e,t,n,r){return 0===e?i(t,n,r):1===e||3===e?a(t,n,r):2===e?o
    (t,n,r):void 0},t.s1_256=function(e){return r(e,6)^r(e,11)^r(e,25)},t.g0_256=function(e){return r(e,7)^r(e,18)^e
    >>>3},t.g1_256=function(e){return r(e,17)^r(e,19)^e>>>10}}
5 });
```

Figure 1: A simplified version of a real-world bundle from nytimes.com. With dashed lines we highlight the compartments and with the arrow we show a direct dependency between the last two compartments.

J. Rack and C. Staicu, "Jack-in-the-box: An Empirical Study of JavaScript Bundling on the Web and its Security Implications," CCS 2023

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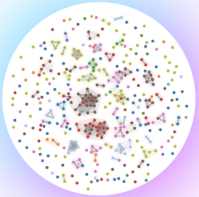
Plagiarism Detection

Dolos

Source code plagiarism detection

Quick and easy plagiarism detection for a wide range of programming languages.



Documentation | Examples | Use Dolos →

Free web application

No installation required. Secure, private and fast. Just upload your files and get a report.

Try Dolos →

Multilingual

Dolos supports many programming languages by leveraging the tree-sitter parser library.

Supported languages →

CLI & Library

Run Dolos from the command line or use it as a library in your own project. For advanced users.

Installation instructions →

Open source

View, use and contribute to the source code. Licensed under the MIT license.

Fueled by research

Dolos is the result of active research in the field of source code plagiarism detection.

Advanced algorithms

Using state-of-the-art algorithms, Dolos helps you discover plagiarism.

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Plagiarism Detection

General Objective: Given *N* inputs, find similar fragments between them

Dolos Input: *N* source code files

Dolos Output: Pairwise similarity score

Algorithm:

1. Tokenization
2. Fingerprinting
3. Indexing
4. Reporting

Plagiarism Detection

Step 1: Tokenization

Immunity against simple modifications is achieved by tokenizing the input into an abstract syntax tree (AST).

```
function sum(a, b) {
  return a + b;
}
```

```
program ([1, 0] - [4, 0])
  function ([1, 0] - [3, 1])
    identifier ([1, 9] - [1, 12])
    formal_parameters ([1, 12] - [1, 18])
      identifier ([1, 13] - [1, 14])
      identifier ([1, 16] - [1, 17])
    statement_block ([1, 19] - [3, 1])
      return_statement ([2, 2] - [2, 15])
        binary_expression ([2, 9] - [2, 14])
          identifier ([2, 9] - [2, 10])
          identifier ([2, 13] - [2, 14])
```

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Step 2: Fingerprinting

Dolos finds common sequences of successive tokens with the following algorithm:

1. Split tokens into *k*-grams
2. Use a fast hashing function
3. Select hashes with a windowed rolling hash function (Winnowing algorithm, window size *w*)

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Step 3: Indexing

For efficient search, the fingerprints are converted into an associative container.

```
index = {
  hash1: SharedFingerprint {
    file1: [ occ1, occ2 ],
    file2: [ occ1 ]
  },
  hash2: SharedFingerprint {
    file1: [ occ3 ],
    file3: [ occ1 ]
  }
}
```

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Step 4: Reporting

There are multiple metrics of comparing source files with each other:

Similarity: $\mathrm{sim}(a, b) = \frac{S_a + S_b}{T_a + T_b}$

Total Overlap: $S_a + S_b$

Longest fragment: Longest run of consecutively shared fingerprints

Plagiarism Detection: Dolos Example

Comparing chunk-vendors.34601dc3.js with index.js

The compare view matches code fragments & differences between 2 files.

MATCHES | DIFF

Similarity: 0% | Longest fragment: 7 | Total overlap: 127

chunk-vendors.34601dc3.js — VIEW SUBMISSION

index.js — VIEW SUBMISSION

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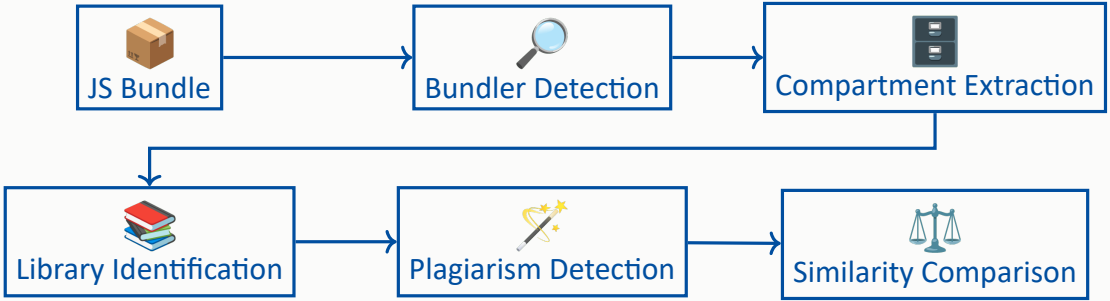
Plagiarism Detection

JavaScript Bundle Analysis Pipeline



Plagiarism Detection

The implementation of Dolos needs some **adaptations, fixes and improvements** to work well with our pipeline.

As Dolos works on single source files, we need to **generate a single file** from a package.

When comparing similarities with Dolos, it is important to **select the correct source files** which end up in the bundle.

Furthermore, it is best to **only consider specific compartments** which belong to the library that is analyzed.

The similarity metric can be improved as it is **inaccurate for small files**.

Good values for k **and** w may be chosen adaptively depending on properties of the library.

Structural Analysis

Dynamic Analysis

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Dynamic Analysis

Structural dynamic analysis compares the behavior of the system under test to those supplied by a reference system.

We consider structural dynamic analysis on the example of automata learning for TLS.

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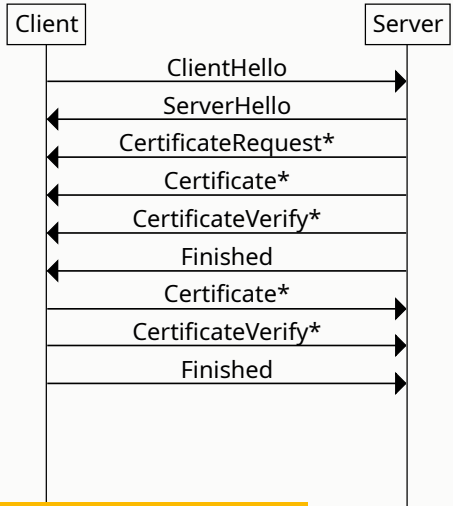
TLS in a nutshell

TLS provides confidentiality, authenticity and integrity for a connection.

A.2. Server

```
                              START <-----+
               Recv ClientHello |         | Send HelloRetryRequest
                                v         |
                             RECVD_CH ----+
                                | Select parameters
                                v
                             NEGOTIATED
                                | Send ServerHello
                                | K_send = handshake
                                | Send EncryptedExtensions
                                | [Send CertificateRequest]
Can send                        | [Send Certificate + CertificateVerify]
app data                        | Send Finished
after   -->                     | K_send = application
here                  +---------+--------+
                No 0-RTT |                  | 0-RTT
                         |                  |
  K_recv = handshake     |                  | K_recv = early data
[Skip decrypt errors]    |    +------> WAIT_EOED -+
                         |    |       Recv |      | Recv EndOfEarlyData
                         |    | early data |      | K_recv = handshake
                         |    +------------+      |
                         |                        |
                         +> WAIT_FLIGHT2 <--------+
                                   |
                         +---------+--------+
                No auth  |                  | Client auth
                         |                  |
                         |                  v
                         |             WAIT_CERT
                         |        Recv |       | Recv Certificate
                         |       empty |       v
                         | Certificate |    WAIT_CV
                         |             |       | Recv
                         |             v       | CertificateVerify
                         +-> WAIT_FINISHED <---+
```



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Version Detection for TLS

Existing TLS fingerprints focus on **application fingerprinting**. It is used in digital forensics and botnet detection.

Library identification and version detection strongly limits the suitable resources. All packets are processed by the application before being handed over to the library. Additionally, every application **must** configure the library when using it. Even default configurations may be depending on compilation flags.

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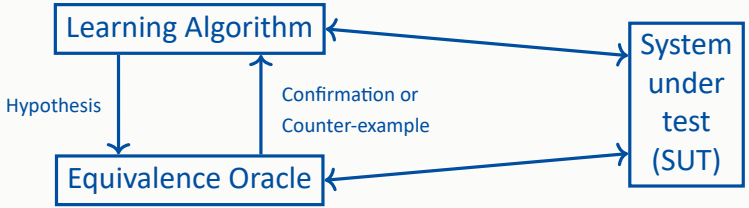
Automata Learning

Automata Learning is able to derive the implemented state machine in a black-box scenario. It works with an input alphabet Σ_I and an output alphabet Σ_O.



Examples for active learning algorithms: **L***, NL*, TTT, AAAR
Examples for equivalence methods: **random walk**, **W-method**, Wp-method, distinguishing bounds

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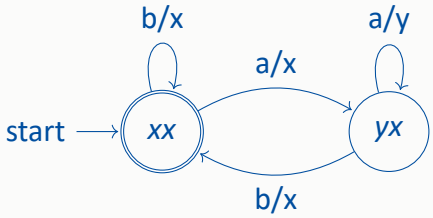
The L^* algorithm

The central datastructure of the L^* algorithm is the **observation table**. It classifies members as members or non-members of the SUT's language $\mathcal{L}$.

Observation table

		E	
		a	b
S	ϵ	x	x
	a	y	x
$S.\Sigma_I$	b	x	x
	$a.a$	y	x
	$a.b$	x	x

State machine



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The L^* algorithm

The central datastructure of the L^* algorithm is the **observation table**. It classifies members as members or non-members of the SUT's language $\mathcal{L}$.

The datastructure contains three elements (S, E, T).

- $S \subset (\Sigma_I)^*$: Non-empty prefix-closed set of strings
- $E \subset (\Sigma_I)^*$: Non-empty suffix-closed set of strings
- $T : (S \cup S \times \Sigma_I) \times E \mapsto \Sigma_O$: Observed outputs from the SUT

When viewed as a table, it has

- row captions from $S \cup S \times \Sigma_I$
- column captions from E
- entries given by T

A. Rasoamanana, "Derivation and Analysis of Cryptographic Protocol Implementations," PhD Thesis, 2023
Original from: D. Angluin, "Learning Regular Sets from Queries and Counterexamples,", Inf. Comput. 75(2), 1987

The L^* algorithm

Observation table

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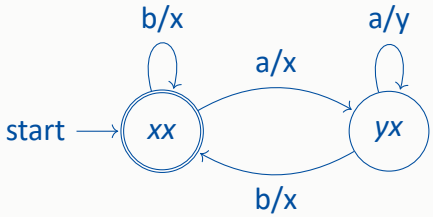
State machine



The observation table corresponds to a state machine iff it is **closed** and **consistent**.

The L^* algorithm

Observation table

		E	
		a	b
S	ϵ	x	x
	a	y	x
$S.\Sigma_I$	b	x	x
	$a.a$	y	x
	$a.b$	x	x

An observation table is **closed** if for all $t \in S \times \Sigma_I$ there exists $s \in S$ such that $\text{row}(t) = \text{row}(s)$.
An observation table is **consistent** if for all $(s_1, s_2) \in S \times S$ with $\text{row}(s_1) = \text{row}(s_2)$ then for all $a \in \Sigma_i$, $\text{row}(s_1 \cdot a) = \text{row}(s_2 \cdot a)$.
Intuitively, rows represent states. Closure means all states are defined. Consistency means that multiple representations of the same state have the same transitions.

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The L^* algorithm

The learning algorithm consists of three steps.

If the observation table is **closed and consistent**, we can derive our hypothesis.

If the observation table is **not closed**, there exists $t \in S \cdot \Sigma_I$ with $\text{row}(t) \neq \text{row}(s)$ for all $s \in S$. Thus, add t to S and query the SUT for any empty cells.

If the observation table is **not consistent**, there exists $(s_1, s_2) \in S \times S$ and $a \in \Sigma_i$ such that $\text{row}(s_1) = \text{row}(s_2)$ and $\text{row}(s_1 \cdot a \cdot e) \neq \text{row}(s_2 \cdot a \cdot e)$ with $e \in E$. Thus, add $a \cdot e$ to E and query the SUT for any empty cells.

Furthermore, if we receive a counter-example $\mathcal{C}$, add $\mathcal{C}$ and all its prefixes to S and query the SUT for any empty cells.

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The equivalence oracle

There is no equivalence oracle.

Fortunately, we can approximate an equivalence oracle. If some assumptions are fulfilled, we might even get certain guarantees for the result.

Equivalence method: Random Walk
A random walk starts in the initial state, performs random transitions and restarts with a certain configurable probability.

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Automata Learning for TLS

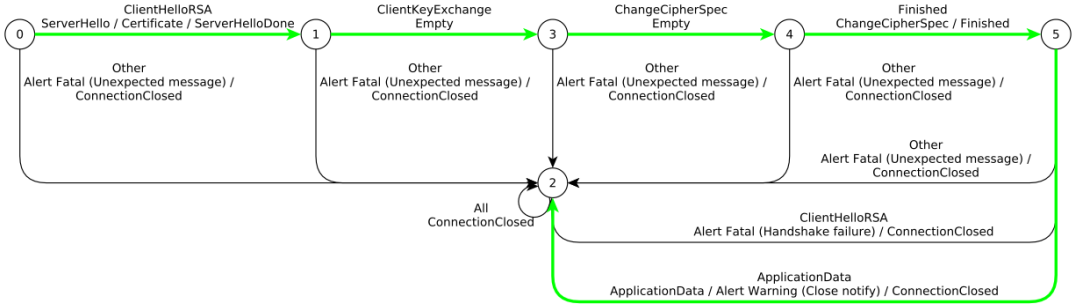

Figure 6: Learned state machine model for RSA BSAFE for Java 6.1.1

J. De Ruiter & E. Poll, "Protocol state fuzzing of TLS implementations," 24th USENIX Security Symposium, 2015

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Automata Learning for TLS

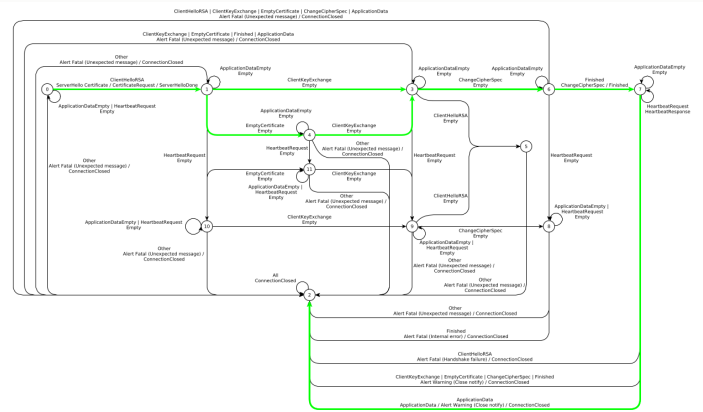

Figure 2: Learned state machine model for GnuTLS 3.3.8

J. De Ruiter & E. Poll, “Protocol state fuzzing of TLS implementations,” 24th USENIX Security Symposium, 2015

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Automata Learning for TLS

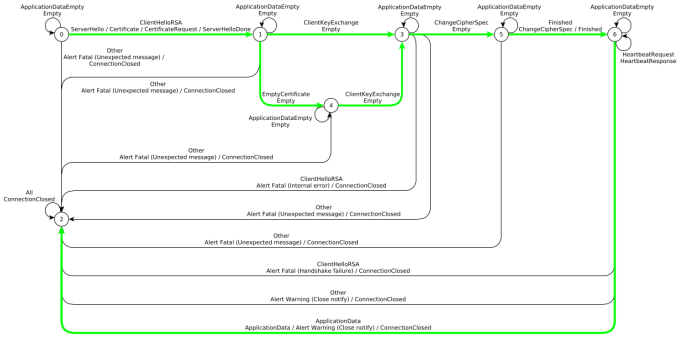

Figure 3: Learned state machine model for GnuTLS 3.3.12. A comparison with the model for GnuTLS 3.3.8 in Fig. 2 shows that the superflous states (8, 9, 10, and 11) are now gone, confirming that the code has been improved.

J. De Ruiter & E. Poll, "Protocol state fuzzing of TLS implementations," 24th USENIX Security Symposium, 2015

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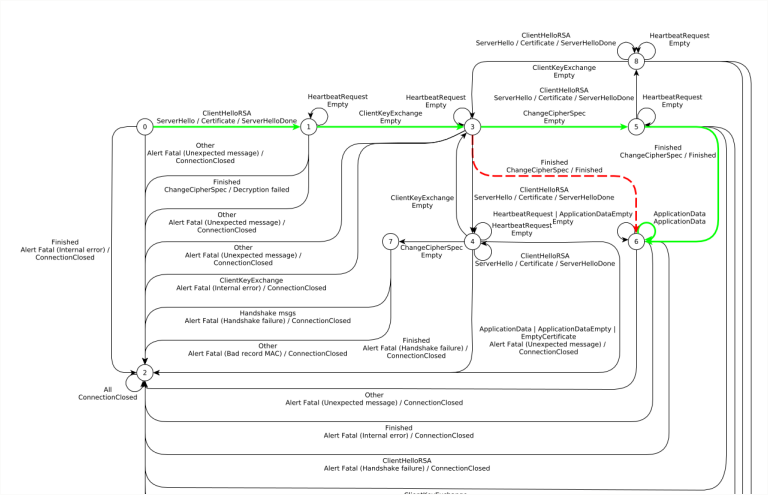
Automata Learning for TLS



J. De Ruiter & E. Poll, "Protocol state fuzzing of TLS implementations," 24th USENIX Security Symposium, 2015

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Automata Learning for TLS Library Version Detection

CVE #	Stack	Versions	Status	Comments
2014-0224	OpenSSL	$\leq$ 0.9.8za $\leq$ 1.0.0l $\leq$ 1.0.1h	Detected	EarlyCCS (unexpected CCS transitions)
2015-0204	OpenSSL	$\leq$ 0.9.8zc $\leq$ 1.0.0o $\leq$ 1.0.1j	Detected	FREAK (client- and server-side EXPORT RSA downgrade)
2015-0205	OpenSSL	$\leq$ 1.0.0p $\leq$ 1.0.1j	Not Reproduced	Client auth. bypass. Requires DH certificate support
2020-24613	wolfSSL	$\leq$ 4.4.0	Reproduced	TLS 1.3 server auth. bypass
2021-3336	wolfSSL	$\leq$ 4.6.0	New	TLS 1.3 server auth. bypass
2022-25638	wolfSSL	$\leq$ 5.1.0	New	TLS 1.3 server auth. bypass
2022-25640	wolfSSL	$\leq$ 5.1.0	New	TLS 1.3 client auth. bypass

Advantages: Robust, configuration independent

Limitations: Runtime, narrow view

A. Rasoamanana, "Derivation and Analysis of Cryptographic Protocol Implementations," PhD Thesis, 2023

Questions?

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Topics for you

Possible Seminar/Lab/Master thesis topics:

- ST24 Lab: Automatic TLS client generation
- Active TLS Fingerprinting
- JavaScript Comment Analysis
- Improving JavaScript code comparisons
- WebAssembly Artifact Analysis
- ...

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