HACKMANIT RUB

Systematic Fuzzing and Testing of TLS Libraries

Juraj Somorovsky

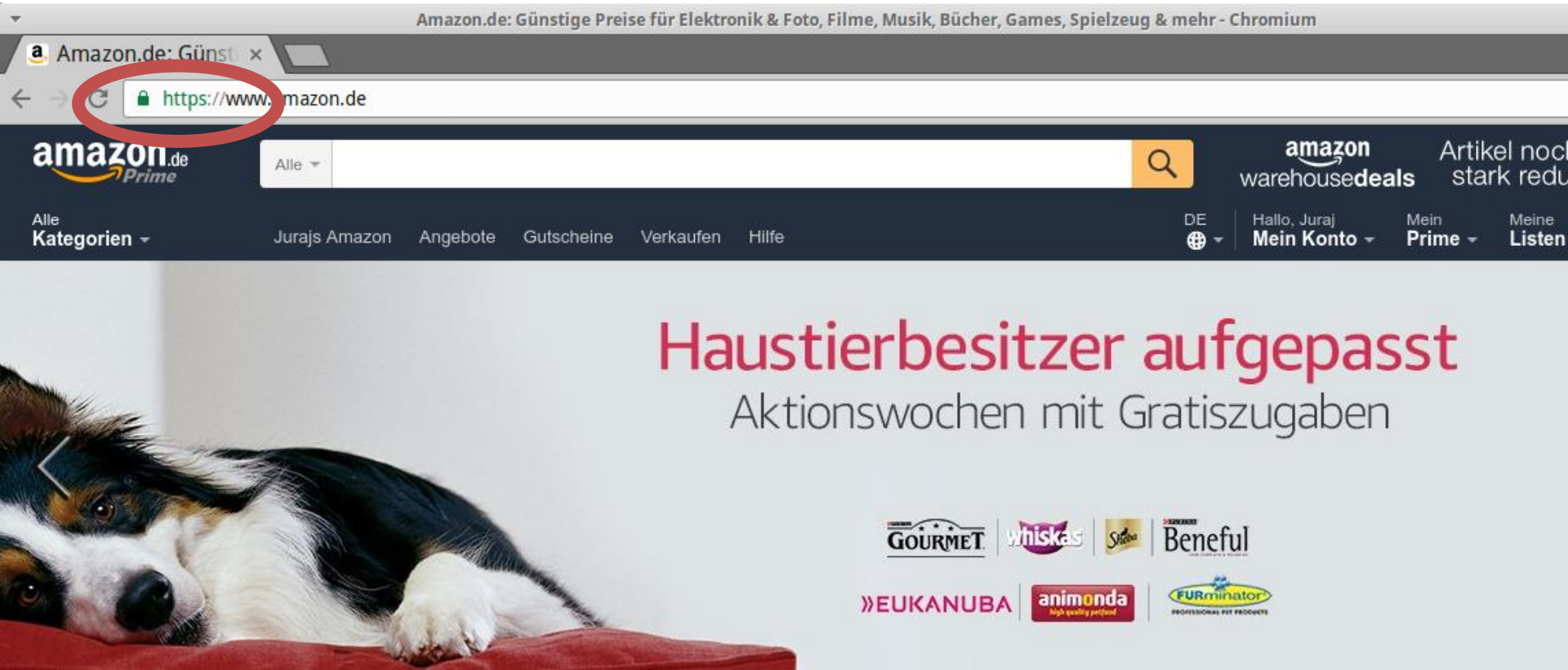
RUHR UNIVERSITÄT BOCHUM RUB

HACKMANIT

DEEPSEC

Transport Layer Security

- The most important crypto protocol
- HTTP, SMTP, IMAP …



TLS History

HACKMANIT

RUB

Secure Sockets Layer (SSL), SSLv2

SSLv3

1995

Wagner, Schneier: Analysis of SSLv3

Bleichenbacher's attack

Trasnsport Layer Security

2000

Padding oracle attack

2005

TLS 1.1

TLS 1.2

2010

BEAST, CRIME, BREACH, Lucky 13

TLS 1.3

2015

Questions

- How can we test these attacks?
- Can we find such attacks automatically?

Approach [SP2-17]

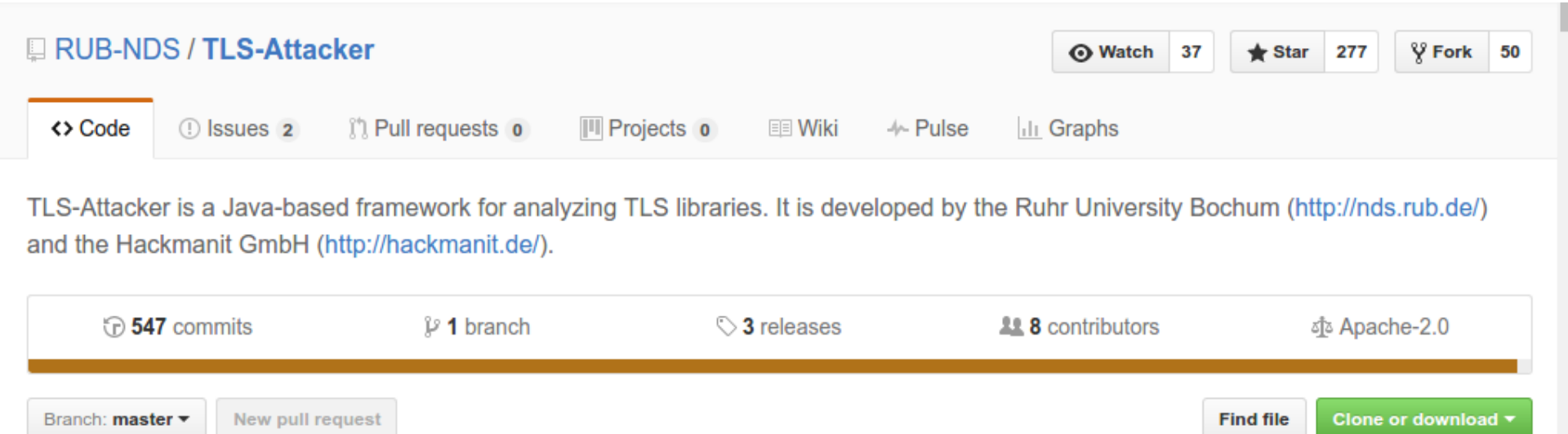
1. Collect TLS libraries
2.
3. Profit

Approach [SP2-17]

1. Collect TLS libraries
2.
3. Profit

Contributions

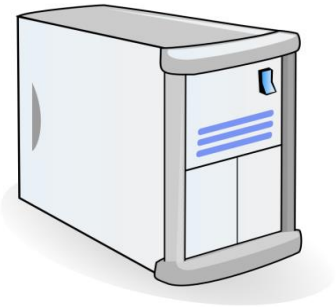
- Flexible TLS framework
- Fuzzing, testing, writing attacks …
- High impact vulnerability in OpenSSL
- Additional vulnerabilities in Botan, MatrixSSL…
- https://github.com/RUB-NDS/TLS-Attacker



Overview

1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions

TLS RSA Handshake



ClientHello →

← ServerHello

← Certificate

← ServerHelloDone

ClientKeyExchange

ChangeCipherSpec

(Client-) Finished →

ChangeCipherSpec

← (Server-) Finished

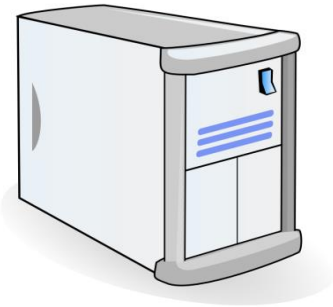
Application →

← Application

TLS is complex …

- Different versions
- Crypto primitives: RSA, EC, AES, 3DES, RC4, Chacha, Poly1305, New Hope
- Extensions
- Protocol flows

TLS is complex …



ClientHello

ServerHello

Certificate

ServerKeyExchange

ServerHelloDone

Certificate

ClientKevExchange

CertificateVerify

ChangeCipherSpec

(Client-) Finished

ChangeCipherSpec

(Server-) Finished

Heartbeat

Heartbeat

Overview

1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions

TLS History

HACKMANIT

RUB

Secure Sockets Layer (SSL), SSLv2

1995

Wagner, Schneier: Analysis of SSLv3

SSLv3

Bleichenbacher's attack

Trasnsport Layer Security

2000

Padding oracle attack

2005

TLS 1.1

TLS 1.2

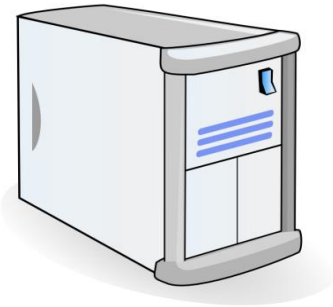
2010

BEAST, CRIME, BREACH, Lucky 13

TLS 1.3

2015

Early CCS



ClientHello →

ServerHello
Certificate
ServerHelloDone

~~Client...hange~~
ChangeCipherSpec
(Client-) Finished →

ChangeCipherSpec
(Server-) Finished ←

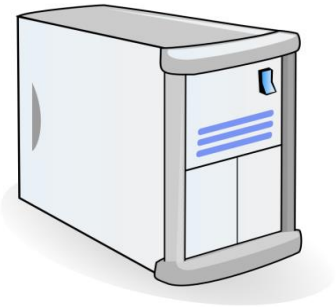
Server computes the master key based on a zero value

Early CCS

- Man-in-the-Middle attacks

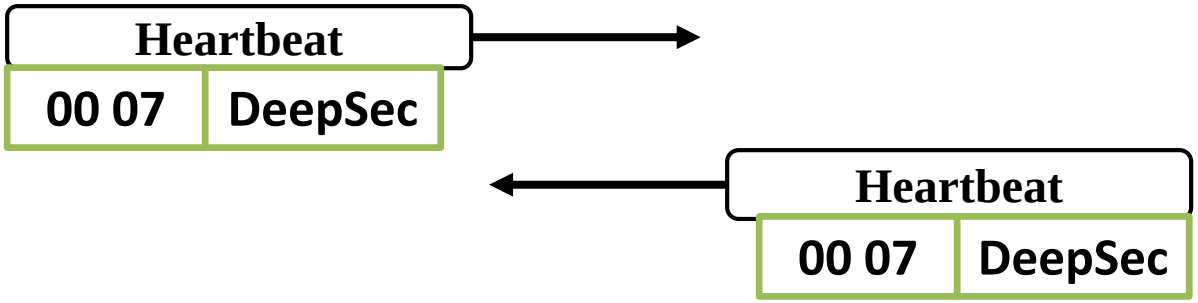
- Further state machine attacks in 2015:
  - Beurdouche et al.: FREAK
  - de Ruiter and Poll

Heartbleed

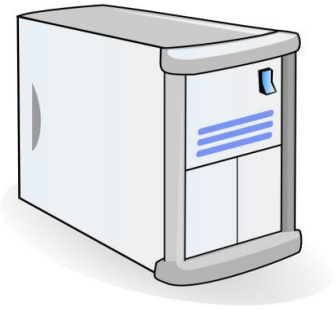


Server

[TLS Handshake]

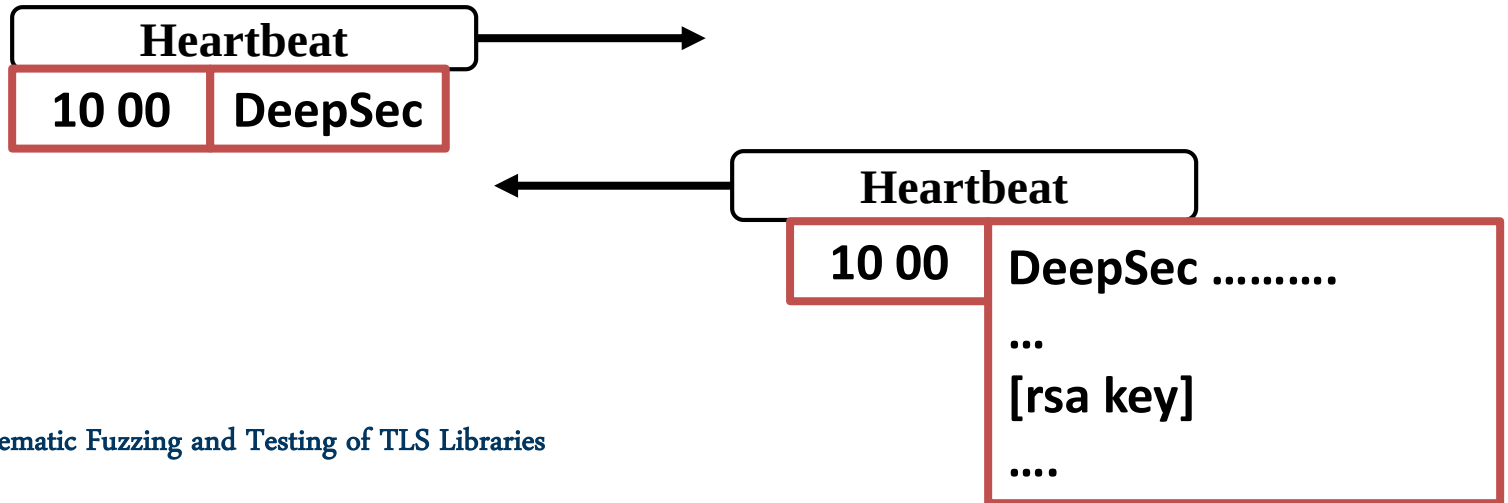


Heartbleed



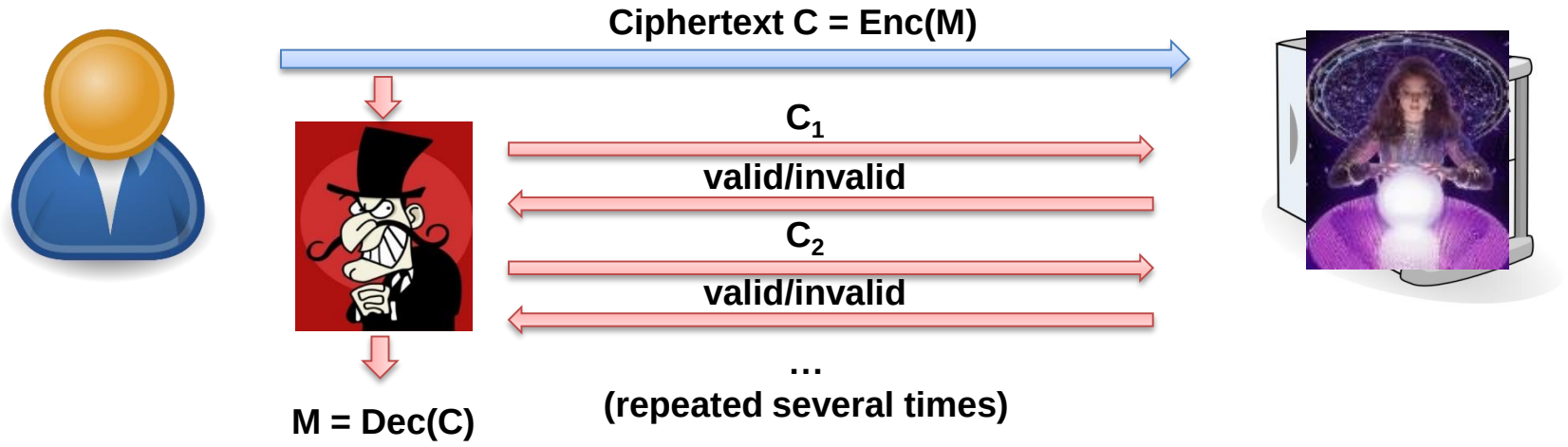
Server

[TLS Handshake]



Padding oracle attacks

- Adaptive chosen-ciphertext attacks



- AES-CBC: Vaudenay's attack
- RSA-PKCS#1: Bleichenbacher's attack

Overview

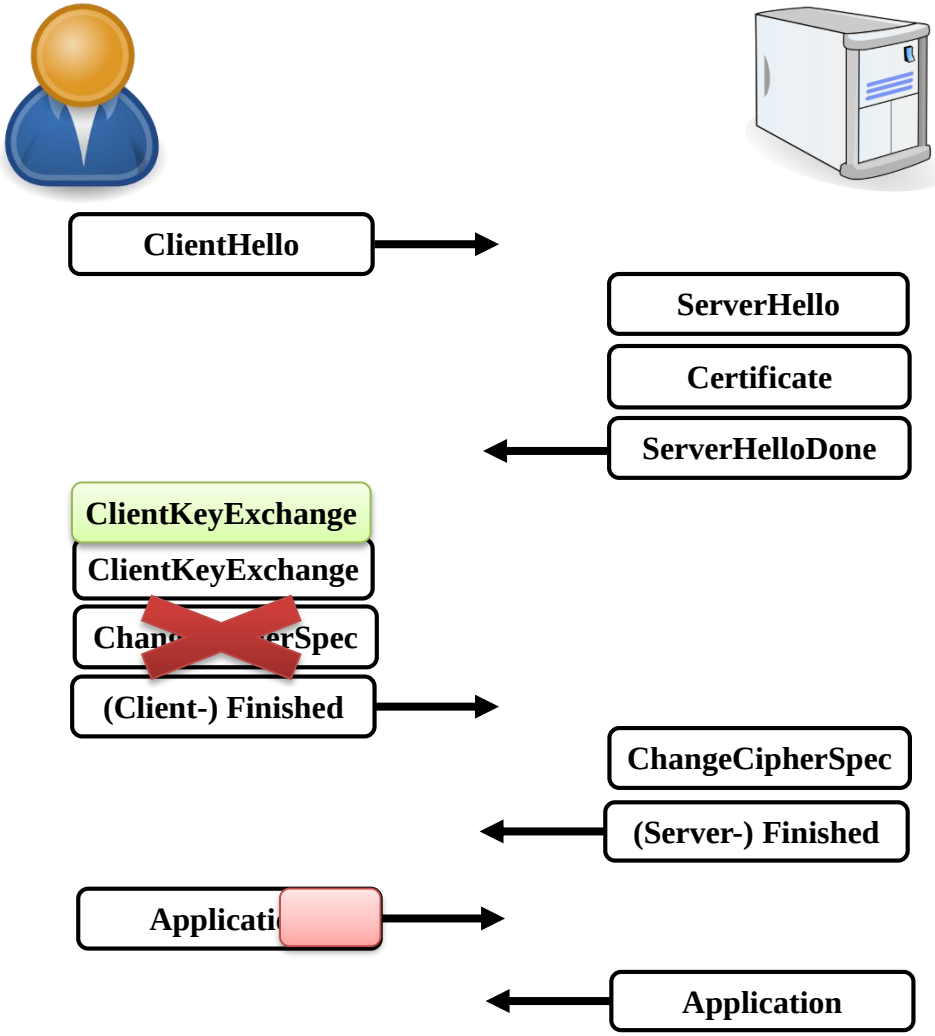
1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions

Recent Attacks on TLS

- Not only crypto attacks …
- Attacks on TLS state machines
  - FREAK
  - Early CCS
- Buffer overflows / overreads
  - Heartbleed
  - CVE-2016-6307 (High) -> CVE-2016-6309 (Critical)
- Tool for flexible protocol executions needed

Framework Prerequisites

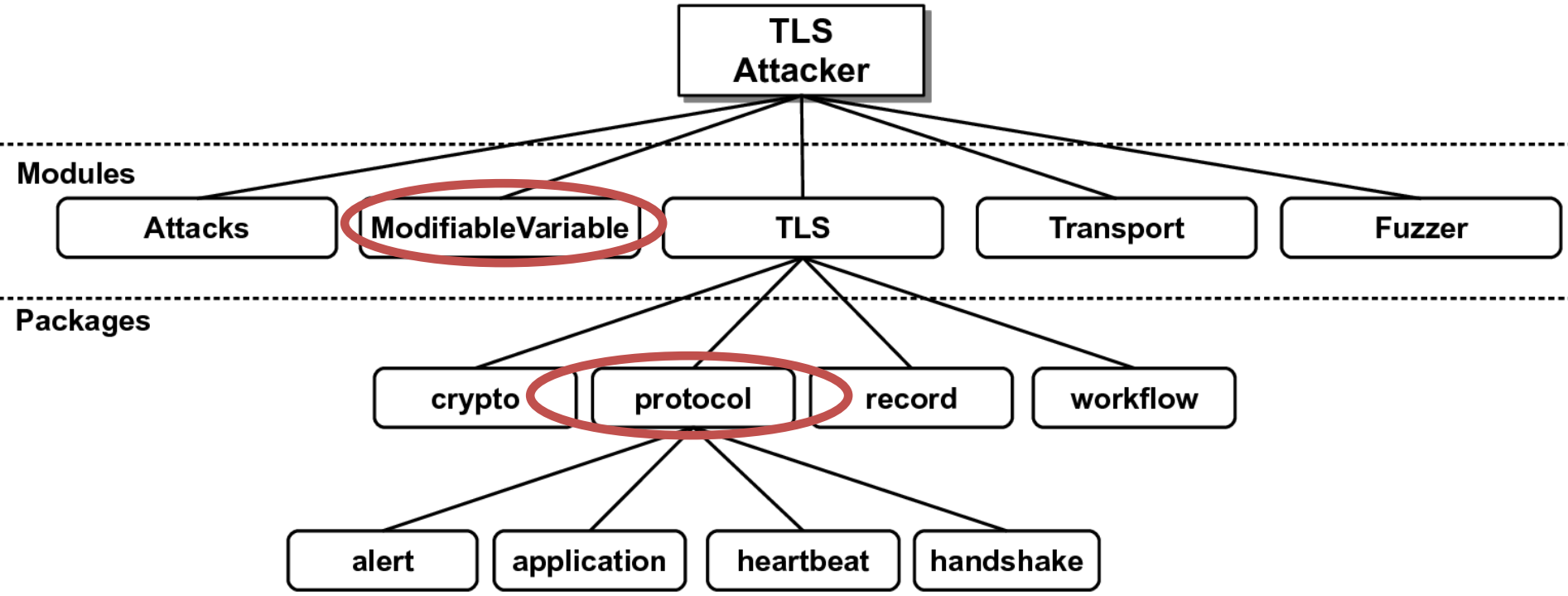
- Flexible protocol flow definition
- Message modifications
- Invalid behavior detection
- Protocol flow reproduction



Overview

1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions

High-Level Overview



Modifiable variables

- Define basic data types (integer, byte, arrays) with modifications

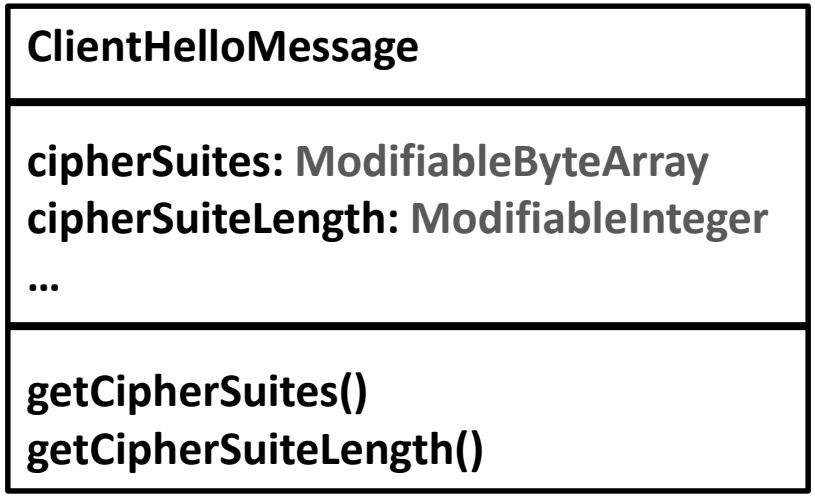
- Example:

```
ModifiableInteger i = new ModifiableInteger();
i.setValue( 30 );
i.setModification(new AddModification( 20 ));
System.out.println(i.getValue());  // 50
```

- Further modifications: xor, shuffle, delete, …

Protocol messages

- ClientHello



- Stored in a message list
- Serializable in XML

Defining a protocol flow

```
<protocolMessages>
  <ClientHello>
    <supportedCipherSuites>
      <CipherSuite>TLS_RSA_WITH_AES_128_CBC_SHA</CipherSuite>
    </supportedCipherSuites>
  </ClientHello>
  <ServerHello/>
  <Certificate/>
  <ServerHelloDone/>
  <RSAClientKeyExchange/>
  <RSAClientKeyExchange/>
  <ChangeCipherSpec/>
  <Finished/>
  <ChangeCipherSpec/>
  <Finished/>
  <Application/>
</protocolMessages>
```

Defining a protocol flow

```
<protocolMessages>
   <ClientHello>
      <supportedCipherSuites>
        <CipherSuite>TLS_RSA_WITH_AES_128_CBC_SHA</CipherSuite>
      </supportedCipherSuites>
   </ClientHello>
   <ServerHello/>
   <Certificate/>
   <ServerHelloDone/>
   <RSAClientKeyExchange/>

   <ChangeCipherSpec/>
   <Finished/>
   <ChangeCipherSpec/>
   <Finished/>
   <Heartbeat/>
</protocolMessages>
```

```
<Heartbeat>
  <payloadLength>
    <integerAddModification>
                20000
    </integerAddModification>
  </payloadLength>
</Heartbeat>
```

Overview

1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions

Vulnerability detection

- How do we detect invalid server behavior?

1. Different TLS alerts
   - Useful by padding oracle attacks
2. Address Sanitizer (ASan)
   - Detects memory errors at runtime
   - Available in recent compilers, e.g. GCC

- Vulnerability found -> protocol stored in XML

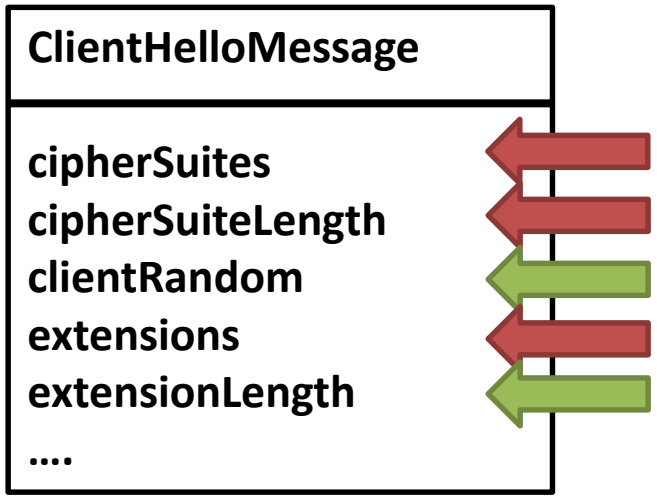
Two-stage concept

- Currently only server evaluation

1. Crypto
   - Padding oracles, Bleichenbacher attack, invalid curve attacks, POODLE …
2. Fuzzing for boundary violations
   - 3 phases

Fuzzing for boundary violations

1. Variable filtering
   - Not all variables suitable



2. Fuzzing with filtered variables
   - Random modifications (add, delete, xor)
   - Boundary v[illegible] (-128, -1, 0, 32768, ...)

Demo

3. Fuzzing with [illegible] flows

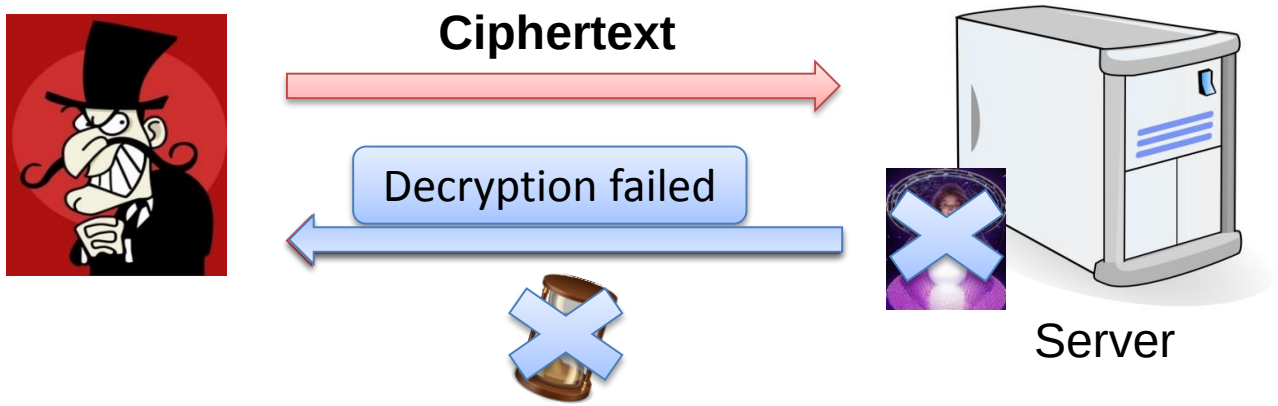
Overview

1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions

Results

- Padding oracle attack
  - OpenSSL (CVE-2016-2107)
  - Botan 1.11.21 (CVE-2015-7824)
  - MatrixSSL 3.8.2
- Bleichenbacher attack
  - MatrixSSL 3.8.2
- Missing length checks
  - GnuTLS 3.4.9
  - OpenSSL 1.0.1
- Out-of-bound reads / writes
  - OpenSSL-1.1.0-pre1 (stack overflow)
  - Botan 1.11.28 (Out-of-bound read)

Padding oracle attack

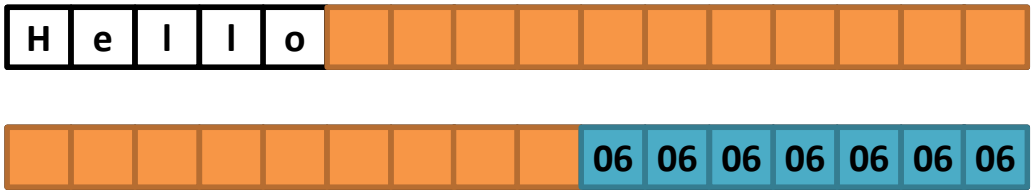


- Applicable to AES-CBC
- Challenge: not to reveal padding validity
  1. **Same** error message
  2. **Constant time** padding and HMAC validation

Lucky 13

AES-CBC in TLS

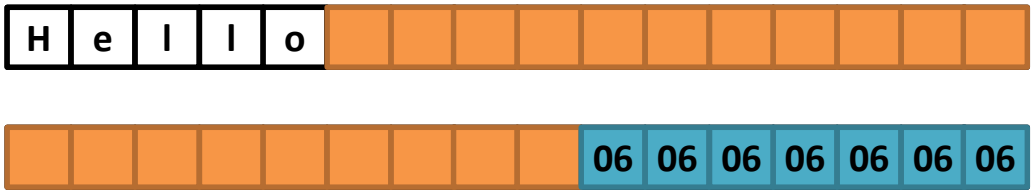
- MAC-Pad-Encrypt
- Example:
  - Two blocks
  - Message: Hello
  - MAC size: 20 bytes (SHA-1)
  - Padding size: 32 – 5 – 20 = 7



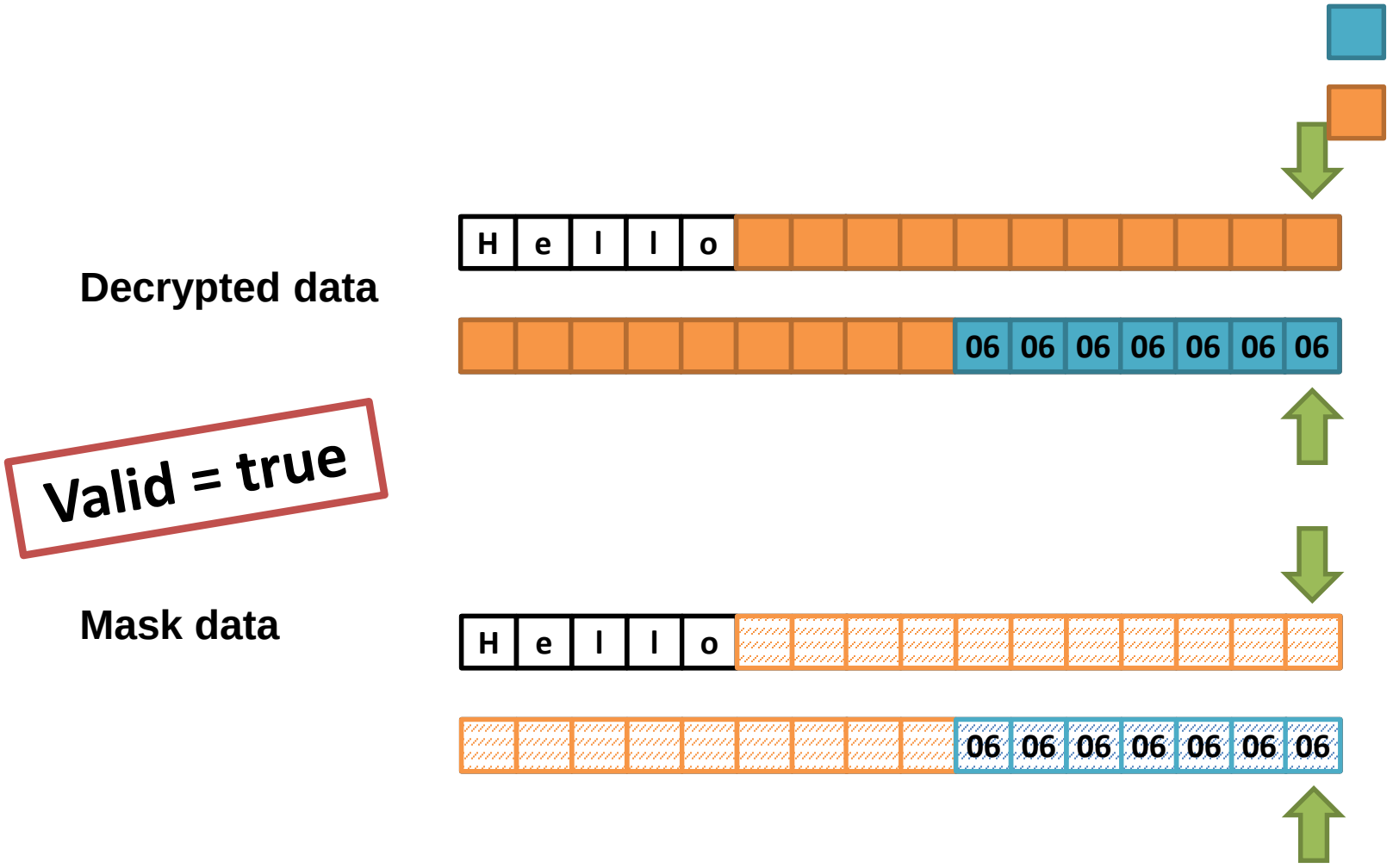
AES-CBC in TLS

- Challenge: not to reveal padding validity
- Always:
  - Padding validation
  - MAC validation
- **Same** error message and timing

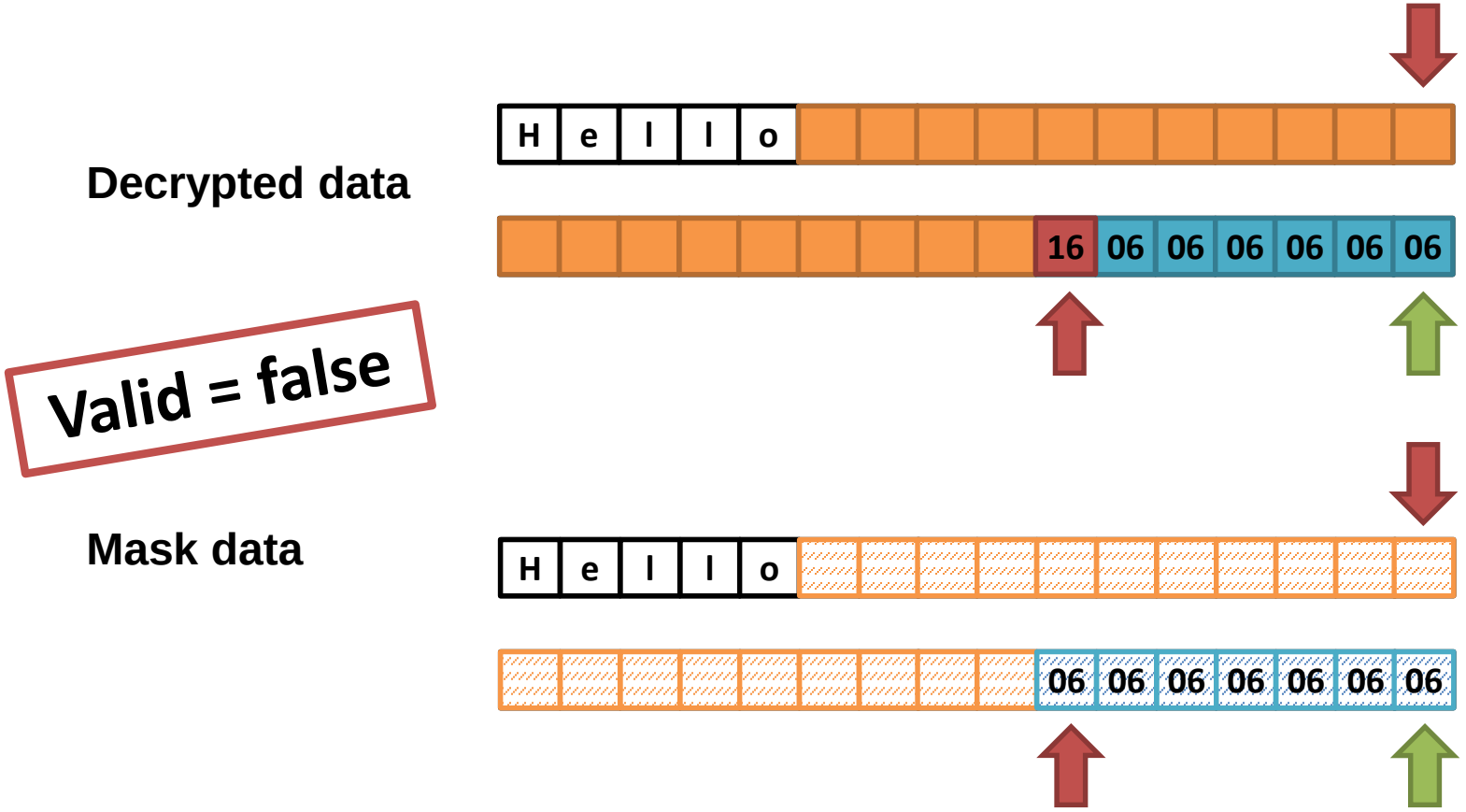
What can go wrong?



Constant Time Validation

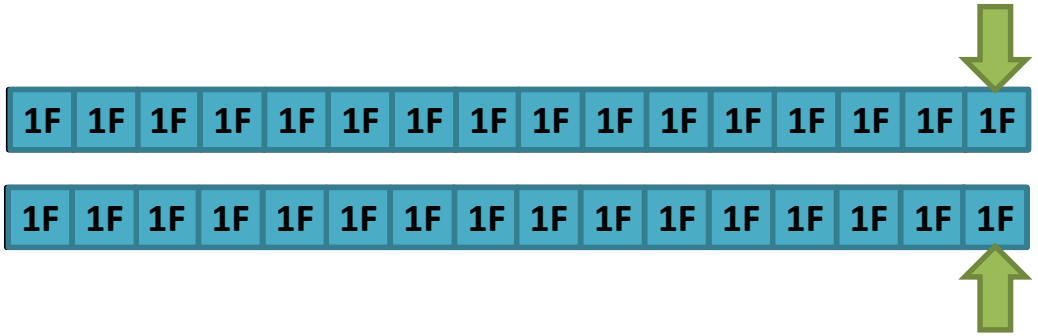


Constant Time Validation



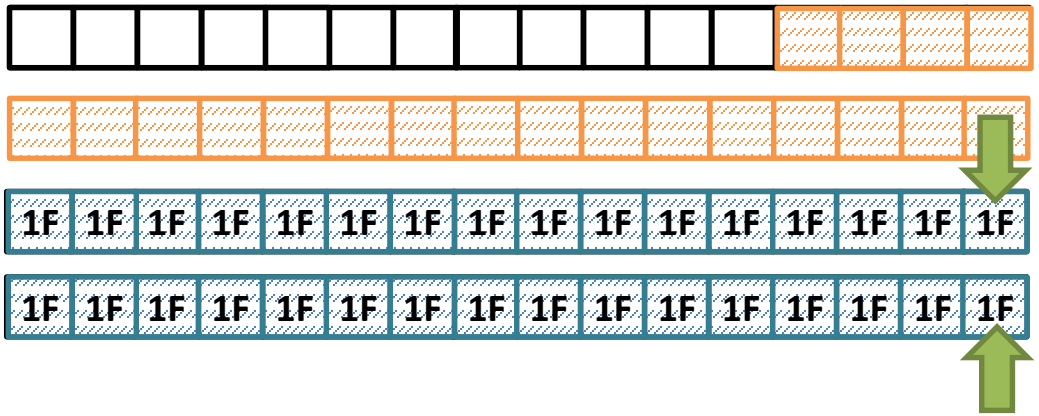
OpenSSL Vulnerability

Decrypted data



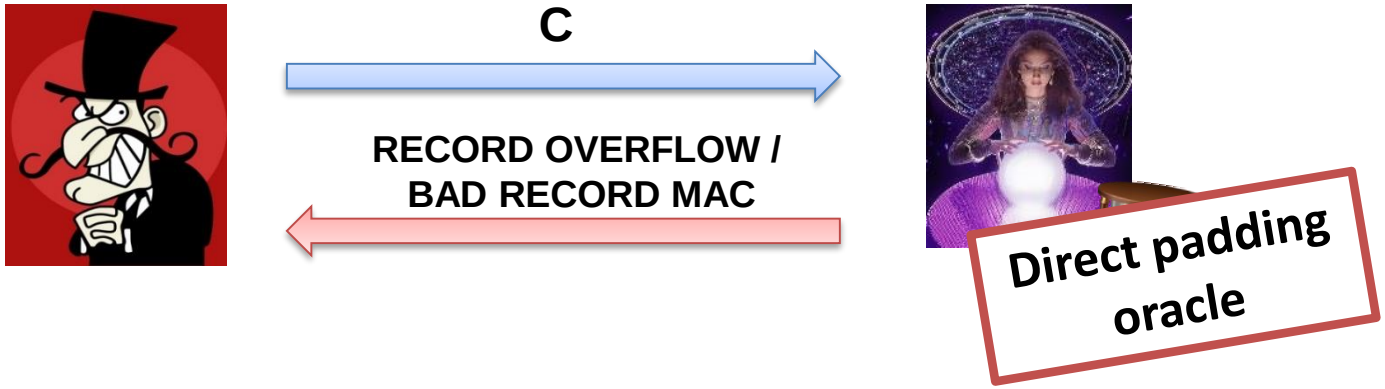
Valid = true

Mask data



OpenSSL Vulnerability (CVE-2016-2107)

- Introduced by patching Lucky 13
- Only when using AES-NI
- Leads to a different server response

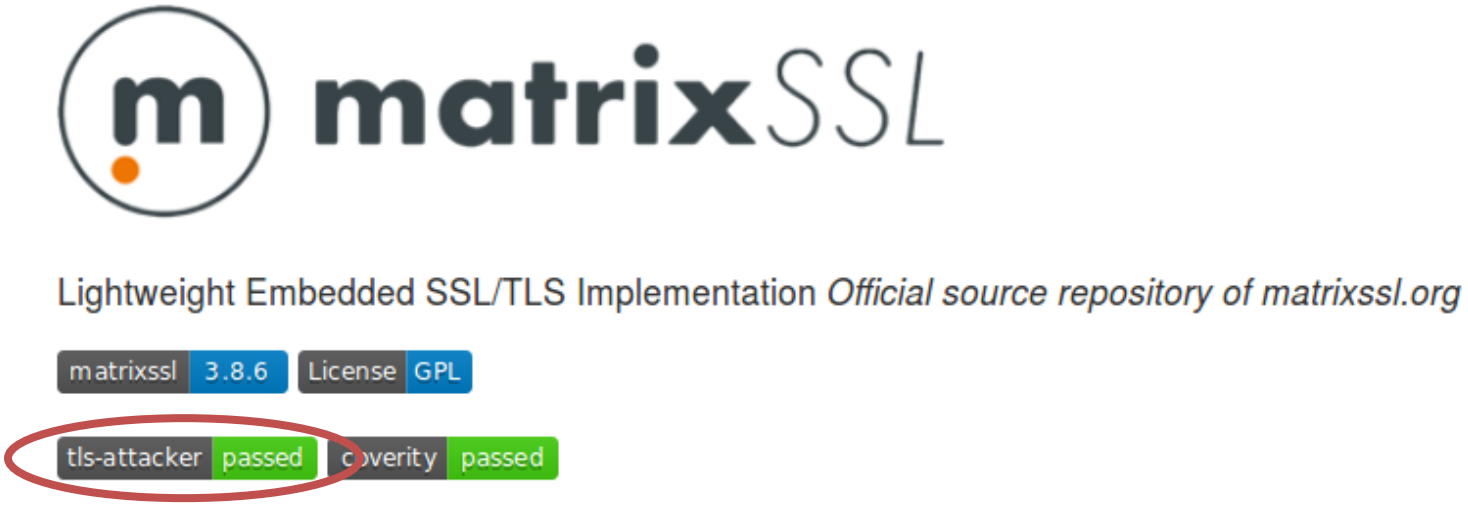


http://web-in-security.blogspot.co.at/2016/05/curious-padding-oracle-in-openssl-cve.html

Can this be even worse?

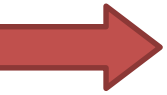
Yes

- MatrixSSL 3.8.2
- Timing attack -> buffer overflow



Overview

1. TLS Protocol
2. Attacks
3. Framework Prerequisites
4. TLS-Attacker Design
5. Fuzzing
6. Results
7. Conclusions



Conclusions and future work

- Maintaining a crypto library is hard
- New code / patches can introduce new flaws
- Systematic fuzzing and evaluation needed
- TLS-Attacker
  - For researchers, pentesters
  - For developers
- Development / fuzzing improvements needed
  - TLS client-side tests
  - Better fuzzing strategies