A study of the TLS ecosystem

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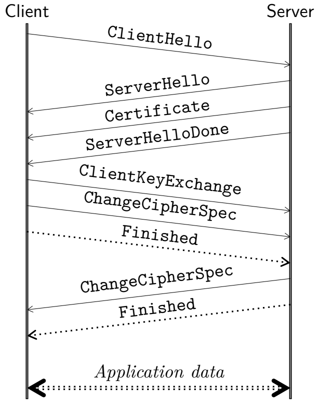
November 18th 2016

SSL/TLS in a nutshell

Overview of the protocol



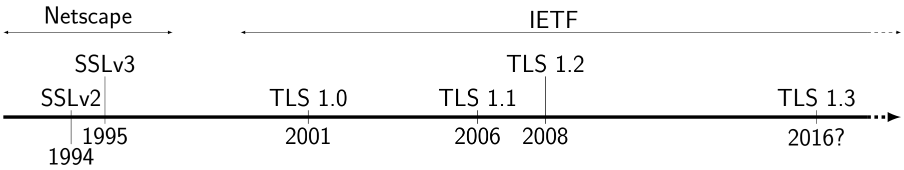
SSL/TLS: a security protocol providing

- server (and client) authentication
- data confidentiality and integrity

Two phases

- Handshake Protocol
  - algorithm negotiation
  - server authentication
  - key exchange
- Record Protocol
  - application data exchanges

SSL/TLS: a basic block of Internet security



A 20-year old protocol

- originally designed by Netscape to secure HTTP connections (SSL)
- maintained since 2001 by the IETF (TLS)
- now used for a broad spectrum of applications
    - to secure almost every cleartext protocols
    - to provide VPNs
    - to authenticate peers in an EAP exchange

The complexity of the protocol

The specifications (50+ RFCs) describe many variants

- 5 protocol versions
- 300+ ciphersuites
- 20+ extensions
- *interesting* features
  - compression
  - renegotiation
  - session resumption (2 methods)

A rich subject to study from different points of view

Part I

State of the art and focus on the Record Protocol

Overview

Many flaws and attacks devised since 1995

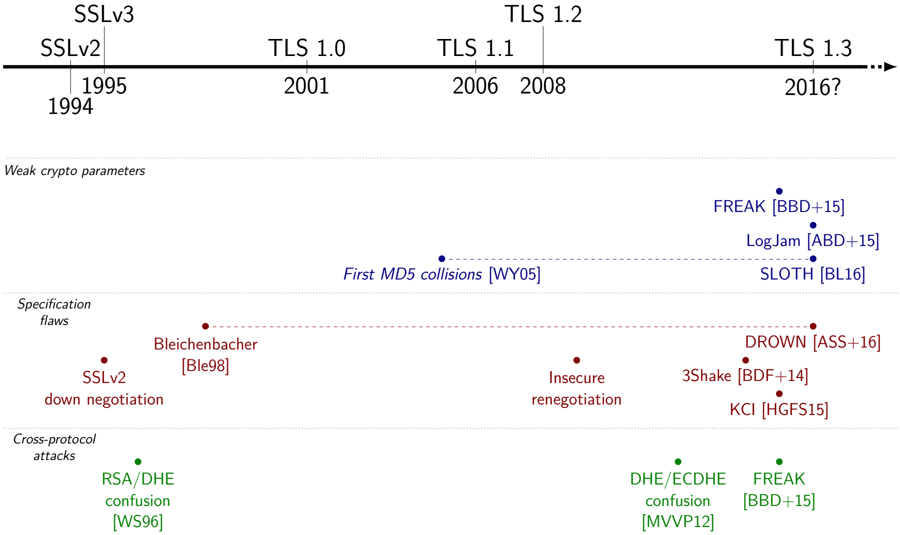
- it is hard to find relevant categories
- several issues may be considered in different categories

The proposed categories are:

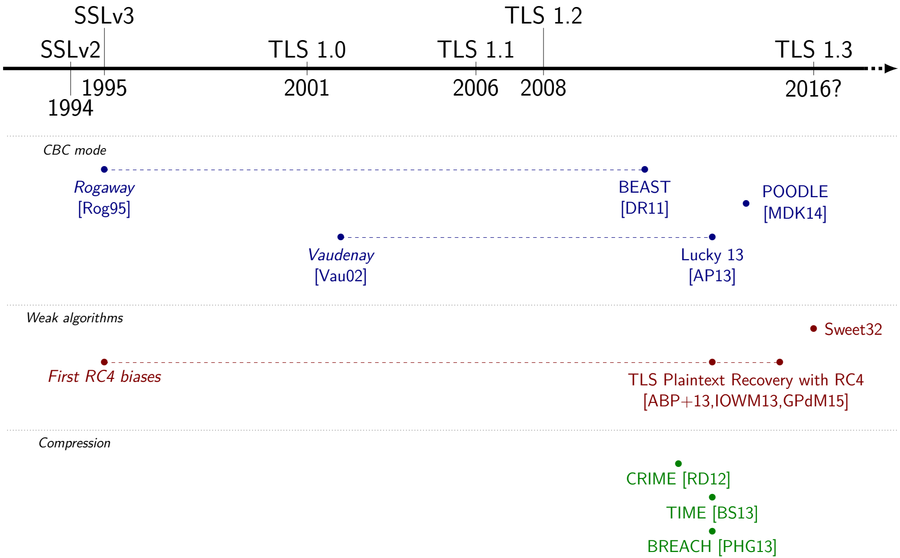
- flaws affecting the Handshake Protocol
- attacks against the Record Protocol
- certificate-related issues
- implementation bugs

Publications describing the state of the art: [SSTIC 12, SSTIC 15]

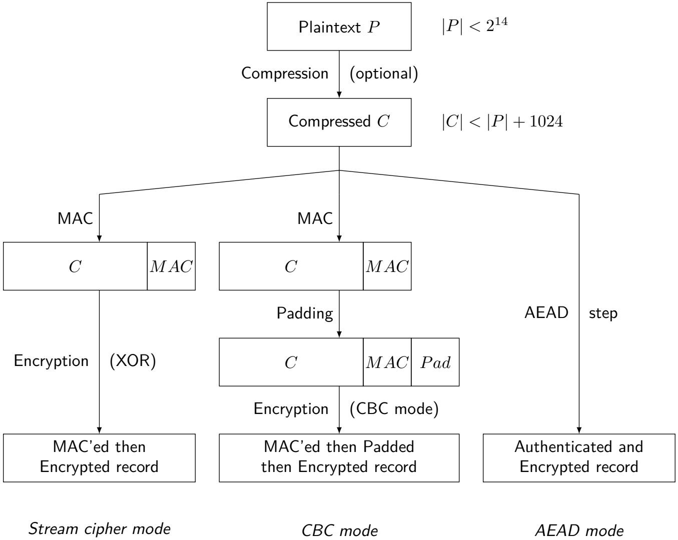
Flaws affecting the Handshake Protocol



Attacks against the Record Protocol



Description of the Record Protocol



Proofs of concept against the Record Protocol

Considered attacks

- BEAST, exploiting CBC using implicit IV
- Lucky 13, a CBC padding oracle
- POODLE, an SSLv3-specific CBC padding oracle

- plaintext recovery using RC4 statistical biases

- CRIME and TIME, compression side-channel (client-side)
- TIME and BREACH, compression side-channel (server-side)

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All the attacks were illustrated by a PoC targeting HTTPS

- powerful (but realistic) attacker
- typical targets are authentication cookies

BEAST: CBC using implicit IV

Hypotheses:

- the connection uses CBC with implicit IV (TLS < 1.1)
- the attacker is able to observe encrypted packets
- the plaintext is partially controlled, adaptively
- **multiple connections containing the secret can be triggered**

Proposed countermeasures:

- use TLS 1.1
- use AEAD suites (requires TLS ≥ 1.2)
- use RC4
- split the records

RC4 statistical biases

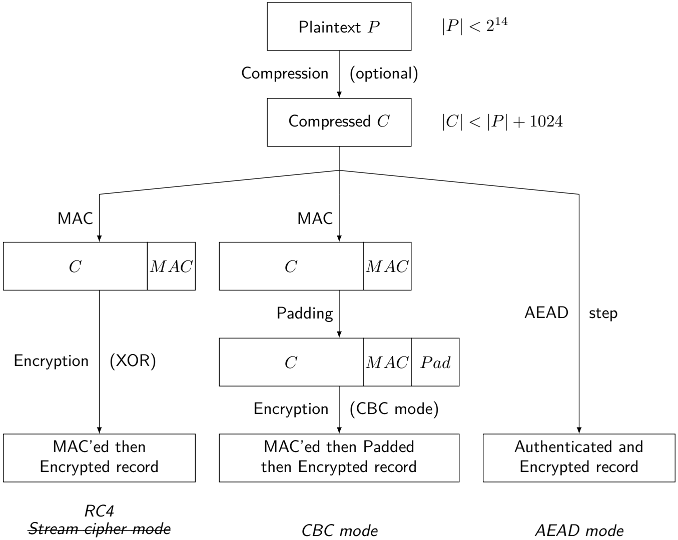
Hypotheses:

- the connection uses RC4
- the attacker is able to observe encrypted packets
- **multiple connections containing the secret can be triggered**

Proposed countermeasures:

- use AEAD suites (requires TLS $\geq$ 1.2)
- use CBC mode
- use another streamcipher
- randomise the secret location

Record Protocol: the long-term solution



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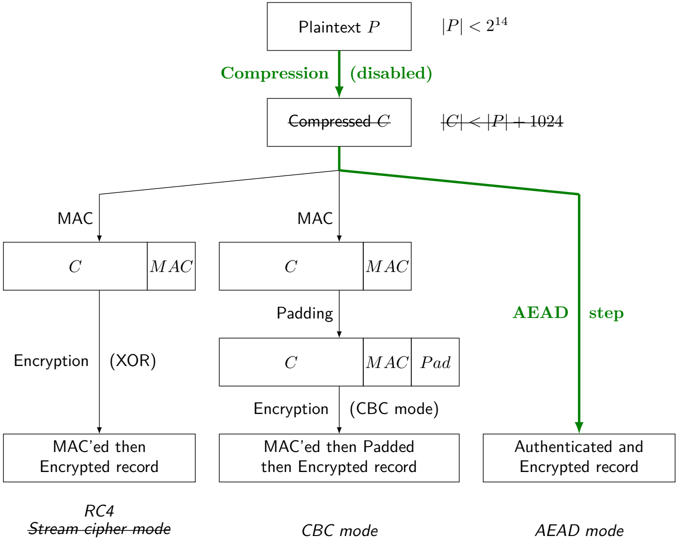


Record Protocol: when TLS 1.2/AEAD is not an option

In the absence of the long-term solution (e.g. for compatibility reasons)

- specific short-term fixes exist for most attacks
- we propose to avoid the repetition as a defense-in-depth mechanism

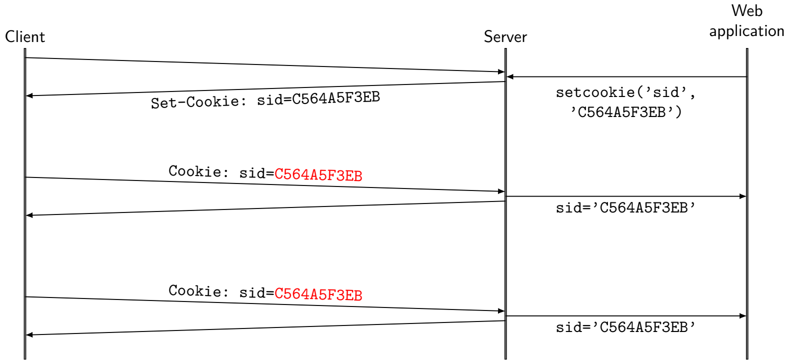
The masking principle (borrowed from the side-channel community):

- instead of sending a secret s
- draw a random string m of the same length as s
- send $(m, s \oplus m)$

- the *intended* value remains the same
- but the representation is different each time

Publication describing MCookies and similar countermeasures: [ASIA-CCS 15]

Application to HTTP cookies: MCookies



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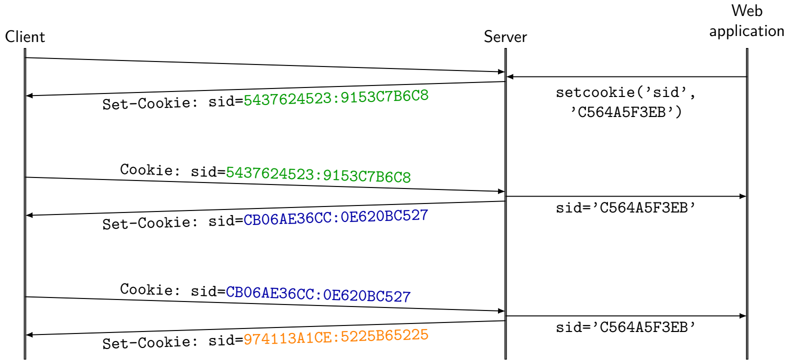

Evaluation of MCookies

Security evaluation

- MCookies cover all first-order attacks...
- as long as the attacker does not tamper with packets

Performance impact

- MCookies used on `secure` `httpOnly` cookies
- 4 % overhead on overall HTTPS traffic

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MCookies with client-side support

- the overhead is reduced by half
- all attacks (including active ones) are thwarted

Part II

Observation and analysis of the HTTPS ecosystem

The motivation behind HTTPS campaigns

The main goal: get concrete data about SSL/TLS usage

- supported versions and features
- feature intolerance
- certificate quality
- at the time (2010-2011), no public datasets

Why choose HTTPS?

- the first and still the major use of SSL/TLS
- HTTPS servers expect to be contacted by strangers
- a diversified ecosystem

Available methodologies

Different ways to get SSL/TLS data:

- IPv4 SYN scan on 443/tcp, followed by SSL/TLS connections
- SSL/TLS connections towards a list of known domain names
- capture of real SSL/TLS traffic from consenting users

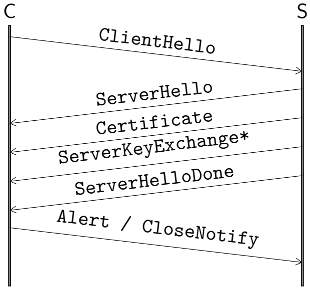
We chose the first method

- the active probing lets us choose the sent stimuli
- not relying on domain names gives access to a wide diversity of servers

Drawbacks

- distribution of the campaign over 3 weeks
- no support for SNI / virtual hosting

Big-picture data regarding our campaigns



About our 2011 campaigns:

- 26 M hosts with an open 443/tcp port
- 7 different stimuli sent
- 11 M answered at least once with SSL/TLS messages
- 140 GB of raw data

The article describing the methodology and the results on 2010-2011 campaigns: [ACSAC 12]

The motivation behind concerto

The tools used to produce the data for [ACSAC 12]

- parsifal to parse the answers
- (mostly undocumented or even not versionned) various scripts

The motivation behind `concerto`

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In 2015, we tried to run similar analyses on new campaigns

- problem: several criteria had to evolve
- how to compare the situation now and then?

The motivation behind `concerto`

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The `concerto` way, towards reproducible analyses

- keep the raw data and the associated metadata
- automate the analysis process
- run it from scratch when needed

concerto, step by step

Context preparation

- NSS certificate store extraction from source code
- metadata injection (stimuli, certificate store)

Answer injection

- answer type analysis
- raw certificate extraction

Certificate analysis

- certificate parsing
- building of all* possible chains

Statistics production

- TLS parameters, certificate chain quality, server behavior

Implementation choices

Design rationale

- store enriched data in CSV tables
- split data processing into simple tools
- avoid tools requiring a global view when possible

*Challenges

- X.509v1 certificates generated by appliances
  - 140,000 self-signed *distinct* certificates
  - containing the *same* subject (and issuer)
  - 20 billion signatures to check
- the `max-transvalid` option

`concerto` is an open-source project available on GitHub

Dataset selection

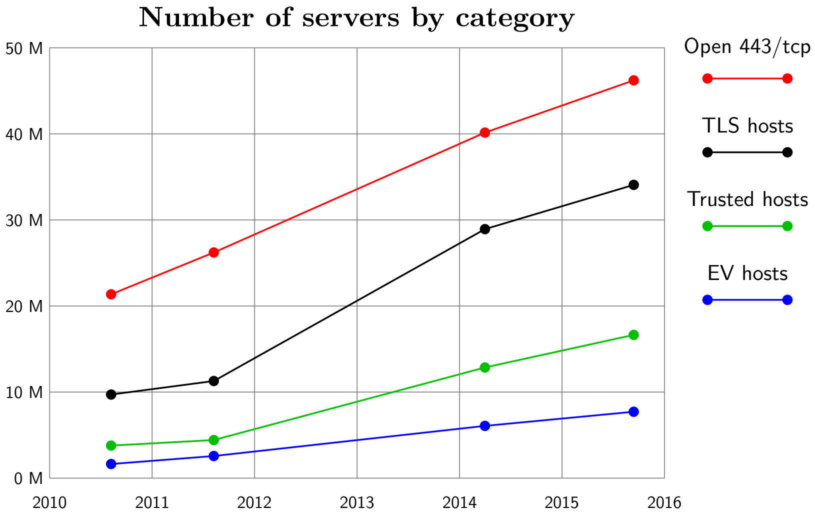
	Campaign type	Date	Available	Retained
EFF	**IP**	**2010**	**yes**	**yes**
Our campaigns	**IP**	**2010-2014**	**yes**	**yes**
[HBKC11]	IP + DN + PO	2011	partially	no
SSLPulse	DN	recurring since 2012	no	no
Internet Census	?	2012	yes	no
[DWH13]	**IP + DN**	**recurring since 2013**	**yes**	**yes**

IP	IPv4 SYN scan followed by active probing
DN	Active probing on a list of Domain Names
PO	Passive Observation

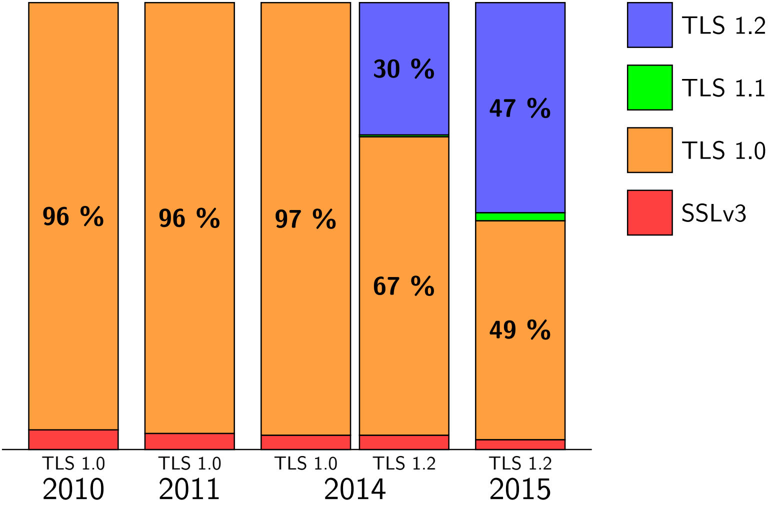
`concerto` offers a portable way to study these different datasets

The results allow us to study trends from 2010, 2011, 2014 and 2015

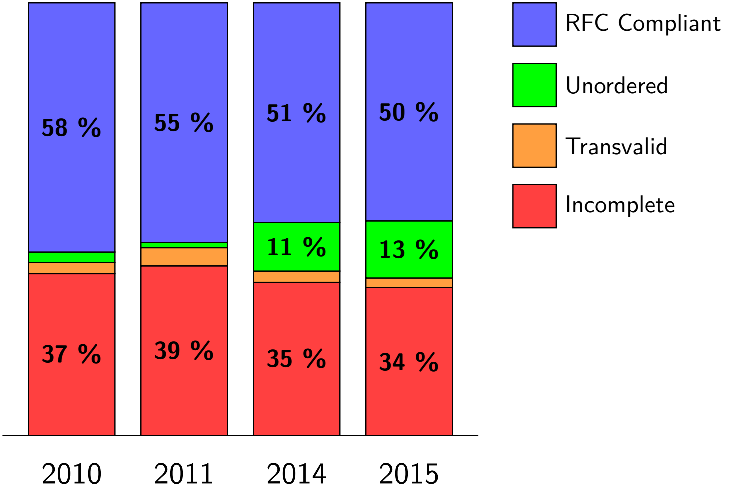
Big picture


Number of servers by category
50 M
40 M
30 M
20 M
10 M
0 M
2010
2011
2012
2013
2014
2015
2016
Open 443/tcp
TLS hosts
Trusted hosts
EV hosts

Evolution of TLS parameters



Certificate chain quality (1/2)



Certificate chain quality (2/2)

Several results about chain validity periods:

- for trusted hosts most chains are valid between 1 and 5 years...
- yet some of them were valid for 20 years

- for TLS hosts in general, 10-year certificates are common
- the record is a 1000-year validity period

RSA is still the most common public key algorithm used:

- we encountered 16,384-bit keys...
- the standard for trusted hosts went from 1024-bit in 2010 to 2048-bit keys in 2015

Server behavior

Beyond the use of different certificate stores, the contribution of our approach in [ACSAC 12] is the use of multiple stimuli:

- using different versions
- including extensions or not
- proposing restricted sets of ciphersuites

Results:

- EC- and TLS 1.2-intolerance has regressed between 2011 and 2014
- The proportion of HTTPS servers accepting SSLv2 is still important in 2014 (40 %)
  - all vulnerable to DROWN attack
  - the situation is worse in practice (SMTPS servers in particular)

Part III

Implementation aspects and focus on the parsing problem

The motivation behind our parsers

How to handle SSL/TLS data and the embedded X.509 certificates?

- reuse existing stacks
  - limited scope (we don't want to reject unknown options)
  - liberal code (we want to see invalid parameters)
  - fragile implementations (the input might be challenging)
- write many parsers in different languages
- develop a framework in OCaml called `parsifal`
  - the idea: automate tedious parts via code generation
  - result: a solution to quickly write robust and efficient parsers

parsifal

Robustness of the code

- OCaml is a statically-typed language
- automatic memory management
- exhaustive pattern matching as a reliable safeguard

Efficiency

- writing concise code, even to describe complex structures
- the result is rather fast

Limitations

- mostly suited for standalone analysis tools
- integration within existing projects might be hard

parsifal led to several publications: [CRiSIS 13, SSTIC 13, SPW 14a]
parsifal is an open-source project available on GitHub

In parsifal we trust

Many unparsed certificates with our early parsers

- we added support for corner cases
- even illegitimate, but popular, ones (with a warning)

What are the remaining files?

- corrupted files
- private keys...

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Similarly, we encountered interesting invalid certificate signatures:

- C and C', differing only on extensions...
- with the same signature

Anomalies signaled by our tools are usually something worth investigating

2014: a tough year for TLS implementations

In 2014, all major TLS stacks were affected by a critical vulnerability

- February: `goto fail` in Apple
- February: `goto fail` in GnuTLS
- April: *Heartbleed* in OpenSSL
- June: *Early CCS* in OpenSSL
- August: Bleichenbacher revival attack in JSSE
- September: Universal signature forgery in NSS, CyaSSL and PolarSSL
- November: remote code execution in SChannel (MS)

A thorough analysis of implementation flaws has been submitted to CT-RSA 17

Classical programming errors

Bugs in this category:

- memory management errors (Heartbleed)
- trivial mistakes in the logic (`goto fail`)
- missing checks (`BasicConstraints`)

Lessons to learn:

- some mistakes are repeated in different independent code bases
- it may be time to use better languages / tools
- negative and non-regression tests should be improved and shared

Parsing bugs

Bugs in this category:

- ASN.1 DER encoding (null chars, signature forgery)
- TLS record splitting (OpenSSL downgrade attack, *Heartbleed*)

Lessons to learn:

- parsing is often overlooked
- simple specs are beautiful... and more secure

The real impact of obsolete cryptography on security

Bugs in this category:

- MAC-then-Encrypt is *hard* to implement safely
- similarly, RSA encryption using PKCS#1 v1.5 is still a problem

Lessons to learn:

- obsolete and dangerous cryptographic schemes must be removed...
- including in the code base...
- without any delay (TLS 1.1 should have included EtM)

The consequences of complex state machines

Bugs in this category:

- automata are not properly implemented

Lessons to learn:

- an implementation should only parse expected messages
- simple (and well-specified) state machines are beautiful

Conclusions and perspectives

Conclusion

SSL/TLS is a rich protocol with a troubled history

- an important corpus of specifications, with many features
- a diversified ecosystem, with a slow evolution
- many implementations facing interesting challenges

TLS 1.3: a new hope?

- most of the obsolete algorithms have been removed!
- without 0 RTT, the specification has been simplified
- 0 RTT mode(s) might revert all this benefit
- a long-awaited RFC, but the devil is in the detail

Perspectives

- Propose MCookies standardization to the W3C
- Prove TLS 1.3 security properties
  - or propose a restricted profile if needed
- Extend the study to other protocols (IKEv2/IPsec, SSH)
- Study the interaction between TLS and the application protocol

Questions ?

Thank you for your attention

SSL/TLS SoKs

[SSTIC 12] *SSL/TLS: état des lieux et recommandations*, O. Levillain.

[SSTIC 15] *SSL/TLS, 3 ans plus tard*, O. Levillain.

MCookies and other defense-in-depth mechanisms for HTTP

[ASIA-CCS 15] *TLS Record Protocol: Security Analysis and Defense-in-depth Countermeasures for HTTPS*, O. Levillain, B. Gourdin, H. Debar.

Methodologies and tools to analyse the SSL/TLS ecosystem

[ACSAC 12] *One Year of SSL Internet Measurement*, O. Levillain, A. Ebalard, B. Morin, H. Debar.

[SPW 14a] *Parsifal: A Pragmatic Solution to the Binary Parsing Problem*, O. Levillain.

Other contributions

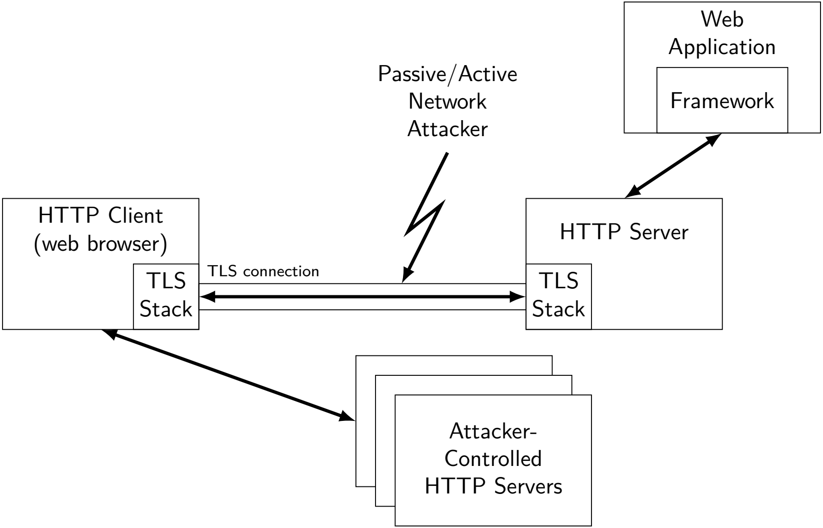
[SPW 14b] *Mind your Language(s)*, É. Jaeger, O. Levillain.

[CT-RSA 15] *Format Oracles on OpenPGP*, F. Maury, J.-R. Reinhard, O. Levillain, H. Gilbert.

[SPW 16] *Caradoc: a pragmatic approach to PDF parsing and validation*, G. Endignoux, O. Levillain et J.-Y. Migeon.

Backup slides

The attacker's models



An example about the diversity of the TLS ecosystem

What can a TLS server answer to a client proposing the following ciphersuites: `AES128-SHA` and `ECDH-ECDSA-AES128-SHA`?

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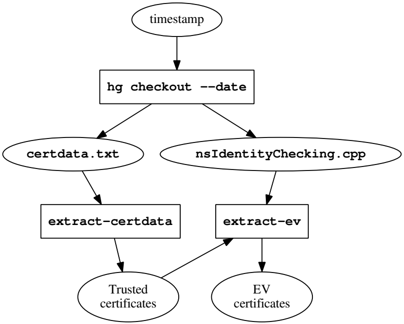
D something else (`RC4_MD5`)

The explanation?

- a ciphersuite is a 16-bit integer
- until (relatively) recently, all ciphersuites were of the form `00 XX`
- so why bother with the most significant byte?

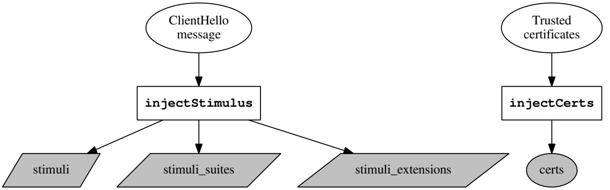
Context preparation



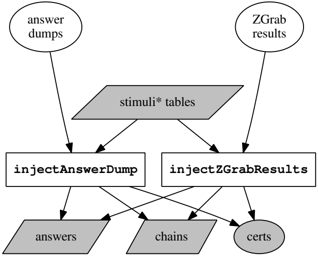
NSS certificate store extraction

Note: the file used to extract EV does not exist anymore

Metadata injection



Answer injection



Typical figures for a full IPv4 campaign

Table	N rows	Size
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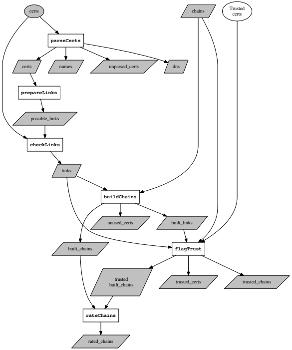
Binary contents	**N**	**Size**
raw certificates	10 M	10 GB

Certificate analysis



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links.csv	14 M	1 GB
built_chains.csv	120 M	12 GB
trusted_certs.csv	6 M	300 MB
trusted_chains.csv	9 M	450 MB

Statistics production

TLS parameters

- proportion of TLS answers
- negotiated versions
- chosen ciphersuites
- RFC 5746 support

Certificate chain quality

- RFC-compliance
- trusted chains w.r.t a given certificate store

Server behavior

- intolerance to a given stimulus
- comparison of answers to a duplicate stimulus

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$\mathcal{PT}$ypes: the basic blocks of a `parsifal` parser

- an OCaml type `t`;
- a `parse_t` function (`bytes -> t`)
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The goal: relieve the programmer from writing tedious code

To this aim, three kinds of $\mathcal{PT}$ypes:

- basic $\mathcal{PT}$ypes, provided by the standard library
- keyword-assisted $\mathcal{PT}$ypes
- custom $\mathcal{PT}$ypes

Implementing TLS records

```
enum tls_version (16, UnknownVal V_Unknown) =
  | 0x0002 -> SSLv2          | 0x0302 -> TLSv1_1
  | 0x0300 -> SSLv3          | 0x0303 -> TLSv1_2
  | 0x0301 -> TLSv1

enum tls_content_type (8, Exception) =
  | 0x14 -> ChangeCipherSpec    | 0x16 -> Handshake
  | 0x15 -> Alert               | 0x17 -> ApplicationData

struct tls_record = {
  content_type : tls_content_type;
  record_version : tls_version;
  content_length : uint16;
  record_content : binstring[content_length];
}
```

Perspectives on the specification front

MCookies development

- propose MCookies to the W3C
- propose MTokens to web application framework
- extend the concept to other secrets/protocols, when possible

TLS 1.3

- ensure the specification is as clear and simple as possible
- continue to model the protocol and to prove its security properties
- propose a secure restricted profile if needed

Other protocols

- IKEv2/IPsec
- SSH

Perspectives on the knowledge of the SSLiverse

Launch new campaigns

- multi-stimuli campaigns on IPv4 space are still rare
- explore more protocols
- extend existing efforts to publish dashboards such as SSL Labs

Relation to specification and deployment goals

- use campaigns as a laboratory to test the intolerance to new features
- use campaigns as a way to check when obsolete features can be safely removed

Perspectives on software improvement

Study TLS implementations using safe(r) languages

- miTLS in $F^\star$
- nqsb-TLS in OCaml
- assess the security and the usability of such stacks

Analyse and test existing stacks

- static analysis tools
- protocol fuzzers (FlexTLS, `tlsfuzzer`)
- black-box state-machine inference using $L^\star$
- assess the coverage of such methodologies