Transport Layer Security

194.144 Privacy Enhancing Technologies

Dr. Wilfried Mayer

Outline 1/2

- Overview
- TLS Protocols
- PKI
- Implementations
- Cryptographic primitives

Outline 2/2

- Application of TLS
- HTTPS
- User Behaviour
- Incidents, Flaws and Attacks
- Improvements
- TLS 1.3

Overview

Goals of TLS[1]

- Authentication
- Confidentiality
- Integrity
- TLS is application protocol independent

[1] RFC8446

Goals of TLS 1.2[3]

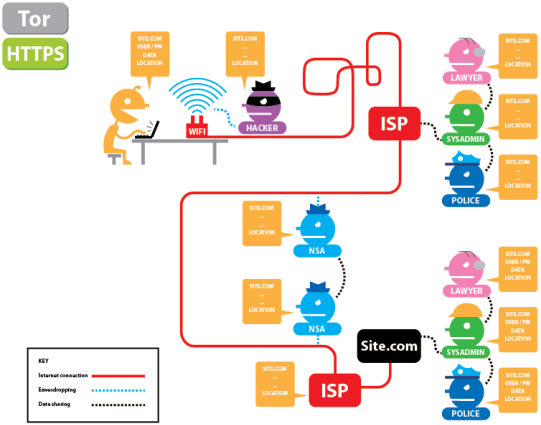
- Cryptographic security
- Interoperability
- Extensibility
- Relative efficiency[2]

[2] https://istlsfastyet.com/

[3] RFC5246

TLS / PETS

- **Foundation of encrypted internet**
- Improvements / Incidents / Vulnerabilites
- Metadata not private
- No silver bullet for security



Interactive Overview (EFF)

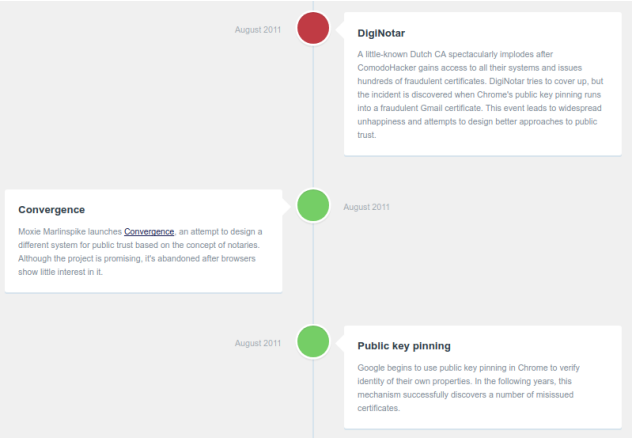
Timeline

- SSL 2 by Netscape (1994)
- SSL 3 (1995)
- TLS 1.0 (1999, RFC 2246)
- TLS 1.1 (2006, RFC 4346)
- TLS 1.2 (2008, RFC 5246)
- TLS 1.3 (2018, RFC 8446 (after 28 drafts))

Name

Secure Sockets Layer vs. **Transport Layer Security**

Interactive SSL/TLS History



See at feistyduck.com

TLS Protocols

RFC complexity

RFC5246, RFC2246, RFC4346, RFC6101, RFC2595, RFC2712, RFC2817, RFC2818, RFC3207, RFC3268, RFC3546, RFC3749, RFC3943, RFC4132, RFC4162, RFC4217, RFC4279, RFC4347, RFC4366, RFC4492, RFC4680, RFC4681, RFC4785, RFC5054, RFC5077, RFC5081, RFC5288, RFC5289, RFC5746, RFC5878, RFC5932, RFC6066, RFC6091, RFC6176, RFC6209, RFC6347, RFC6367, RFC6460, RFC6655, RFC7027, RFC7251, RFC7301, RFC7366, RFC7465, RFC7507, RFC7568, RFC7627, RFC7685, RFC5216, RFC7457, RFC7525, RFC8446, ...

Two primary concepts

- Handshake protocol
  - authenticates the communicating parties
  - negotiates cryptographic modes
  - establishes shared keying material
- Record protocol
  - protect traffic between the communicating peers

Full Handshake TLS 1.2

```
Client                                               Server

ClientHello                  -------->
                                                ServerHello
                                               Certificate*
                                         ServerKeyExchange*
                                        CertificateRequest*
                             <--------      ServerHelloDone
Certificate*
ClientKeyExchange
CertificateVerify*
[ChangeCipherSpec]
Finished                     -------->
                                         [ChangeCipherSpec]
                             <--------             Finished
Application Data             <------->     Application Data
```

Full Handshake TLS 1.3

```
       Client                                           Server

Key  ^ ClientHello
Exch | + key_share*
     | + signature_algorithms*
     | + psk_key_exchange_modes*
     v + pre_shared_key*       -------->
                                                  ServerHello  ^ Key
                                                 + key_share*  | Exch
                                            + pre_shared_key*  v
                                        {EncryptedExtensions}  ^  Server
                                        {CertificateRequest*}  v  Params
                                               {Certificate*}  ^
                                         {CertificateVerify*}  | Auth
                                                   {Finished}  v
                               <--------  [Application Data*]
     ^ {Certificate*}
Auth | {CertificateVerify*}
     v {Finished}              -------->
       [Application Data]      <------->  [Application Data]
```

Handshake Resumption TLS 1.2

```
Client                                                  Server
ClientHello
(SessionTicket extension)      -------->
                                                   ServerHello
                               (empty SessionTicket extension)
                                                NewSessionTicket
                                              [ChangeCipherSpec]
                                <--------             Finished
[ChangeCipherSpec]
Finished                        -------->
Application Data                <------->     Application Data
```

Figure 2: Message Flow for Abbreviated Handshake Using New Session Ticket

0-RTT Handshake TLS 1.3

```
Client                                                  Server

ClientHello
+ early_data
+ key_share*
+ psk_key_exchange_modes
+ pre_shared_key
(Application Data*)     -------->
                                                   ServerHello
                                              + pre_shared_key
                                                  + key_share*
                                         {EncryptedExtensions}
                                                + early_data*
                                                   {Finished}
                        <--------       [Application Data*]
(EndOfEarlyData)
{Finished}              -------->
[Application Data]      <------->        [Application Data]
```

Security properties for 0-RTT data are weaker!

PKI

Public Key Infrastructure

- Certificates based on Pubkey encryption
- CA (Certificate Authority) issues certificates
- CA rights can be delegated: Sub-CAs
- Chain of trust (Chain of certificates) to the root CAs
- Root CAs are trusted

Certificate

This certificate has been verified for the following usages:

SSL Server Certificate

Issued To

Common Name (CN)	www.tuwien.ac.at
Organization (O)	Technische Universität Wien
Organizational Unit (OU)	ZID

Issued By

Common Name (CN)	TERENA SSL CA 3
Organization (O)	TERENA
Organizational Unit (OU)	<Not Part Of Certificate>

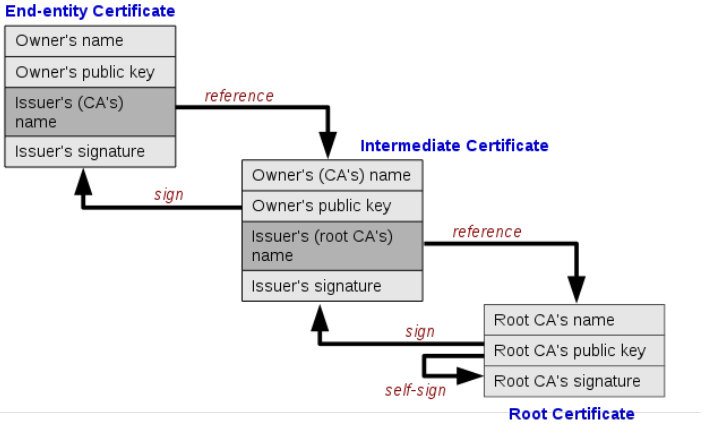
Validity Period

Issued On	Friday, October 9, 2015 at 2:00:00 AM
Expires On	Wednesday, October 17, 2018 at 2:00:00 PM

X.509

- Standard for pubkey certificates
- Structured, e.g.:
  - Issuer Name
  - Subject name (inkl. Common Name)
  - Validity period
  - Extensions
  - ...
- .pem / .crt / .cer / .der / not .csr / not .key / ...

Chain of trust



Root CAs, Trust stores

- Each browser and operating system has its set of trusted CAs
- These CAs could sign everything
- Not all signed HTTPS Certificates
- Controlled by different organizations, nations, ...
- Three organizations controlling 75% of trusted certificates

Root CAs

Organization Type	Organizations	
Academic Institution	273	(39.79%)
Commercial CA	135	(19.67%)
Government Agency	85	(12.39%)
Corporation	83	(12.09%)
ISP	30	(4.37%)
IT/Security Consultant	29	(4.22%)
Financial Institution	17	(2.47%)
Unknown	*unknown*	
Hosting Provider	7	(1.02%)
Nonprofit Org	7	(1.02%)
Library	5	(0.72%)
Museum	4	(0.58%)
Healthcare Provider	3	(0.43%)
Religious Institution	1	(0.14%)
Military	1	(0.14%)

Durumeric et al., Analysis of the HTTPS Certificate Ecosystem

CA/Browser Forum

- Defines Baseline Requirements
- Rules that CAs have to follow
- https://cabforum.org/baseline-requirements-documents/

Implementation

Implementations

- OpenSSL: de-facto standard, swiss army knife
- LibreSSL: fork by the OpenBSD team
- BoringSSL: fork by Google
- GnuTLS: initial GNU implementation
- NSS: by Mozilla
- Microsoft Secure Channel
- s2n: implementation by Amazon
- miTLS: Verified Implementation
- See full comparison here

OpenSSL problems

- Had its own memory management which prevented many analysis tools
- Bugs unfixed for a long time
- Code base completely unreadable
- Extensive backward compatibility

OpenSSL vs. LibreSSL

- BSD team forked OpenBSD 1.0.1g after Heartbleed
- 90.000 LOC deleted within 30 days (initially 388.000)
- Part of OpenBSD now

Google forked towards BoringSSL

Cryptographic primitives

Ciphersuites until 1.2

- Remember: Extensibility
- Specifies cryptographic algorithms and modes

Ciphersuites consist of:

- Key exchange
- Authentication
- Symmetric cryptography for transport
- Integrity (Hash)

Ciphersuites until 1.2

TLS_DHE_RSA_WITH_AES_256_CBC_SHA

- DHE for key exchange
- RSA for authentication
- AES 256bit in CBC mode for encryption
- SHA for hashing

IANA:

- More than 500 defined[4]
- Two bytes define the ciphersuite

[4] Source: list by IANA

Ciphersuites until 1.2

Key exchange (selection):

- RSA for authentication
- Problem with RSA: private key can decrypt previous communication content

Forward secrecy:

- DHE_RSA: ephemeral Diffie-Hellman
- ECDHE_RSA: elliptic curve Diffie-Hellman

Ciphersuites until 1.2

Encryption:

- Block or stream ciphers
- Block: AES, 3DES, Camellia
- Stream: RC4, ChaCha

Ciphersuites until 1.2

- Server supports a certain set
- Browser supports a certain set
- Negotiated while Handshake

Ciphersuites for TLS 1.3

- Highly reduced set (5)!
- Not compatible with TLS 1.2
- All support Forward Secrecy
- Authenticated Encryption with Associated Data (AEAD)

Which Ciphersuites to use?

- e.g., recommendations by Mozilla
- Recommended configurations
- Mozilla SSL Configuration Generator

Application of TLS

HTTPS

- Most widely used application layer protocol for TLS
- HTTP over 443
- You all use it!

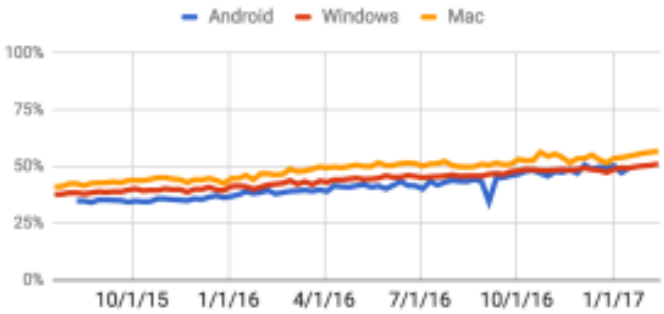
HTTPS Problems

- HTTPS Adoption
- Secure Deployment
- Usability
- Who leads the way?

HTTPS Adoption

- HTTPS was not used widely enough
- HTTPS used only for “high important” pages
- Certificates cost money (pre Let’s Encrypt era)
- Self-signed certificates bring problems

HTTPS Adoption



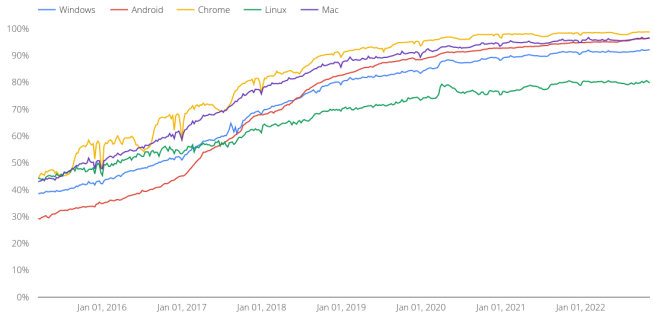
Felt et al., Measuring HTTPS Adoption on the Web

HTTPS Adoption 2022

HTTPS Encryption by Chrome platform

Since early 2015, we have been able to measure the prevalence of HTTPS connections thanks to Chrome users who choose to **share usage statistics**. The graphs below show the growth in HTTPS usage across platforms and countries/regions. Desktop users load more than half of the pages they view over HTTPS and spend two-thirds of their time on HTTPS pages. HTTPS is less prevalent on sites accessed on mobile devices, but there is still an upward trend in encryption usage there.

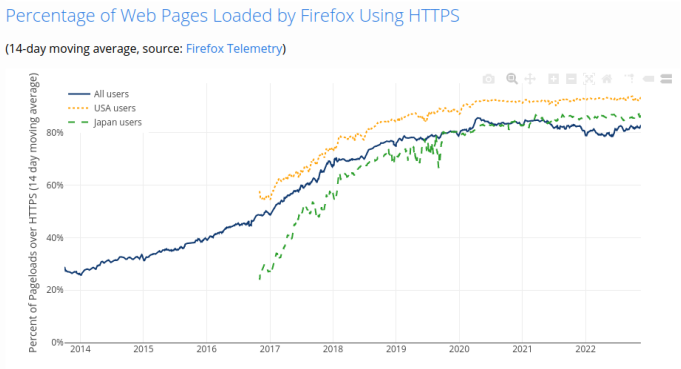
Percentage of pages loaded over HTTPS in Chrome by platform



Fragment navigations, history push state navigations, and all schemes besides HTTP/HTTPS (including new tab page navigations) are not included.

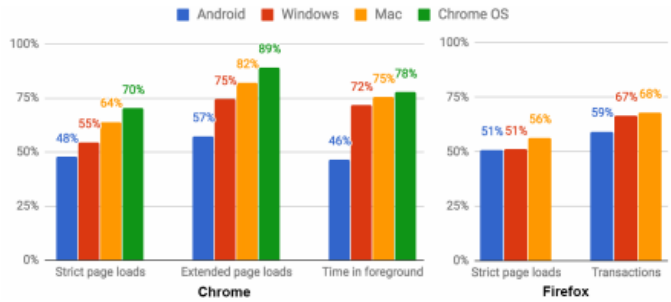
https://transparencyreport.google.com/https/overview

HTTPS Adoption 2022



https://letsencrypt.org/stats/

HTTPS Adoption



Felt et al., Measuring HTTPS Adoption on the Web

HTTPS Adoption - Browser Warnings

- 2016/10 Warning for unencrypted form data
- 2018/07 Warning for HTTP
- 2020/10 Chrome 86 forbids mixed content
- 2021/04 Chrome 90 defaults to HTTPS

Secure Deployment

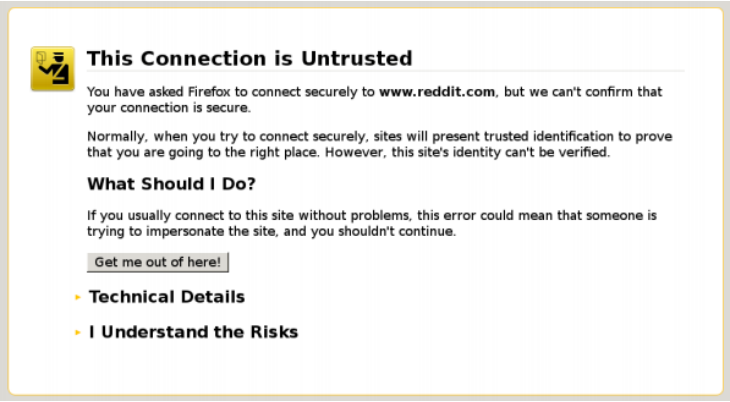
- Complex task
- How to do correctly?
- What is a “secure” deployment?
- e.g., correct Ciphersuites (see above)
- Grading with SSLTest (see below)

HTTPS Usability

- Security for people (TUW mission: Technology for people)
- Disruptive Security Concepts (Browser Warnings)
- Connection Security Indicators (Browser Icons)
- Admins should be seen as users too
- *Given a choice between dancing pigs and security, the user will pick dancing pigs every time*[5]

[5] Felten and McGraw

Browser Warnings



Akhawe, Felt: Alice in Warningland: A Large-Scale Field Study of Browser Security Warning Effectiveness

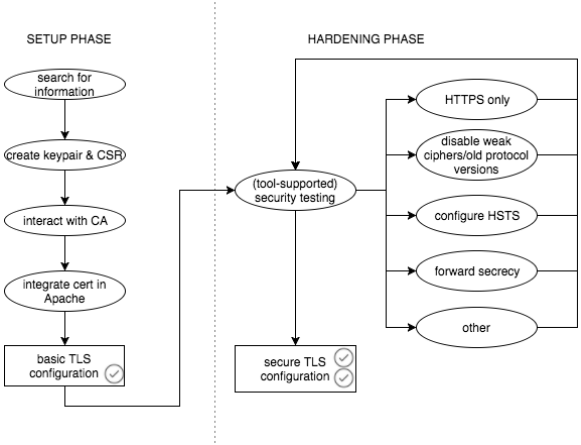
Connection Security Indicators

Browser	HTTPS	HTTPS minor error	HTTPS major error	HTTP	EV	Malware
Chrome 48 Win	https://www	https://mixe	~~https~~://wro	www.examp	Symantec Co	https://dow
Edge 20 Win	example.	https://mix	wrong.host.badss	example.com	Symantec Co	Unsafe website der
Firefox 44 Win	https://www.e	https://mixec	https://expire	www.example	Symantec Corpo	https://spacet
Safari 9 Mac	example.com	mixed.badssl.c	*URL hidden*	example.com	Symantec Corp	downloadgam
Chrome 48 And	https://v	https://mixe	~~https~~://v	www.examp	https://v	https://spac
Opera Mini 14 And	www.examp	mixed.badssl.c	wrong.host.ba	www.example	www.syma	*Unavailable*
UC Mini 10 And	Example D	mixed.bads	*Blocked*	Example D	Endpoint, C	*Blocked*
UC Browser 2 iOS	Example Do.	mixed.bads..	wrong.host..	Example Do.	Endpoint, C.	*Unavailable*
Safari 9 iOS	example.c	mixed.badss	wrong.host	example.con	Symantec	*Unavailable*

Figure 2: Security indicators for major browsers on Windows (Win), Mac, Android (And), and iOS. For categories that trigger warnings (e.g., malware), we include the security indicator state during the warning.

Felt et al., Rethinking Connection Security Indicators

TLS Deployment process



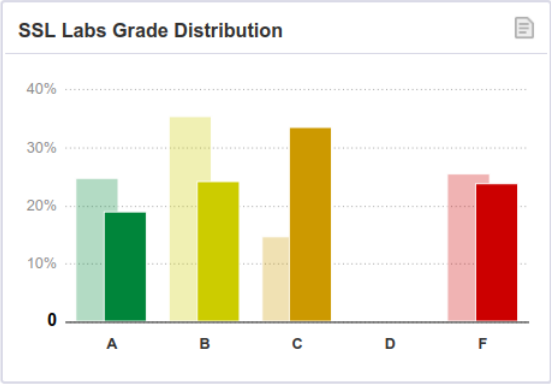
Krombholz, Mayer, Schmiedecker, Weippl: ”I Have No Idea What I’m Doing” - On the Usability of Deploying HTTPS

Deployments

- Hard to find a good configuration
- No secure defaults
- Bad documentation
- Lacking tool support
- Situation is constantly improved

TLS Deployment

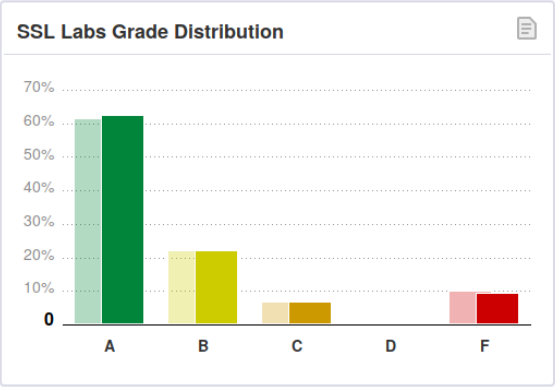
Monthly Scan: June 11, 2015



SSLPulse

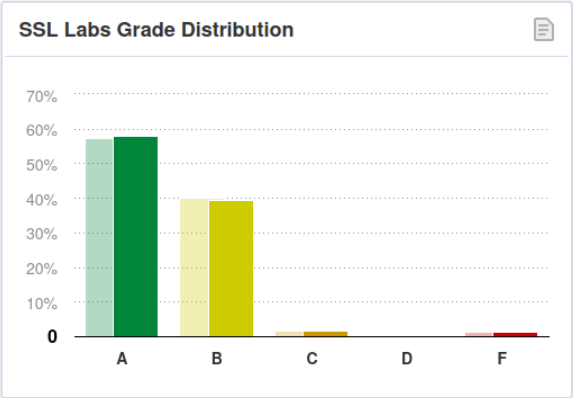
TLS Deployment

Monthly Scan: September 03, 2018



SSLPulse

TLS Deployment



SSLPulse

Who leads the way?

- Browsers, CAs, Service provider
  - Gmail HTTPS by default since January 2010
  - Google Search (if users logged in) since 2011
  - Forward secrecy since November 2011
  - Facebook for all since July 2013
  - Google Search for all since Sept. 2013
  - Let's Encrypt 2015
  - Google+Facebook warning for HTTP passwords 2017
  - Google requires CT in April 2018

TLS for Email

- Dedicated TLS ports (465, 993, 995)
- STARTTLS to upgrade unencrypted connections
  - Important for all email protocols: POP, IMAP, SMTP (110, 143, 25)
  - “Opportunistic encryption” - if possible
  - Does not defeat active attackers

TLS for Email

Differences for SMTP vs. POP/IMAP:

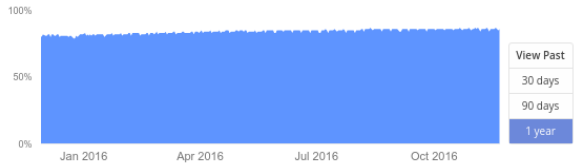
- How do two parties verify certificates?
- All extensions from HTTPS not applicable
- No user warnings (lock icon), ...

STARTTLS Transparency

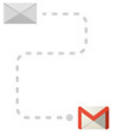
Outbound

86%

Messages from Gmail to other providers.

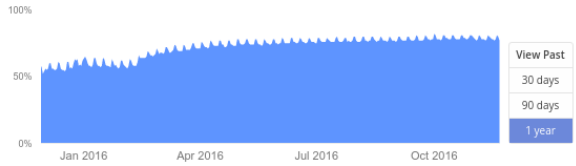


Inbound



77%

Messages from other providers to Gmail.



Incidents, Attacks and Flaws

Incidents, Attacks and Flaws

- Remember:
  - Protocol
  - PKI
  - Implementations
  - Cryptographic primitives
  - Applications (HTTPS, Email)
  - User Behaviour
- add Murphy's law

Incidents PKI: DigiNotar

- CA from the Netherlands, hacked in July 2011
- Fox-IT investigated the attack
- DigiNotar went bankrupt, was removed from all browsern in August 2011

Incidents PKI: DigiNotar

Problems:

- All signing servers were in one AD, weak password
- Reachable over the management LAN
- No antivirus on the servers
- Public webserver was unpatched

Incidents PKI

..com
*.android.com
*.balatarin.com (3)
*.globalsign.com (7)
*.logmein.com
*.mozilla.org
*.skype.com (22)
*.torproject.org (14)
*.wordpress.com (14)
Comodo Root CA (20)
Equifax Root CA (40)
login.live.com (17)
secure.logmein.com (17)
VeriSign Root CA (21)
www.balatarin.com (16)
www.Equifax.com
www.google.com (12)
www.sis.gov.uk (10)

..org
*.aol.com
*.comodo.com (3)
*.google.com (26)
*.microsoft.com (3)
*.RamzShekaneBozorg.com
*.startssl.com
*.walla.co.il (2)
addons.mozilla.org (17)
CyberTrust Root CA (20)
friends.walla.co.il (8)
login.yahoo.com (19)
Thawte Root CA (45)
wordpress.com (12)
www.cia.gov (25)
www.facebook.com (14)
www.hamdami.com
www.update.microsoft.com (4)

*.10million.org (2)
*.azadegi.com (2)
*.digicert.com (2)
*.JanamFadayeRahbar.com
*.mossad.gov.il (2)
*.SahebeDonyayeDigital.com
*.thawte.com (6)
*.windowsupdate.com (3)
azadegi.com (16)
DigiCert Root CA (21)
GlobalSign Root CA (20)
my.screenname.aol.com
twitter.com (18)
www.10million.org (8)
www.cybertrust.com
www.globalsign.com
www.mossad.gov.il (5)

Incidents PKI: DigiNotar

Operation Black Tulip:

- Detected due to TLS pinning in Chrome
- At least 531 fraudulent certificates were issued
- Visualization using OCSP requests[6]
- Used to attack Gmail users MITM in Iran (95% of all the OCSP requests)

[6] Link: Video

Incidents PKI: TLS Incidents

Sometimes using sub-CA issuer and certificates:

- Turktrust: December 2012
  - Sub-CA certificate which was deployed in firewalls
- ANSSI: December 2013,
  - French sub-CA issuing certificates for Google
- India: July 2014
  - Indian sub-CA got hacked

Incidents PKI: CAs distrusted

- October 2016: Apple, Chrome, and Mozilla distrust WoSign and StartCom
- ... multiple rule violations ...
- September 2017: Google and Mozilla decide to stop trusting existing Symantec certificates
- Announcement in March
- ...Despite having knowledge of these issues, Symantec has repeatedly failed to proactively disclose them....

Incidents PKI

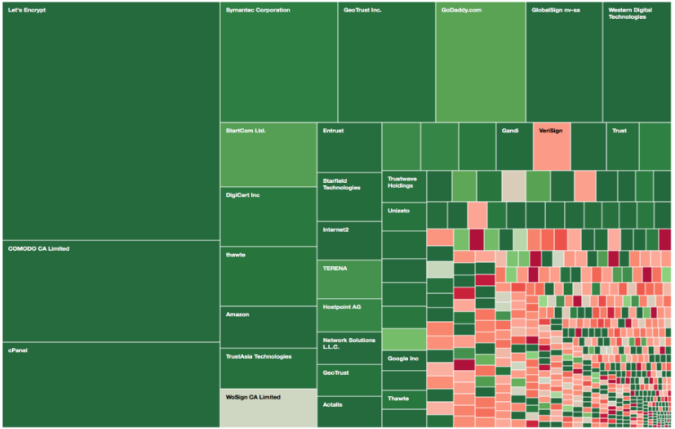


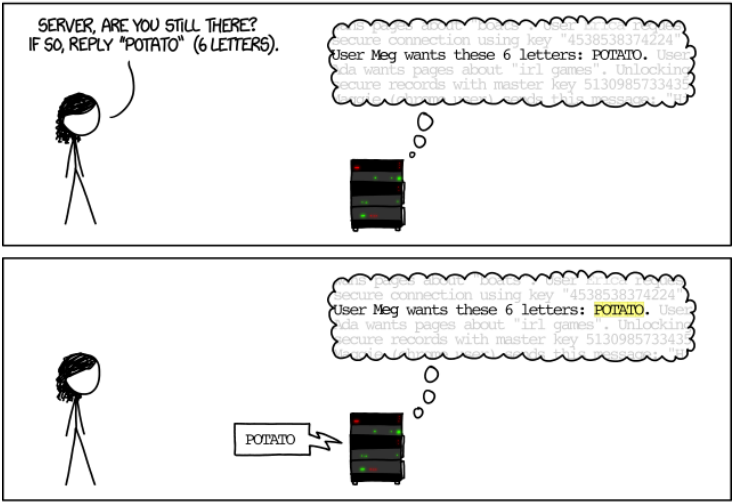
Fig. 5: **Percent ZLint Errors by Total Certificates Issued**—Large certificate authorities generally issue certificates with fewer ZLint errors than smaller authorities.

Kumar et al., Tracking Certificate Misissuance in the Wild

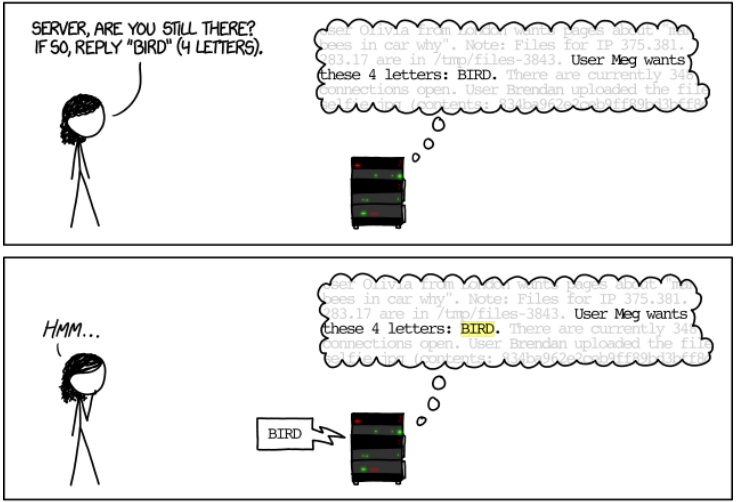
Implementation bug: Heartbleed

- Vulnerability in OpenSSL, April 2014
- In the Heartbeat protocol in TLS, missing bounds check
- Up to 64kb readable from the heap
- Could contain user data, passwords and TLS private key

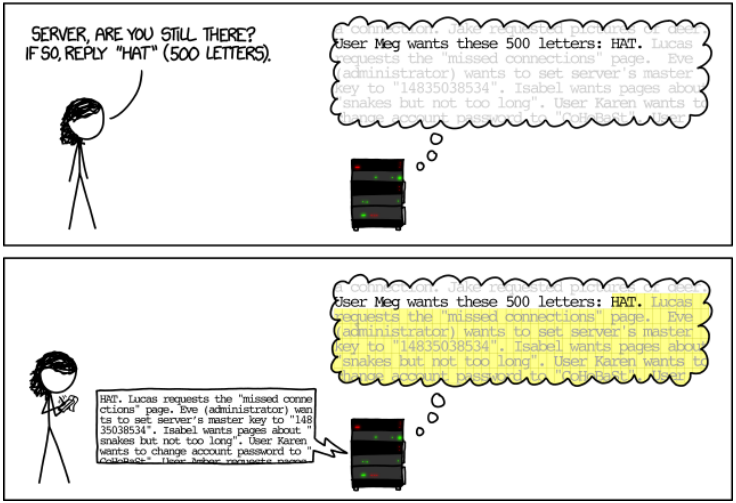
HOW THE HEARTBLEED BUG WORKS:



Source: xkcd

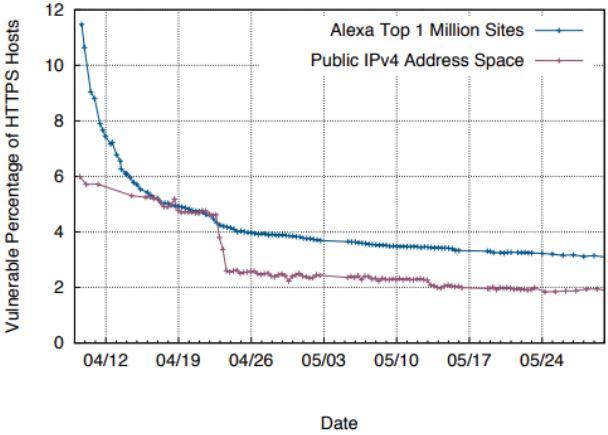

SERVER, ARE YOU STILL THERE? IF SO, REPLY "BIRD" (4 LETTERS).
these 4 letters: BIRD.
HMM...
BIRD

Source: xkcd


SERVER, ARE YOU STILL THERE? IF SO, REPLY "HAT" (500 LETTERS).
User Meg wants these 500 letters: HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to
HAT. Lucas requests the "missed connections" page. Eve (administrator) wants to set server's master key to "14835038534". Isabel wants pages about "snakes but not too long". User Karen wants to change account password to "

Source: xkcd

Heartbleed worldwide



Durumeric et al., The Matter of Heartbleed

Crypto - Ps and Qs

- Problem for creating pubkeys
- RSA chooses parameter at random for pubkey
- For devices with low entropy collision possible
- In particular problematic for embedded devices
- 0.5% of all IPv4 in 2012

Heninger et al., Mining Your Ps and Qs: Detection of Widespread Weak Keys in Network Devices

Crypto - Other Flaws

- Attacks against RC4
  - Considered a work around after BEAST, 2013
  - Insecure, Break RC4 feasable
  - Forbidden by RFC, Feb. 2015
- Debian Weak Keys
  - Weak Random Number Generator 2005
  - Weak keys

Protocol Flaws

- DROWN
  - Decrypting RSA with Obsolete and Weakened eNcryptio
  - Exploits support of SSLv2
  - Certificate on other server with SSLv2?
- POODLE
  - Padding Oracle On Downgraded Legacy Encryption
  - Design of SSLv3 - Padding oracle attack against CBC mode
  - Prevent downgrade with TLS_FALLBACK_SCSV

Other TLS Attacks

- SMACK (State Machine AttaCKs)
- Logjam (Downgrade, Weak Diffie-Hellman)
- FREAK (Downgrade, Factoring RSA Export Keys)
- CRIME, BREACH (HTTP compression)
- Lucky 13 (cryptographic timing attack against CBC mode)
- STRIPTLS attack (opportunistic encryption - application)
- ....

Improvements

Why improving TLS?

You still ask?

Improvements

- HSTS
- Certificate Pinning
- HPKP (dead)
- Certificate Transparency
- CAA
- Let's Encrypt
- Tool Support

HSTS

- HTTP Strict Transport Security
- Part of the HTTP Header response from the server
- Stores HTTPS preference
- `Strict-Transport-Security max-age=31536000`
- Error message instead of warning

HSTS cont.

- Problem: TOFU (Trust On First Use)
- Preload list
- Firefox and Chrome HSTS preload list[7]

[7] List of URLS: https://www.chromium.org/hsts

Pinning

- Key Distribution Problem
- ”Solved” with PKI, but PKI has it’s problems
- Pin the certificate or public key
- e.g., directly in browser or source code
- not scalable

HPKP

- No Support! Dead idea...
- HTTP Public Key Pinning
- Part of the HTTP Header response from the server
- Stores Pinned Key
- `Public-Key-Pins:`
  `pin-sha256="cUPcTAZWKaASuYWhhneDttWpY3oBAkE3h2+soZS`
  `pin-sha256="M8HztCzM3elUxkcjR2S5P4hhyBNf6lHkmjAHKhp`
  `max-age=5184000; includeSubDomains;`
  `report-uri="https://www.example.org/hpkp-report"`

HPKP dead?

- Pin: Leaf cert, Intermediate cert or Root cert
- Public-Key-Pins-Report-Only
- Is HTTP Public Key Pinning Dead?[8]
- Fixing HPKP with Pin Revocation[9]
- Dead... Planned removal in Chrome 67, May 2018[10]

[8] https://blog.qualys.com/ssllabs/2016/09/06/is-http-public-key-pinning-dead

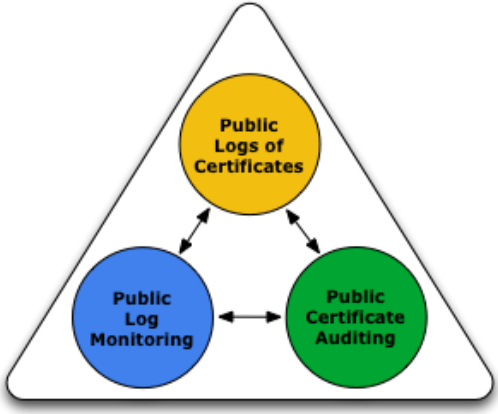
[9] https://blog.qualys.com/ssllabs/2017/09/05/fixing-hpkp-with-pin-revocation

[10] https://groups.google.com/a/chromium.org/forum/#!msg/blink-dev/he9tr7p3rZ8/eNMwKPmUBAAJ?hn

CAA

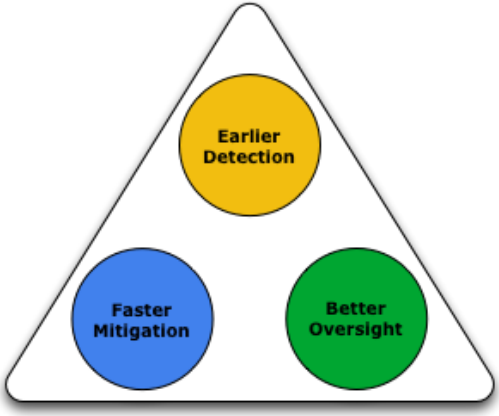
- DNS record: Certification Authority Authorization
- ”Which CAs are allowed to issue a certificate for my domain?”
- `example.com.  IN CAA 0 issue "letsencrypt.org"`
- Mandatory for CAs from September 2017
- CA check - not client system check

Certificate Transparency



Source: Certificate Transparency

Certificate Transparency



Source: Certificate Transparency

Certificate Transparency

- RFC6962
- Logs: records of certificates
- Logs: everyone could host, but currently Google and CAs
- Monitor: watch for suspicious certificates
- Auditor: verify that logs are behaving correctly
- Warning for Certificates without CT Log Entry

Let's
Encrypt

Let’s Encrypt

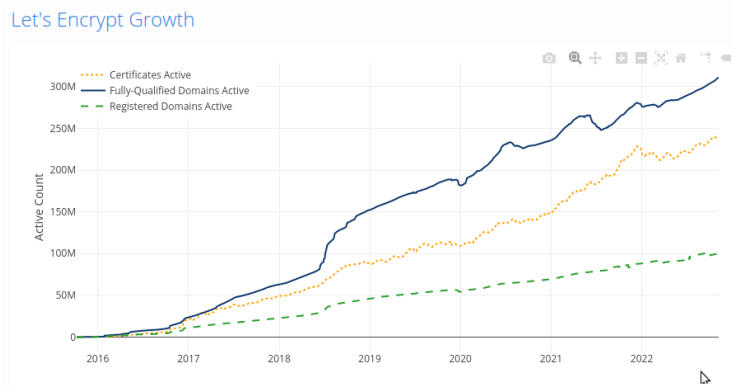
- Free CA!
- Open CA!
- Automated CA (Domain-based validation)!

Let's Encrypt

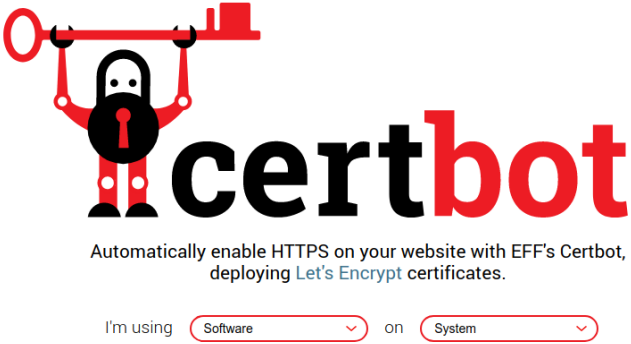
- ACME protocol in background[11]
- Easy TLS setup:
- "sudo apt-get install letsencrypt; letsencrypt run"
- Issued 100 million certs in June 2017

[11] https://github.com/letsencrypt/acme-spec

Active Let's Encrypt certificates

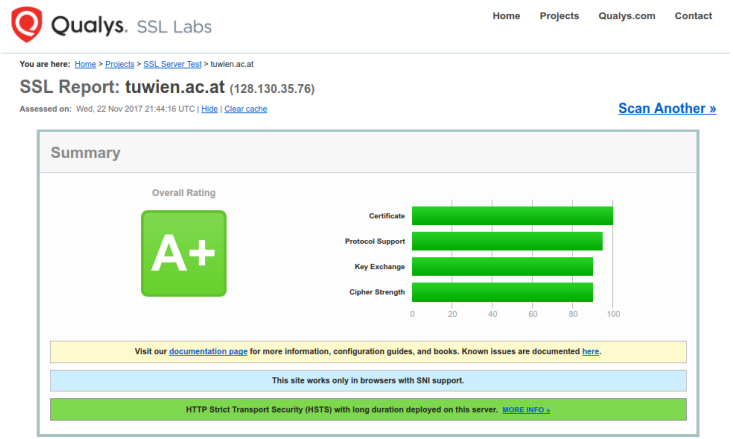


Certbot



Certbot EFF

SSL Test



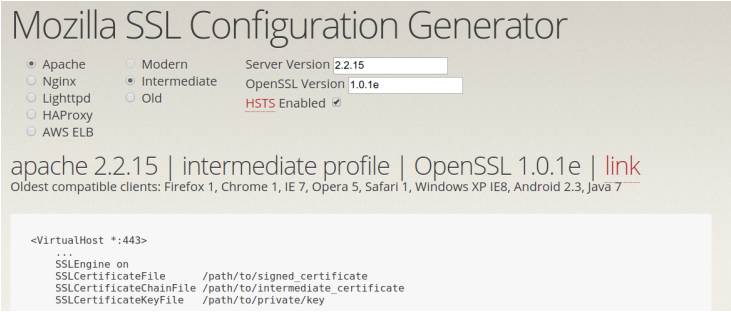
ssllabs ssltest

Qualys Tools

SSL Pulse:

- Monthly scan for 200k top-websites
- Checks for complete certificate chain, CipherSuites, HSTS, ...
- But also attacks like CRIME, Beast, Heartbleed, ...
- Ranking according to Qualys SSL Labs

Mozilla SSL Configuration Generator



HTTPS Everywhere

- Browser extension for Firefox & Chrome, by EFF
- Changes connections from HTTP to HTTPS (where available)
- Rule-based
- Manually maintained list
- link here

DANE

- DNS-based Authentication of Named Entities
- Replace PKI and ask DNS
- Needs DNSSEC
- Not really used

MTA-STS

- SMTP MTA Strict Transport Security
- ”HSTS for Email”
- RFC8461 (End of September 2018)

TLS 1.3.

Major differences

- Static RSA removed
- Forward Secrecy everywhere!
- CBC mode removed (Lucky13, Poodle, ...)
- Only AEAD (Authenticated Encryption with Associated Data) algorithms
- RC4, SHA1, MD5 removed
- Compression removed
- Renegotiation removed

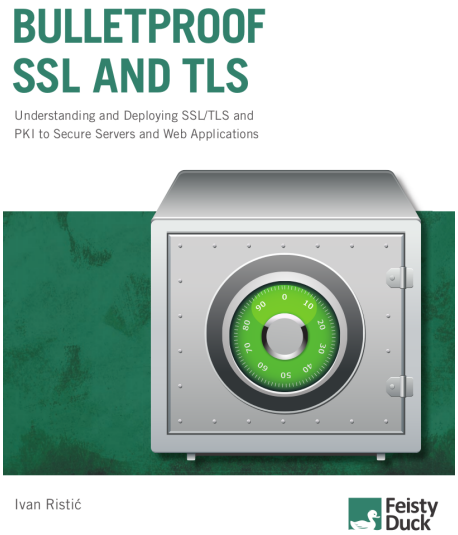
Major differences

- Cipher suite concept changed
- Zero-RTT (Zero round-trip time (0-RTT) mode)
- Handshake state machine has been significantly restructured
- Fixed DHE groups (simplified)
- Session IDs + Tickets - Tickets + PSK
- Downgrade protection
- Full handshake signature

Problems introducing TLS 1.3

- Middlebox decryption
- Version intolerance
  - TLS 1.3. (3.4. / 3.3.)
  - Make TLS 1.3. look like TLS 1.2.

TLS Reference



Questions?