TLS – Security and Future

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Content

Fixing issues in practice

- Trust, Checking certificates, OCSP stapling
- Certificate pinning, Certificate Transparency
- Using TLS: HSTS, STARTTLS

Selected vulnerabilities and problems

- Implementation bugs
- Protocol/cryptography problems

TLS 1.3

Trust – certificates (PKI)

- trusted CA certificates distributed by browsers/OS
- example: Firefox ≈ 154 trusted CA (december 2020)
- Do you trust them all?
- Certificate validation – chain, expiration, server name, signatures, check revocation, … *bugs are common*
- User – let's ignore warnings/errors

Trust – reality

- (2014-2015) Lenovo Superfish – self-signed CA pre-installed, automatic MITM attack (inserting ads to web pages), private key shared among installations
- (2011) DigiNotar (NL) – compromised since 2009, fake certificates (MITM), removed from the list od trusted CA, bankruptcy
- (2011) Comodo – registration authority account compromised, 9 fake certificates
- (2017-2018) distrust of Symantec CA (and its subordinates: Thawte, GeoTrust, RapidSSL) – business sold to DigiCert
- (2018) Trustico (former reseller for Symantec) – sending 23.000 private keys to DigiCert by e-mail . . . to revoke the certificates

- Serrano et al. *A complete study of P.K.I. (PKI's Known Incidents)*, 2019

Checking certificates

- checking certificate status: OK or revoked?
- several standard options:
  - CRL (Certificate revocation list) – a list signed by CA, issued frequently (e.g. at least every 24 hours); can be large (e.g. GlobalSign's CRL from 22 kB to 4.7 MB thanks to Heartbleed)
  - OCSP (Online Certificate Status Protocol) – requesting info from CA; response with timestamp; signed by CA
- non-standard approach:
  - CRLSet (Chrome), OneCRL (Firefox) – list of selected revoked certificates distributed as an update to the browser (Chrome – selected certificates; FF – intermediate certificates)

OCSP stapling

- problems with OCSP:
  - What to do if there is no response from CA – block or allow?
  - user privacy (CA learns what certificates client wants to check)
  - CA flooded with requests related to sites with high traffic.
  - slower user experience.
- TLS Certificate Status Extension
- idea: server requests OCSP response at regular intervals and adds it as Certificate Status message in the Handshake
  - the response cannot be forged (timestamp, signed by CA)
- Multiple Certificate Status Request Extension
  - providing status for all certificates in a chain
  - original extension: only for server's own certificate
- OCSP Must-staple
  - certificate extension – server must staple, otherwise the certificate is invalid

HTTP Public key pinning (HPKP)

- problem: compromised CA issues fake certificates
- bind host to known public-key (or keys)
- information in HTTP header
- “trust on first use” mechanism
- limitations
  - cannot detect MITM attack in the first connection
  - attacker can even insert own pinning info in this case
- now deprecated, replaced by Certificate Transparency

Certificate Transparency

- goals:
  - make hard for a CA to issue a certificate for domain that is not visible to domain owner
  - allow to monitor and audit issued certificates (e.g. by domain owners or CA)
  - protect users against certificates issued maliciously or mistakenly
- Certificate Transparency log
  - Merkle tree of certificate chains (or precertificate chains)
  - publicly verifiable
  - signed root
- CA publishes certificates (precertificates) to public logs
- SCT – Signed Certificate Timestamp – log's promise to incorporate the certificate in the Merkle tree
  - new certificates conatins SCT(s)

HSTS

- SSL Stripping
  - attacker: MITM proxy replacing links https with http links
  - user clicks on a link ...
  - victim communicates with attacker via http
  - attacker communicates with the web server via https
- HSTS (HTTP Strict Transport Security, RFC 6797)
  - HSTS headers over https – instructing browser to use only https for all future requests
  - browser transforms all http links into https links
  - browser does not allow unsecured connections to the web server
- limitations
  - HSTS header stripped in first visit (pre-loaded list of HSTS sites in browsers – does not scale)
- supported: Firefox, Chrome, IE, Edge

STARTTLS

- Opportunistic TLS, switch from plaintext to TLS connection
- STARTTLS command
  - supported: SMTP, POP3, IMAP, LDAP, etc.
- STRIPTLS attack – removing STARTTLS

Apple “goto” fail (2014)

```
SSLVerifySignedServerKeyExchange(...)
{
  OSStatus  err;
  ...
  if ((err = SSLHashSHA1.update(&hashCtx, &serverRandom)) != 0)
      goto fail;
  if ((err = SSLHashSHA1.update(&hashCtx, &signedParams)) != 0)
      goto fail;
      goto fail;
  if ((err = SSLHashSHA1.final(&hashCtx, &hashOut)) != 0)
      goto fail;
  ...
  err = sslRawVerify(...)

fail:
  ...
  return err;
}
```

Heartbleed (2014)

- bug in OpenSSL (2012 – 2014)
- heartbeat extension (RFC 6520):
  1. $A \longrightarrow B$: please, reply with these 3 bytes: "abc"
  2. $B \longrightarrow A$: "abc"
- the problem:
  1. $A \longrightarrow B$: please, reply with these 10000 bytes: "abc"
  2. $B \longrightarrow A$: "abc" 00 a3 30 e2 ... 7f
- possible leaks: private keys, master secret, passwords, ...
- huge impact on security – OpenSSL everywhere
- client software affected as well (server can issue a heartbeat request too)

Do you use some 3rd party code critical to the security of your system? How well is it maintained, reviewed, audited?

Discussion on security of TLS (informal)

- TLS 1.2 (RFC 5246)
- Appendix F: Security Analysis
  - F.1. Handshake Protocol
    - F.1.1. Authentication and Key Exchange
      - F.1.1.1. Anonymous Key Exchange
      - F.1.1.2. RSA Key Exchange and Authentication
      - F.1.1.3. Diffie-Hellman Key Exchange with Authentication
    - F.1.2. Version Rollback Attacks
    - F.1.3. Detecting Attacks Against the Handshake Protocol
    - F.1.4. Resuming Sessions
  - F.2. Protecting Application Data
  - F.3. Explicit IVs
  - F.4. Security of Composite Cipher Modes
  - F.5. Denial of Service
  - F.6. Final Notes
- interesting part: D.4. Implementation Pitfalls

Problem with PKCS #1 v1.5 (RSA encryption)

- (1998) Bleichenbacher
- RSA key exchange
- plaintext (after padding) contains bytes 00 02 (ClientKeyExchange)
- server's response for a ciphertext indicates correct/incorrect format
- access to this oracle allows to decrypt arbitrary ciphertext (i.e. pre-master secret)
- requires approx. 1 million queries for 1024 bit modulus

Problem with PKCS #1 v1.5 – solutions

- treat incorrect format as a correct one:

  "In any case, a TLS server MUST NOT generate an alert if processing an RSA-encrypted premaster secret message fails, or the version number is not as expected. Instead, it MUST continue the handshake with a randomly generated premaster secret."

- use RSA-OAEP (not used in TLS 1.2):

  "The RSAES-OAEP encryption scheme defined in [PKCS1] is more secure against the Bleichenbacher attack. However, for maximal compatibility with earlier versions of TLS, this specification uses the RSAES-PKCS1-v1_5 scheme."

- avoid RSA key exchange altogether (TLS 1.3)

ROBOT (2017)

- Böck, Somorovsky, Young (2017)
- ROBOT (Return Of Bleichenbacher's Oracle Threat)
- affected vendors: F5, Cisco ACE, Citrix, Radware, ...
- affected web sites: Facebook, PayPal, etc.
- countermeasures specified in TLS 1.2 not implemented correctly
- expected: TLS alert 20 (bad_record_mac) after Finished for all RSA decryption failures
- examples of problems:
  - immediate reset of TCP connection for prefix/padding errors
  - ChangeCipherSpec/Finished withheld – waiting for these messages iff the ciphertext in ClientKeyExchange was valid
  - specific alert (not 20) vs. timeout allowed for valid ciphertext
  - different error messages for valid and invalid ciphertexts

Timing attack, PRNG

- Timing attack
  - (2003) Boneh, Brumley
  - timing RSA decryptions (processing ClientKeyExchange by server)
  - analyzing correlations between time and private key allows to reconstruct the private key
  - improvements for RSA with CRT and Montgomery multiplication exist
  - solution: RSA blinding
- PRNG
  - client and server nonces, pre-master secret for RSA key exchange, DH private parameters for (EC)DHE key exchange, IV for AEAD
  - unpredictability, initialization
  - (2006-2008) Debian OpenSSL PRNG initialization bug
  - (2017) DUHK – Don't Use Hardcoded Keys – some (usually older) FIPS 140-2 certified implementations of ANSI X9.31 PRNG (seed key hardcoded in firmware)

“Renegotiation” problem (2009)

- renegotiation – a new handshake can be initialized anytime by client or server (inside an existing TLS connection)
- attacker creates his own TLS connection with the server and inserts victim’s handshake as a renegotiation . . . inserting arbitrary data as a prefix to the victim’s data
- root cause: missing binding between renegotiation handshake and TLS parameters in use
- RFC 5746 (TLS Renegotiation Extension):
  - basically, Hello messages must contain verification data from previous Finished messages

BEAST (2011)

- BEAST (Browser Exploit Against SSL/TLS)
- known vulnerability of CBC mode implementation made practical
- CBC mode (TLS 1.0 and older) – IV for a packet is the last block from previous packet
- assumptions: plaintext (request) manipulation (e.g. Javascript), access to the ciphertext (eavesdropping)

BEAST (2)

- attack idea:
  - let $C_0, \ldots, C_l$ be a ciphertext (a packet)
  - attacker wants to decrypt P_j
  - attacker chooses plaintext with the first block $P'_1 = C_{j-1} \oplus C_l \oplus x$
  - then $C'_1 = E_k(P'_1 \oplus C_l) = E_k(C_{j-1} \oplus x)$
  - therefore $C'_1 = C_j \Leftrightarrow x = P_j$
  - guessing an entire block is hard
  - attacker moves the boundaries of plaintext (e.g. a cookie) so he will guess just 1 byte (other bytes can be known "any_session_id=?")
  - different shift allows "ny_session_id=7?") etc.
- fix in TLS 1.1 – explicit IV
- other mitigation strategy in browsers: 1/n-1 record splitting
- remark:
  - weakness in CBC known since 2002; TLS 1.1 standardized in 2006
  - practical attack: BEAST in 2011
  - default support for TLS 1.1 in browsers in 2011: none

CRIME (2012)

- CRIME (Compression Ratio Info-leak Made Easy)
- using compression in SSL/TLS for leaking plaintext information
- assumptions: compression, plaintext (request) manipulation, access to the ciphertext (eavesdropping)
- attack idea:
  - attacker adds data to plaintext, e.g. “Cookie: company_session_id=??”
  - ciphertext will be probably shorter if “??” is guessed correctly
  - subsequent bytes can be tested after correct guess
  - “playing” with the plaintext to see differences when padding is used
  - divide et impera approach: add strings for half of all guessed values $\Rightarrow$ less requests, faster attack
- fix: disable compression in TLS

BREACH (2013)

- BREACH (Browser Reconnaissance and Exfiltration via Adaptive Compression of Hypertext)
- CRIME variant against HTTP compression
- it is really hard to turn off HTTP compression

POODLE (2014)

- POODLE (Padding Oracle On Downgraded Legacy Encryption)
- attacking CBC mode padding in SSL 3.0
- SSL 3.0 prescribes only the value of the last byte in padding (e.g. 07 for a complete padding block and 3DES algorithm)
- padding is not an input to MAC (SSL: MAC-then-Encrypt)
- client and server might be willing to use SSL 3.0 in case of problems with the handshake (even though they both support TLS)
- assumptions: attacker can create requests (e.g. Javascript), manipulate the ciphertext, and observe server's responses

POODLE (2)

- padding oracle attack, and shifting unknown plaintext (e.g. cookie)
- request || MAC fits to block boundary (i.e. padding fills an entire block)
  GET /path Cookie: secret=xx || xxxxxxYX || ... || MAC || padding 07
- attacker replaces last ciphertext block with the CT block for the red block
  server continues ⇒ final byte 07, compute X (prob. 1/256)
  server rejects ⇒ new handshake; new test
- attacker shifts the plaintext to decrypt other bytes of cookie:
  GET /path2 Cookie: secret=x || xxxxxxY || X.. || MAC || padding 07
  etc.
- fix – remove SSL 3.0 from browsers (at least disable)

POODLE (3)

- TLS padding is a special case of SSL 3.0 padding

  msg || 00
  msg || 01 01
  msg || 03 03 03 03

- What if padding verification is performed as in SSL 3.0 case?
- no need for fallback to SSL 3.0
- POODLE for TLS (SSL Pulse, https://www.ssllabs.com/ssl-pulse/) vulnerable severs:
  - 10.1% (XII/2014)
  - 1.9% (XII/2016)
  - 0.4% (XII/2018)
  - 0.0% (XII/2020) …end of story?

POODLE continues

- various methods of detecting padding oracles
  - in the handshake (Finished message) or in application data
  - in/valid/missing MAC combined with in/valid padding
  - different ciphersuites behave differently, …
- GOLDENDOODLE, Zombie POODLE, Sleeping POODLE, …
- Merget et al. (2019): *Scalable Scanning and Automatic Classification of TLS Padding Oracle Vulnerabilities*
  - systematic analysis of servers' behavior
  - conservative estimate: 1.83% of TLS servers vulnerable

FREAK (2015)

- "export-grade" algorithms – RSA 512 bits
- clients (usually) did not request such algorithms . . . but they accepted such short RSA public key
  - note: TLS 1.1 and older allow temporary RSA key in key exchange
- supported by web servers (March 2015, approx. 36%)
- MITM attack:
  1. attacker replaces cipher suites with export RSA in ClientHello
  2. attacker decrypts pre-master secret and computes keys
  3. knowing master secret allows "fixing" Finished messages
- no need to factorize 512 bit RSA often:
  - apache: generated when server starts and reused when needed
  - March 2015: 1 factorization ~ 7.5 hours in EC2 for 104 USD

Logjam (2015)

- "export-grade" algorithms again – DHE (short group, e.g. 512-bit)
- clients (usually) did not request . . . but they accepted
- MITM attack (similar to FREAK):
  1. attacker replaces cipher suites with export DHE in ClientHello
  2. attacker computes dlog, obtains pre-master secret and computes keys
  3. knowing master secret allows "fixing" Finished messages
- computing dlog (even with export-grade parameters) is not possible in real-time
  - 2 phases: pre-computation (slow, but depends on group and g only) and on-line (for given input, fast)
  - DHE_EXPORT: 99% hosts choose one of three 512-bit primes
- remark: fixed groups are used everywhere (IPSec, TLS, SSH); 1024-bit primes within reach of a state-sponsored agency
  - passive eavesdropping on VPN, SSH?

DROWN (2016)

- DROWN (Decrypting RSA using Obsolete and Weakened eNcryption)
- TLS and SSL 2.0 enabled on server (or servers), sharing the same RSA key
- RSA key exchange
- cross-protocol attack
- decrypting pre-master secret from TLS 1.x RSA key exchange
  - using SSL 2.0 to mount Bleichenbacher's attack
  - exploiting export-grade cipher suite, and other SSL 2.0 weaknesses
- fix: disable SSL 2.0 everywhere

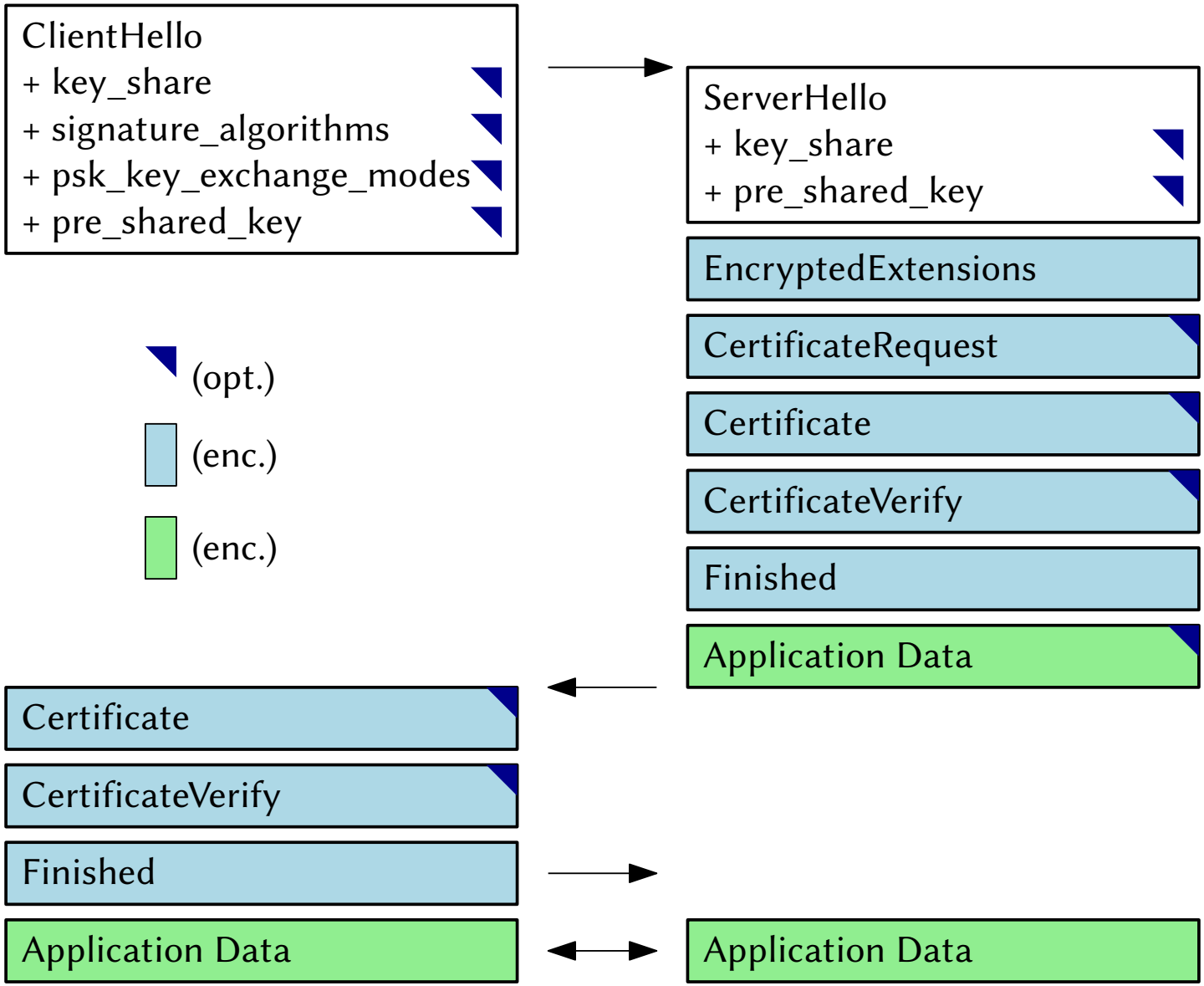
TLS 1.3 – major changes from TLS 1.2

- RFC 8446 (2018)
- AEAD ciphers only (support for non-AEAD ciphers removed)
- public-key key exchange with forward secrecy (static RSA and Diffie-Hellman removed)
- redesigned key derivation function: HMAC-based Extract-and-Expand Key Derivation Function (HKDF)
- reworked handshake: 1-RTT (1 round trip time) mode
- new zero round-trip time (0-RTT) mode
- other things removed: custom DHE groups, support for compression, DSA
- RSA-PSS is used instead of PKCS#1 v1.5 for handshake signatures
- TLS supports three basic key exchange modes:
  - Diffie-Hellman (over the finite fields and or elliptic curves)
  - pre-shared symmetric key (PSK)
  - combination of PSK and Diffie-Hellman

TLS 1.3 – mandatory cipher suites

- symmetric cipher suite (AEAD + hash function HKDF):
  - MUST: TLS_AES_128_GCM_SHA256
  - SHOULD: TLS_AES_256_GCM_SHA384, TLS_CHACHA20_POLY1305_SHA256
- digital signatures:
  - MUST: rsa_pkcs1_sha256 (for certificates), rsa_pss_rsae_sha256 (for CertificateVerify and certificates), and ecdsa_secp256r1_sha256
- key exchange:
  - MUST: secp256r1 (NIST P-256)
  - SHOULD: X25519

TLS 1.3 – Handshake protocol



Discussion on security of TLS 1.3 (informal)

- TLS 1.3 (RFC 8446)
- Appendix E. Overview of Security Properties
  - E.1. Handshake
    - E.1.1. Key Derivation and HKDF
    - E.1.2. Client Authentication
    - E.1.3. 0-RTT
    - E.1.4. Exporter Independence
    - E.1.5. Post-Compromise Security
    - E.1.6. External References
  - E.2 Record Layer
    - E.2.1. External References
  - E.3. Traffic Analysis
  - E.4. Side-Channel Attacks
  - E.5. Replay Attacks on 0-RTT
    - E.5.1. Replay and Exporters
  - E.6. PSK Identity Exposure
  - E.7. Sharing PSKs
  - E.8. Attacks on Static RSA
- interesting part: C.3. Implementation Pitfalls

TLS 1.3 – Selfie

- Selfie (2019) – first protocol attack on TLS 1.3
  - rarely used case of (external) PSK authentication
  - scenario: client can also be a server
  - simple reflection: attacker resend all messages back to client
  - client establishes connection with itself
  - limited impact in practice