Secure Socket Layer (SSL)

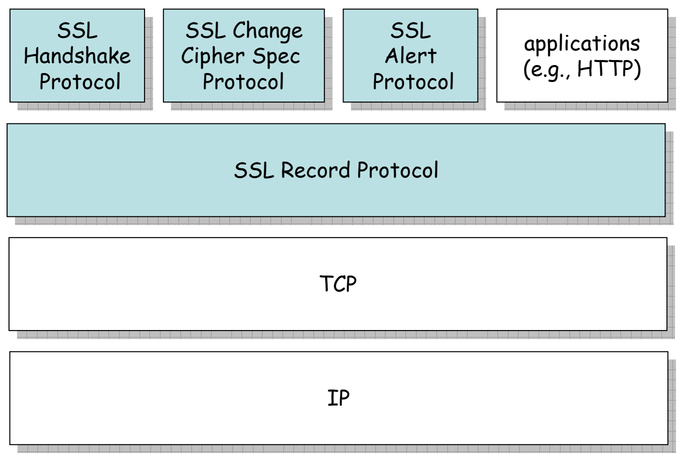
-- architecture and services
-- SSL Record Protocol
-- SSL Handshake Protocol
-- analysis and attacks
-- SSL vs. TLS

(c) Levente Buttyán (buttyan@crysys.hu)

What is SSL?

- SSL – Secure Socket Layer
- it provides a secure transport connection between applications (e.g., a web server and a browser)
- SSL was developed by Netscape
- SSL version 3.0 has been implemented in many web browsers (e.g., Netscape Navigator and MS Internet Explorer) and web servers and widely used on the Internet
- SSL v3.0 was specified in an Internet Draft (1996)
- it evolved into RFC 2246 and was renamed to TLS v1.0 (Transport Layer Security)
- current version is TLS v1.1 (RFC 4346)
  - modifications to handle CBC attacks: explicit IV and bad_record_mac error message instead of decryption_failed

SSL architecture



SSL components

- SSL Handshake Protocol
  - negotiation of security algorithms and parameters
  - key exchange
  - server authentication and optionally client authentication
- SSL Record Protocol
  - fragmentation
  - compression
  - message authentication and integrity protection
  - encryption
- SSL Alert Protocol
  - error messages (fatal alerts and warnings)
- SSL Change Cipher Spec Protocol
  - a single message that indicates the end of the SSL handshake

Sessions and connections

- an SSL session is an association between a client and a server
- sessions are stateful; the session state includes security algorithms and parameters
- a session may include multiple secure connections between the same client and server
- connections of the same session share the session state
- sessions are used to avoid expensive negotiation of new security parameters for each connection
- there may be multiple simultaneous sessions between the same two parties, but this feature is not used in practice

Session state

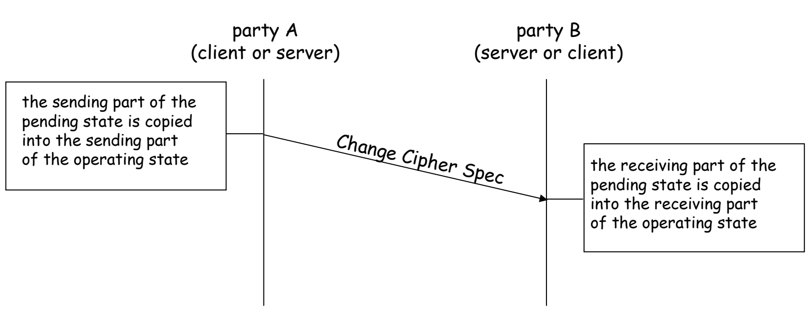
- session identifier
  - arbitrary byte sequence chosen by the server to identify the session
- peer certificate
  - X509 certificate of the peer
  - may be null
- compression method
- cipher spec
  - bulk data encryption algorithm (e.g., null, DES, 3DES, …)
  - MAC algorithm (e.g., MD5, SHA-1)
  - cryptographic attributes (e.g., hash size, IV size, …)
- master secret
  - 48-byte secret shared between the client and the server
- is resumable
  - a flag indicating whether the session can be used to initiate new connections
- connection states
  - see next slide…

Connection state

- server and client random
  - random byte sequences chosen by the server and the client for every connection
- server write MAC secret
  - secret key used in MAC operations on data sent by the server
- client write MAC secret
  - secret key used in MAC operations on data sent by the client
- server write key
  - secret encryption key for data encrypted by the server
- client write key
  - secret encryption key for data encrypted by the client
- initialization vectors
  - an IV is maintained for each encryption key if CBC mode is used
  - initialized by the SSL Handshake Protocol
  - final ciphertext block from each record is used as IV with the following record
- sending and receiving sequence numbers
  - sequence numbers are 64 bits long
  - reset to zero after each Change Cipher Spec message

State change

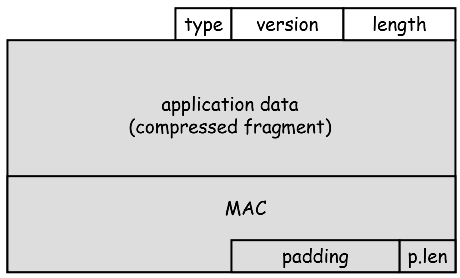
- operating state
  - currently used state
- pending state
  - state to be used
  - built using the current state
- operating state ← pending state
  - at the transmission and reception of a Change Cipher Spec message



SSL Record Protocol – processing overview

- fragmentation
- compression
- MAC computation
- padding
- encryption

→ SSL Record Protocol message:



Header

- type
  - the higher level protocol used to process the enclosed fragment
  - possible types:
    - change_cipher_spec
    - alert
    - handshake
    - application_data
- version
  - SSL version, currently 3.0
- length
  - length (in bytes) of the enclosed fragment or compressed fragment
  - max value is $2^{14} + 2048$

MAC

MAC = hash(MAC_wr_sec | pad_2 |
hash(MAC_wr_sec | pad_1 | seq_num | type | length |frag))

- similar to HMAC but the pads are concatenated
- supported hash functions:
  - MD5
  - SHA-1
- pad_1 is 0x36 repeated 48 times (MD5) or 40 times (SHA-1)
- pad_2 is 0x5C repeated 48 times (MD5) or 40 times (SHA-1)

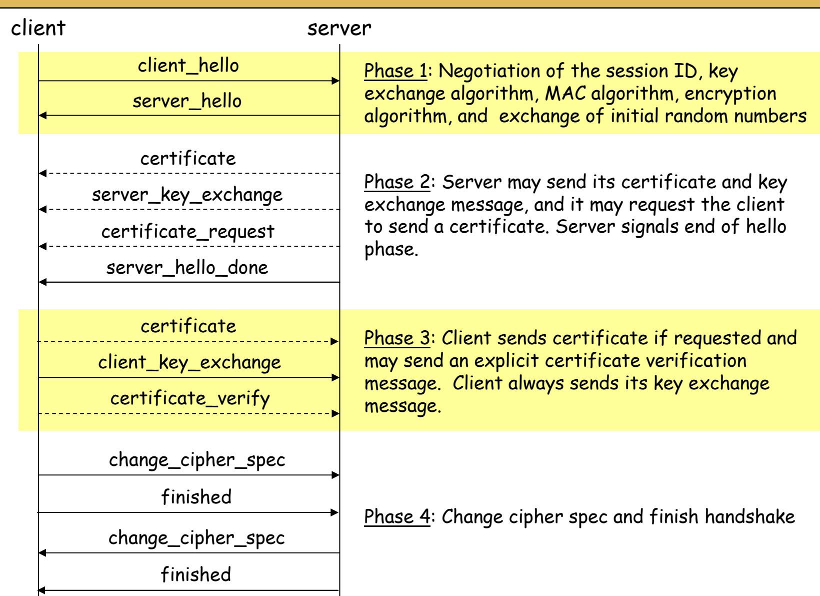
Encryption

- supported algorithms
  - block ciphers (in CBC mode)
    - RC2_40
    - DES_40
    - DES_56
    - 3DES_168
    - IDEA_128
    - Fortezza_80
  - stream ciphers
    - RC4_40
    - RC4_128
- if a block cipher is used, than padding is applied
  - last byte of the padding is the padding length

SSL Alert Protocol

- each alert message consists of 2 fields (bytes)
- first field (byte): “warning” or “fatal”
- second field (byte):
  - fatal
    - unexpected_message
    - bad_record_MAC
    - decryption_failure
    - …
  - warning
    - close_notify
    - no_certificate
    - bad_certificate
    - unsupported_certificate
    - …
- in case of a fatal alert
  - connection is terminated
  - session ID is invalidated → no new connection can be established within this session

SSL Handshake Protocol – overview



Client hello message

- client_version
  - the highest version supported by the client
- client_random
  - current time (4 bytes) + pseudo random bytes (28 bytes)
- session_id
  - empty if the client wants to create a new session, or
  - the session ID of an old session within which the client wants to create the new connection
- cipher_suites
  - list of cryptographic options supported by the client ordered by preference
  - a cipher suite contains the specification of the
    - key exchange method, the encryption and the MAC algorithm
    - the algorithms implicitly specify the hash_size, IV_size, and key_material parameters (part of the Cipher Spec of the session state)
  - exmaple: SSL_RSA_with_3DES_EDE_CBC_SHA
- compression_methods
  - list of compression methods supported by the client

Server hello message

- server_version
  - min(highest version supported by client, highest version supported by server)
- server_random
  - current time + random bytes
  - random bytes must be independent of the client random
- session_id
  - session ID chosen by the server
  - if the client wanted to resume an old session:
    - server checks if the session is resumable
    - if so, it responds with the session ID and the parties proceed to the finished messages
  - if the client wanted a new session
    - server generates a new session ID
- cipher_suite
  - single cipher suite selected by the server from the list given by the client
- compression_method
  - single compression method selected by the server

Supported key exchange methods

- RSA based (SSL_RSA_with...)
  - the secret key (pre-master secret) is encrypted with the server's public RSA key
  - the server's public key is made available to the client during the exchange
- fixed Diffie-Hellman (SSL_DH_RSA_with… or SSL_DH_DSS_with…)
  - the server has fix DH parameters contained in a certificate signed by a CA
  - the client may have fix DH parameters certified by a CA or it may send an unauthenticated one-time DH public value in the client_key_exchange message
- ephemeral Diffie-Hellman (SSL_DHE_RSA_with… or SSL_DHE_DSS_with…)
  - both the server and the client generate one-time DH parameters
  - the server signs its DH parameters with its private RSA or DSS key
  - the client may authenticate itself (if requested by the server) by signing the hash of the handshake messages with its private RSA or DSS key
- anonymous Diffie-Hellman (SSL_DH_anon_with…)
  - both the server and the client generate one-time DH parameters
  - they send their parameters to the peer without authentication
- Fortezza
  - Fortezza proprietary key exchange scheme

Server certificate and key exchange msgs

- certificate
  - required for every key exchange method except for anonymous DH
  - contains one or a chain of X.509 certificates (up to a known root CA)
  - may contain
    - public RSA key suitable for encryption, or
    - public RSA or DSS key suitable for signing only, or
    - fix DH parameters
- server_key_exchange
  - sent only if the certificate does not contain enough information to complete the key exchange (e.g., the certificate contains an RSA signing key only)
  - may contain
    - public RSA key (exponent and modulus), or
    - DH parameters (p, g, public DH value), or
    - Fortezza parameters
  - digitally signed
    - if DSS: SHA-1 hash of (client_random | server_random | server_params) is signed
    - if RSA: MD5 hash and SHA-1 hash of (client_random | server_random | server_params) are concatenated and encrypted with the private RSA key

Cert request and server hello done msgs

- certificate_request
  - sent if the client needs to authenticate itself
  - specifies which type of certificate is requested (rsa_sign, dss_sign, rsa_fixed_dh, dss_fixed_dh, …)
- server_hello_done
  - sent to indicate that the server is finished its part of the key exchange
  - after sending this message the server waits for client response
  - the client should verify that the server provided a valid certificate and the server parameters are acceptable

Client authentication and key exchange

- certificate
  - sent only if requested by the server
  - may contain
    - public RSA or DSS key suitable for signing only, or
    - fix DH parameters
- client_key_exchange
  - always sent (but it is empty if the key exchange method is fix DH)
  - may contain
    - RSA encrypted pre-master secret, or
    - client one-time public DH value, or
    - Fortezza key exchange parameters
- certificate_verify
  - sent only if the client sent a certificate
  - provides client authentication
  - contains signed hash of all the previous handshake messages
    - if DSS: SHA-1 hash is signed
    - if RSA: MD5 and SHA-1 hash is concatenated and encrypted with the private key

      MD5(master_secret | pad_2 | MD5(handshake_messages | master_secret | pad_1))

      SHA(master_secret | pad_2 | SHA(handshake_messages | master_secret | pad_1))

Finished messages

- finished
  - sent immediately after the change_cipher_spec message
  - used to authenticate all previous handshake messages
  - first message that uses the newly negotiated algorithms, keys, IVs, etc.
  - contains the MD5 and SHA-1 hash of all the previous handshake messages:

    MD5(master_secret | pad_2 | MD5(handshake_messages | sender | master_secret | pad_1)) |
    SHA(master_secret | pad_2 | SHA(handshake_messages | sender | master_secret | pad_1))

    where “sender” is a code that identifies that the sender is the client or the server (client: 0x434C4E54; server: 0x53525652)

Cryptographic computations

- pre-master secret
  - if key exchange is RSA based:
    - generated by the client
    - sent to the server encrypted with the server’s public RSA key
  - if key exchange is Diffie-Hellman based:
    - pre_master_secret = g^{xy} mod p
- master secret (48 bytes)

  master_secret = MD5(pre_master_sec | SHA(“A” | pre_master_sec | client_random | server_random)) |
  MD5(pre_master_sec | SHA(“BB” | pre_master_sec | client_random | server_random)) |
  MD5(pre_master_sec | SHA(“CCC” | pre_master_sec | client_random | server_random))
- keys, MAC secrets, IVs

  MD5(master_secret | SHA(“A” | master_secret | client_random | server_random)) |
  MD5(master_secret | SHA(“BB” | master_secret | client_random | server_random)) |
  MD5(master_secret | SHA(“CCC” | master_secret | client_random | server_random)) | …

key block :

client write MAC sec	server write MAC sec	client write key	server write key	…

Key exchange alternatives

- RSA / no client authentication
  - server sends its encryption capable RSA public key in server_certificate
  - server_key_exchange is not sent
  - client sends encrypted pre-master secret in client_key_exchange
  - client_certificate and certificate_verify are not sent

  or
  - server sends its RSA or DSS public signature key in server_certificate
  - server sends a temporary RSA public key in server_key_exchange
  - client sends encrypted pre-master secret in client_key_exchange
  - client_certificate and certificate_verify are not sent

Key exchange alternatives cont'd

- RSA / client is authenticated
  - server sends its encryption capable RSA public key in server_certificate
  - server_key_exchange is not sent
  - client sends its RSA or DSS public signature key in client_certificate
  - client sends encrypted pre-master secret in client_key_exchange
  - client sends signature on all previous handshake messages in certificate_verify

  or
  - server sends its RSA or DSS public signature key in server_certificate
  - server sends a one-time RSA public key in server_key_exchange
  - client sends its RSA or DSS public signature key in client_certificate
  - client sends encrypted pre-master secret in client_key_exchange
  - client sends signature on all previous handshake messages in certificate_verify

Key exchange alternatives cont'd

- fix DH / no client authentication
  - server sends its fix DH parameters in server_certificate
  - server_key_exchange is not sent
  - client sends its one-time DH public value in client_key_exchange
  - client_ certificate and certificate_verify are not sent
- fix DH / client is authenticated
  - server sends its fix DH parameters in server_certificate
  - server_key_exchange is not sent
  - client sends its fix DH parameters in client_certificate
  - client_key_exchange is sent but empty
  - certificate_verify is not sent

Key exchange alternatives cont'd

- ephemeral DH / no client authentication
  - server sends its RSA or DSS public signature key in server_certificate
  - server sends signed one-time DH parameters in server_key_exchange
  - client sends one-time DH public value in client_key_exchange
  - client_certificate and certificate_verify are not sent
- ephemeral DH / client is authenticated
  - server sends its RSA or DSS public signature key in server_certificate
  - server sends signed one-time DH parameters in server_key_exchange
  - client sends its RSA or DSS public signature key in client_certificate
  - client sends one-time DH public value in client_key_exchange
  - client sends signature on all previous handshake messages in certificate_verify

Key exchange alternatives cont'd

- anonymous DH / no client authentication
  - server_certificate is not sent
  - server sends (unsigned) one-time DH parameters in server_key_exchange
  - client sends one-time DH public value in client_key_exchange
  - client_certificate and certificate_verify are not sent
- anonymous DH / client is authenticated
  - not allowed

Eavesdropping

+ all application data is encrypted with a short term connection key
+ short term key is derived from per-connection salts (client and server randoms) and a strong shared secret (master secret) by hashing (one-way operation)
  + even if connection keys are compromised the master secret remains intact
+ different keys are used in each connection and in each direction of the connection
+ supported encryption algorithms are strong

Traffic analysis

- SSL doesn't attempt to protect against traffic analysis
  – padding length is not random
  – no padding if a stream cipher is used (this is the default option)
- if SSL is used to protect HTTP traffic, then an attacker
  – can learn the length of a requested URL
  – can learn the length of the HTML data returned
  – could find out which URL was requested with high probability

Replay attacks

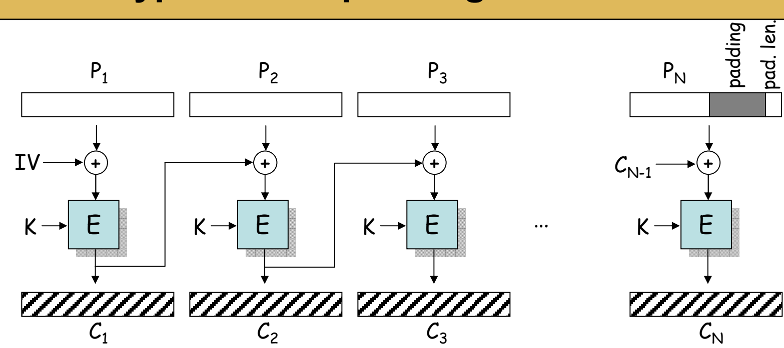
+ SSL protects against replay attacks by including an implicit sequence number in the MAC computation
  + prevents re-order and deletion of messages
+ sequence numbers are 64 bit long
  + practically never wraps around

Message authentication

+/- SSL uses a HMAC-like MAC
  – it actually uses an obsolete version of HMAC
  + HMAC is provably secure

+ MAC secret is 128 bits long
+ different MAC secrets are used in different directions and connections
- the MAC doesn't involve the version number (part of the message)
  - if the version number is ever used, then it should be covered by the MAC
  - if the version number is never used, then it should not be sent

CBC encryption with padding in SSL/TLS



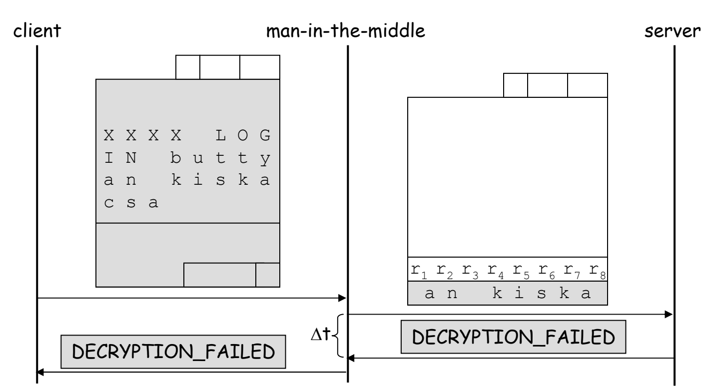
- SSL padding
  – last byte is the length n of the padding (not including the last byte)
  – all padding bytes have the value n
  – examples for correct padding: 0, 11, 222, 3333, …
- verification of SSL padding:
  – if the last byte is n, then verify if the last n+1 bytes are all n

Padding oracle attack (reminder)

- send a random message to a TLS server
- the server will drop the message with overwhelming probability
  - either the padding is incorrect (the server responds with a DECRYPTION_FAILED alert)
  - or the MAC is incorrect with very high probability (the server responds with BAD_RECORD_MAC alert)
- if the response is BAD_RECORD_MAC, then the padding was correct → we get 1 bit of information !
- such an oracle can be used to decrypt any encrypted message (see slides on block encryption modes)
- problems in practice
  - alert messages are encrypted → BAD_RECORD_MAC and DECRYPTION_FAILED cannot be distinguished
    - measure timing between oracle call and oracle response
    - BAD_RECORD_MAC takes more time than DECRYPTION_FAILED
  - BAD_RECORD_MAC and DECRYPTION_FAILED are fatal errors → connection is closed after one oracle call
    - a password can still be broken if it is sent periodically to a server using TLS (a different session (and key) is used each time the password is sent, but the password is always the same)

Example: IMAP over TLS

- Outlook Express checks for new mail on the server periodically (every 5 minutes)
- each time the same password is sent for every folder
  XXXX LOGIN “username” “password”<0D><0A>
- it is possible to uncover the password using the attack as follows:

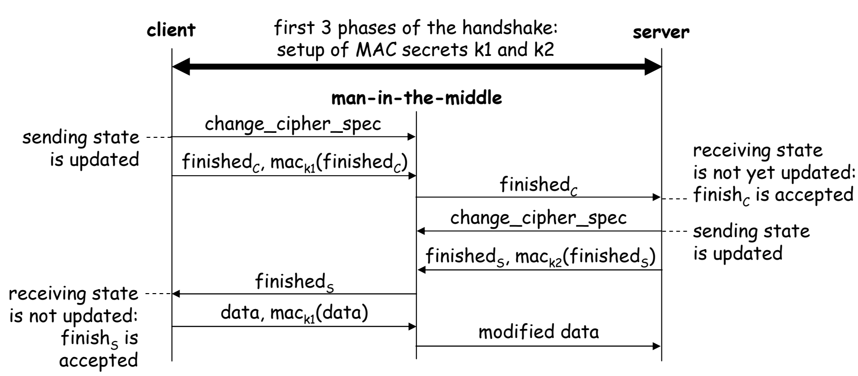


Cipher suite rollback attack

- in SSL 2.0, an attacker could force the use of an export-weakened encryption algorithm by modifying the list of supported cipher suites in the hello messages
- this is prevented in SSL 3.0 by authenticating all handshake messages with the master secret (in the finished messages)
- the master secret itself is authenticated by other means
  - for the client:
    - implicit authentication via the server certificate
      - only the server could decrypt the RSA encrypted pre-master secret
      - only the server could compute the pre-master secret from the client's public DH value
    - explicit authentication via the server_key_exchange message (if sent)
      - ephemeral DH parameters are signed by the server
  - for the server:
    - explicit authentication via the certificate_verify message (if sent)
      - certificate_verify is signed by the client
      - it involves the master secret

Dropping the change_cipher_spec msg

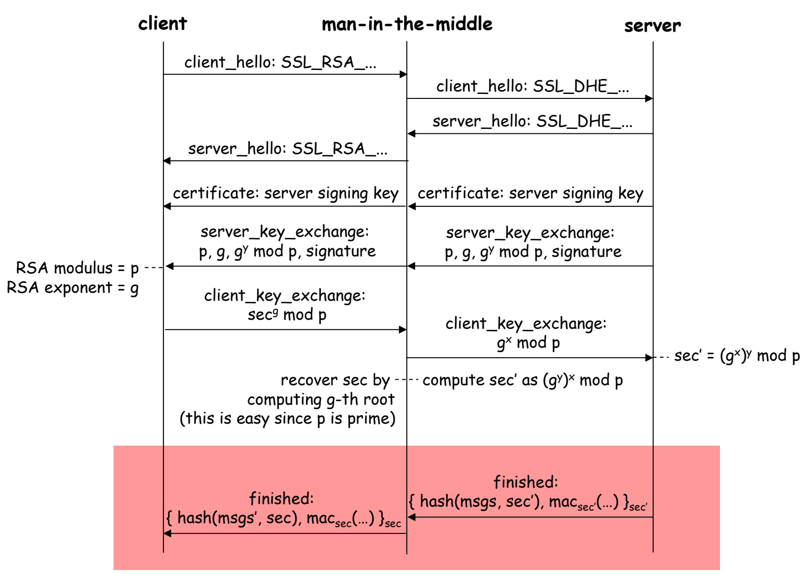
- authentication in the finished message does not protect the change_cipher_spec message (it is not part of the handshake protocol !)
- this may allow the following attack:
  - assume that the negotiated cipher suite includes only message authentication (no encryption)



Dropping the change_cipher_spec msg

- if the negotiated cipher suite includes encryption, then the attacks doesn't work
  - client sends encrypted finished message
  - server expects clear finished message
  - the attacker cannot decrypt the encrypted finished message
- simplest fix: require reception of change_cipher_spec before processing the finished message
  - this seems to be obvious, but…
  - even Netscape's reference SSL implementation SSLRef 3.0b1 allows processing finished messages without checking if a change_cipher_spec has been received
  - SSLRef 3.0b3 contains the fix
- another fix: include the change_cipher_spec message in the computation of the finished message
  - this would require a more radical change in the SSL specification

Key-exchange algorithm rollback



Key-exchange algorithm rollback

- SSL authenticates only the server's (RSA or DH) parameters in the server_key_exchange message
- it doesn't authenticate the context (key exchange algorithm in use) in which those parameters should be interpreted
- this is not compliant with the Horton principle !

- a fix:
  – hash all messages exchanged before the server_key_exchange message
  – include the hash in the signature in server_key_exchange message

Version rollback attacks

- SSL 3.0 implementations may still support SSL 2.0
- an attacker may change the client_hello message so that it looks like an SSL 2.0 client_hello
- as a result the client and the server will run SSL 2.0
- SSL 2.0 has serious security flaws
  – among other things, there are no finished messages to authenticate the handshake
  - the version rollback attack will go undetected

- fortunately, SSL 3.0 can detect version rollback
  – pre-master secret generated on SSL 3.0 enabled clients:

```
struct{
  ProtocolVersion client_version; // latest version supported by the client
  opaque random[46];              // random bytes
} PreMasterSecret;
```

  – an SSL 3.0 enabled server detects the version rollback attack, when it runs an SSL 2.0 handshake but receives a pre-master secret that includes version 3.0 as the latest version supported by the client

MAC usage

- while the SSL Record Protocol uses HMAC (an early version), the SSL Handshake Protocol uses ad-hoc MACs at several points
  - certificate_verify:
    hash(master_secret | pad_2 | hash(handshake_messages | master_secret | pad_1))
  - finished:
    hash(master_secret | pad_2 | hash(handshake_messages | sender | master_secret | pad_1))

- in addition, these ad-hoc MACs involve the master secret
- this is dangerous, and SSL should use HMAC consistently

Analysis summary

- SSL Record Protocol
  - \+ good protection against passive eavesdropping and active attacks
  - – should better protect against traffic analysis (e.g., apply random padding)
  - – should use the latest version of HMAC
- SSL Handshake Protocol
  - \+ some active attacks are foiled
    - cipher suite rollback
    - version rollback
  - – other active attacks could still be possible depending on how an implementation interprets the SSL specification
    - dropping change_cipher_spec messages
    - key-exchange algorithm rollback
  - – ad-hoc MAC constructions should be replaced with HMAC
- <u>overall</u>: SSL 3.0 was an extremely important step toward practical communication security for Internet applications

SSL vs. TLS

- version number
  – for TLS 1.1 the version number is 3.2
- cipher suites
  – TLS doesn't support Fortezza key exchange and Fortezza encryption
- padding
  – variable length padding is allowed (max 255 padding bytes)
- MAC
  – TLS uses the latest version of HMAC
  – the MAC covers the version field of the record header too
- certificate_verify message
  – in SSL, the hash contains the master_secret
  – in TLS, the hash is computed only over the handshake messages
- more alert codes

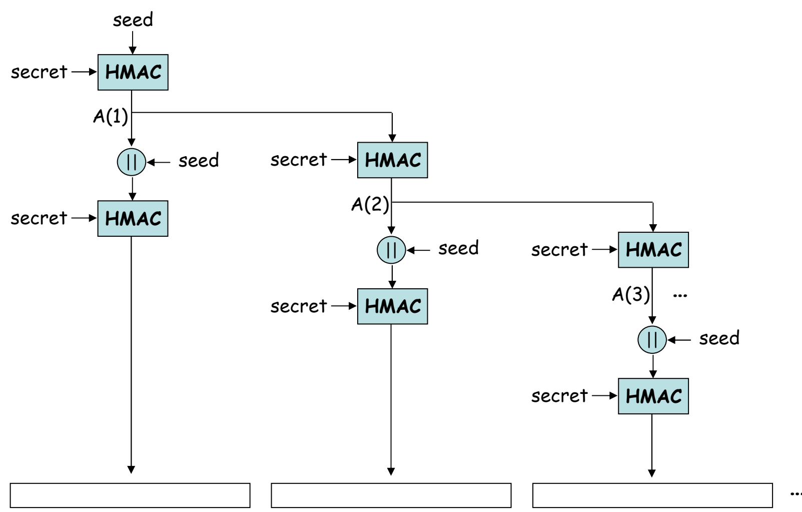
New pseudorandom function (PRF)

- P_hash(secret, seed) = HMAC_hash(secret, A(1) | seed) |
  HMAC_hash(secret, A(2) | seed) |
  HMAC_hash(secret, A(3) | seed) | …

  where
  A(0) = seed
  A(i) = HMAC_hash(secret, A(i-1))

- PRF(secret, label, seed) =
  P_MD5(secret_left, label | seed) ⊕ P_SHA(secret_right, label | seed)

P_hash illustrated



Usage of the new PRF

- finished message

  PRF(master_secret,
  "client finished",
  MD5(handshake_messages) | SHA(handshake_messages))

- cryptographic computations
  - pre-master secret is calculated in the same way as in SSL
  - master secret:

    PRF(pre_master_secret,
    "master secret",
    client_random | server_random)
  - key block:

    PRF(master_secret,
    "key expansion",
    server_random | client_random)

Further readings

- The TLS protocol v1.1, available on-line as RFC 4346
- D. Wagner, B. Schneier, Analysis of the SSL 3.0 protocol, 2nd USENIX Workshop on Electronic Commerce, 1996.