???

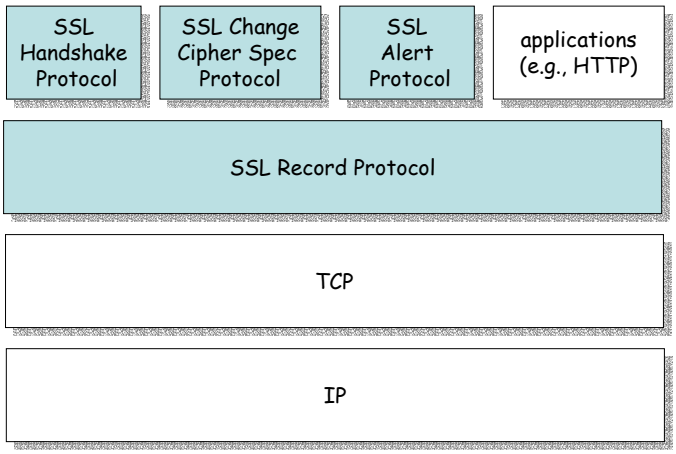
SSL – Secure Socket Layer

- architecture and services
- sessions and connections
- SSL Record Protocol
- SSL Handshake Protocol
- key exchange alternatives
- analysis of the SSL Record and Handshake Protocols
- SSL vs. TLS

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 (Transport Layer Security)
- TLS can be viewed as SSL v3.1

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 and connection states

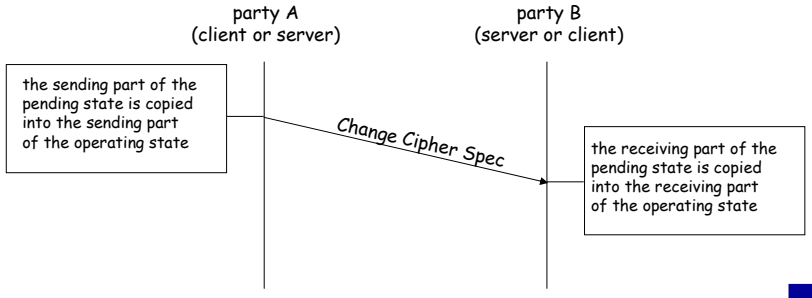
- session state
  - session identifier
    - arbitrary byte sequence chosen by the server to identify the session
  - peer certificate
    - X509 certificate of the peer
    - may be null
  - compression method
  - cipher spec
    - bulk data encryption algorithm (e.g., null, DES, 3DES, …)
    - MAC 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

Session and connection states cont'd

- 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 changes

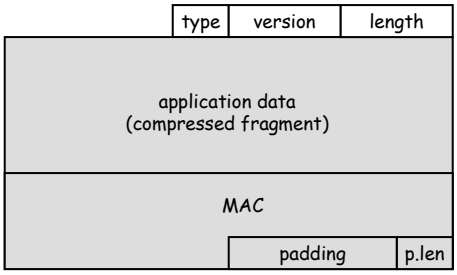
- operating state
  - currently used state
- pending state
  - state to be used
  - built using the current state
- operating state ← pending state
  - at the transmission and reception of a Change Cipher Spec message



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

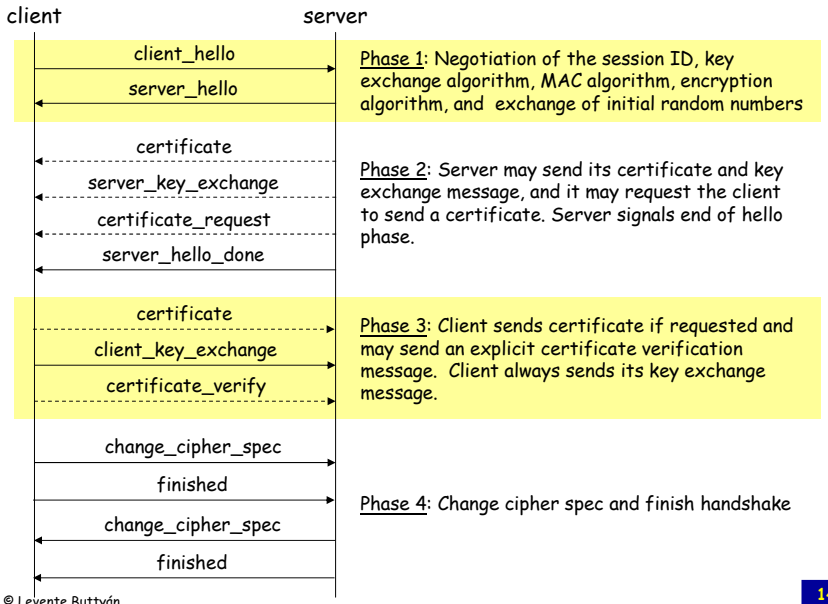
- supported algorithms
  - block ciphers (in CBC mode)
    - RC2_40
    - DES_40
    - DES_56
    - 3DES_168
    - IDEA_128
    - Fortezza_80
  - stream ciphers
    - RC4_40
    - RC4_128
- if a block cipher is used, than padding is applied
  - last byte of the padding is the padding length

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
    - decompression_failure
    - handshake_failure
    - illegal_parameter
  - warning
    - close_notify
    - no_certificate
    - bad_certificate
    - unsupported_certificate
    - certificate_revoked
    - certificate_expired
    - certificate_unknown
- in case of a fatal alert
  - connection is terminated
  - session ID is invalidated → no new connection can be established within this session

SSL Alert Protocol

SSL Handshake Protocol – overview



SSL Handshake Protocol

Hello messages

- client_hello
  - 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

Hello messages cont'd

- server_hello
  - 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

SSL Handshake Protocol / Phase 2

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))

SSL Handshake Protocol / Phase 3

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

SSL Handshake Protocol

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

SSL Handshake Protocol

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

Analysis of the SSL Record and Handshake Protocols

Eavesdropping

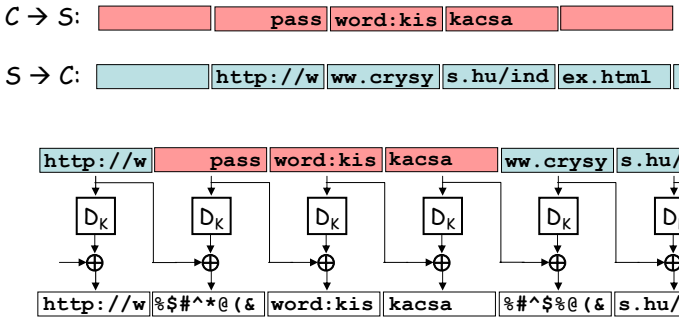
- all application data is encrypted with a short term connection key
- short term key is derived from per-connection salts (client and server randoms) and a strong shared secret (master secret) by hashing (one-way operation)
  - even if connection keys are compromised the master secret remains intact
- 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 which URL was requested with high probability

Active attacks on confidentiality

- cut-and-paste attack



+ SSL prevents cut-and-paste attacks
  + different keys are used in different directions (and connections)
  + all encrypted packets are authenticated by a MAC

Replay attacks

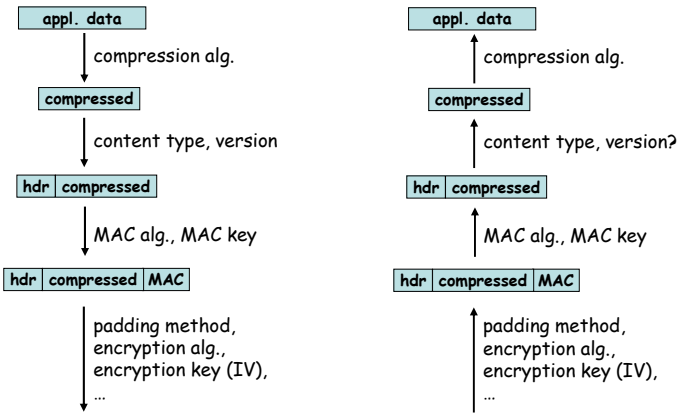
+ SSL protects against replay attacks by including an implicit sequence number in the MAC computation
  + prevents re-order and deletion of messages
+ sequence numbers are 64 bit long
  + practically never wraps around

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

The Horton principle

- not only data should be authenticated, but all context information on which processing and interpretation of the data depend (e.g., algorithms, keys, information added to headers, etc)

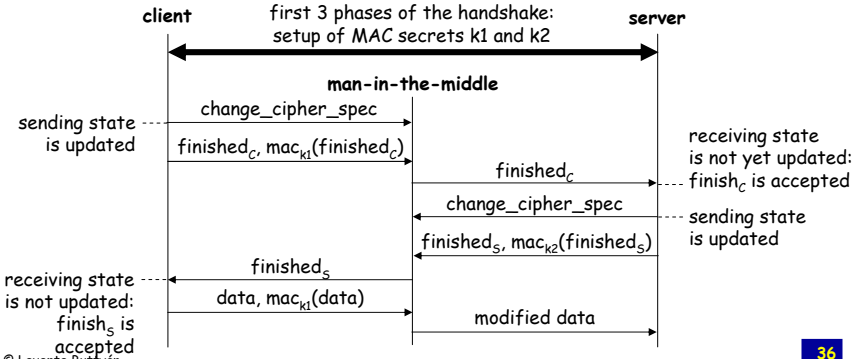


Cipher suite rollback attack

- 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

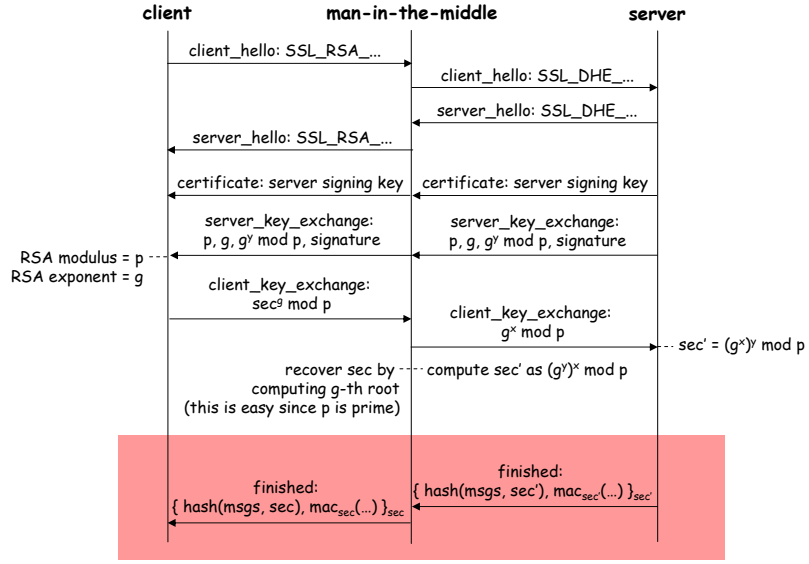
- authentication in the finished message does not protect the change_cipher_spec message (it is not part of the handshake protocol !)
- this may allow the following attack:
  - assume that the negotiated cipher suite includes only message authentication (no encryption)



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
- overall: SSL 3.0 was an extremely important step toward practical communication security for Internet applications

SSL vs. TLS

Miscellaneous changes

- version number
  - for TLS the current version number is 3.1
- 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
  - the hash is computed only over the handshake messages
  - in SSL, the hash contained the master_secret and pads
- 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) | …

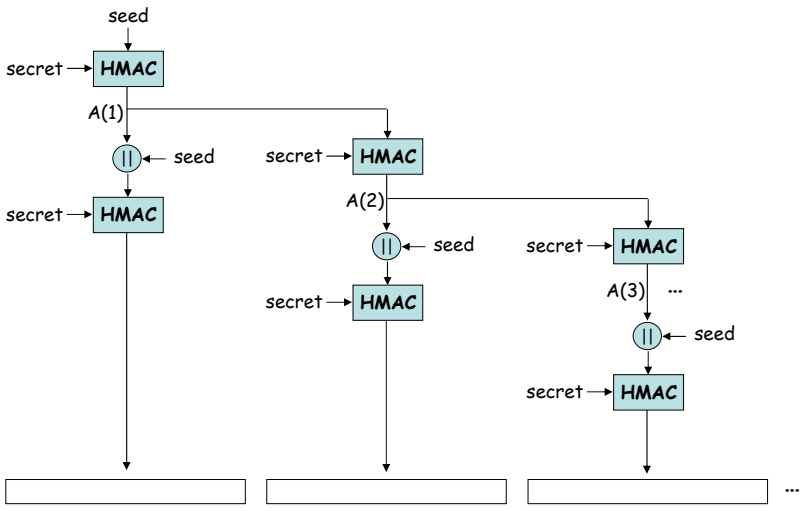
  where

  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)

Recommended readings

- SSL v3.0 specification, available on-line at http://wp.netscape.com/eng/ssl3/index.html
- D. Wagner, B. Schneier, Analysis of the SSL 3.0 protocol, 2nd USENIX Workshop on Electronic Commerce, 1996.
- The TLS protocol v1.0, available on-line as RFC 2246