DIMACS Security & Cryptography Crash Course – day 4

Internet Cryptography Tools, Part I: TLS/SSL

Prof. Amir Herzberg

Computer Science Department, Bar Ilan University

http://amir.herzberg.name

Sources

- This lecture is mostly covered in `SSL and TLS` by Eric Rescorla
- Partial but readable coverage also in Stalling's book, `Cryptography and Network Security`
- TLS is defined in Internet Engineering Task Force (**IETF**) RFC Document 2246, see e.g. at www.ietf.org

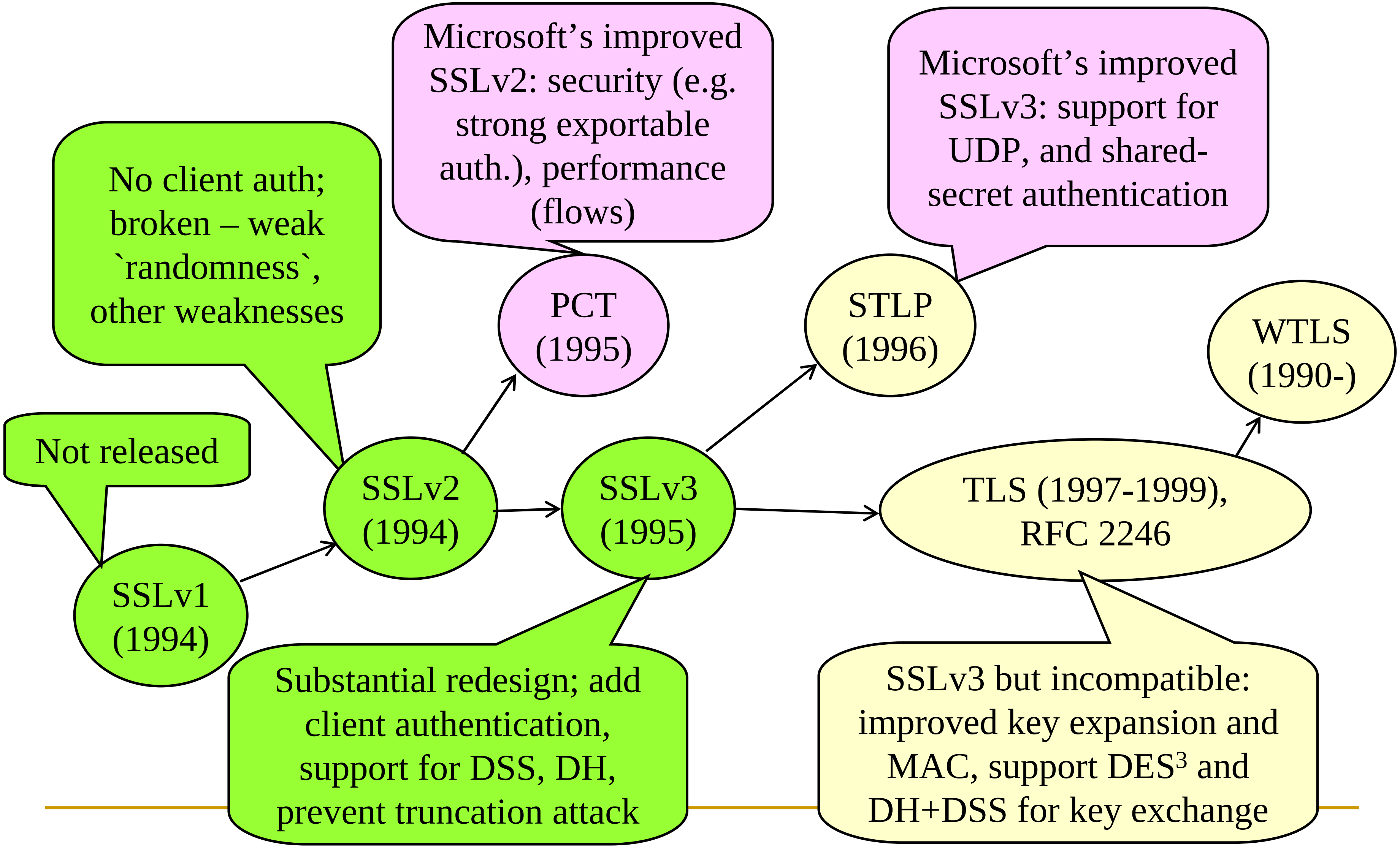
Agenda – Transport Layer Security

- Example: SSL payments
- Evolution of SSL and TLS
- Layer and alternatives
  - Few words about S/MIME
- SSL Protocol
  - SSL phases and services
  - Sessions and connections
  - SSL Handshake
  - SSL protocols and layers
  - SSL Record protocol / layer
- Secure use of SSL
  - Designing SSL applications
  - Client & server authentication
  - Web spoofing attacks
- Cryptographic issues in SSL and TLS
- Conclusions

SSL / TLS in a Nutshell

- SSL provides a `secure TCP tunnel from client to server`:
  - Confidentiality
  - Authentication of server, optionally also of client
  - Message and connection integrity
- SSL: Secure Socket Layer
  - Since SSL (& TLS) operate on top of `standard` Sockets API
- TLS: Transport Layer Security
  - Since TLS (& SSL) secure TCP (the transport layer)
  - IETF standard version of SSL
  - When we describe common aspects we usually say just SSL
- Many implementations, libraries, e.g. Open-SSL
- Original goal and still main use: secure transfer of credit card number… hear more on this in later lecture.

SSL / TLS Evolution

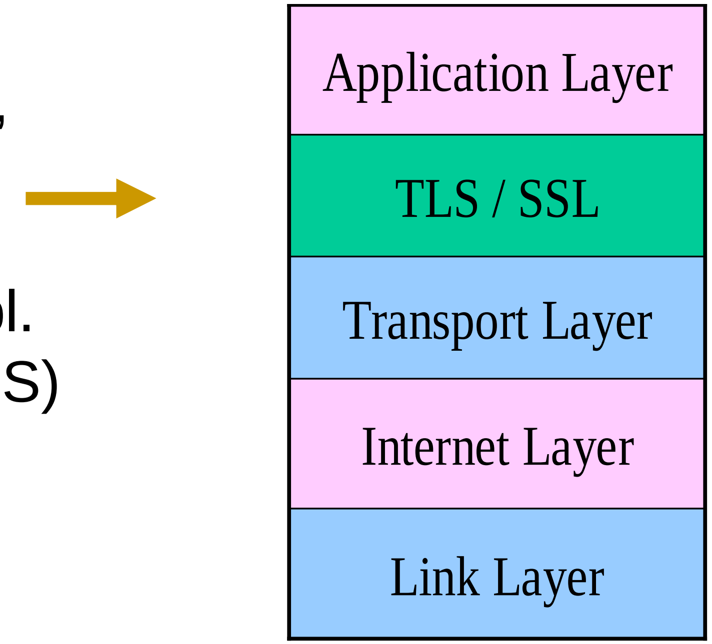


Agenda – Transport Layer Security

- Example: SSL payments
- Evolution of SSL and TLS
- Layer and alternatives
  - Few words about S/MIME
- SSL Protocol
  - SSL phases and services
  - Sessions and connections
  - SSL Handshake
  - SSL protocols and layers
  - SSL Record protocol / layer
- Secure use of SSL
  - Designing SSL applications
  - Client & server authentication
  - Web spoofing attacks
- Cryptographic issues in SSL and TLS
- Conclusions

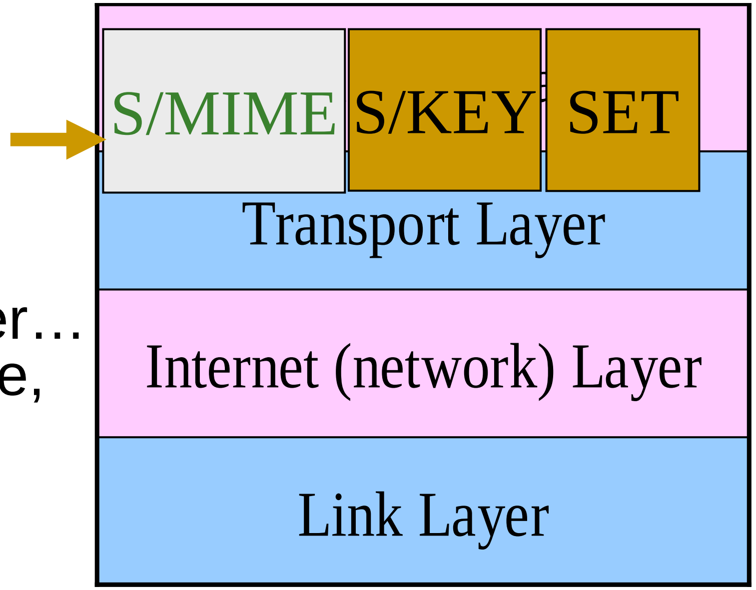
Adding Security in Transport Layer (SSL / TLS)

- SSL: Secure Socket Layer (Sockets is TCP/IP API)
- TLS: Transaction Layer Security (IETF standard SSL)
  - When we say `SSL`, we refer also to TLS
- Pros:
  - Easy to implement and use
  - Deployed in most browsers, servers, …
- Cons:
  - Protects only if used by appl.
  - Vulnerable to Clogging (DOS)
    - Over TCP
  - Only end to end
  - Headers exposed



Adding Security
Alternative 1: Add to Each Application

- Pros: easy, independent; awareness of semantics
- Cons:
  - Change each app, computer… hard, wasteful, error-prone, must trust all computers
  - No protection for headers
- Examples:
  - S/Key (login)
  - Payment protocols, e.g. SET (credit card payments)
  - Tools: XML security, Kerberos, …
  - Secure E-mail (S/MIME,PGP,…)



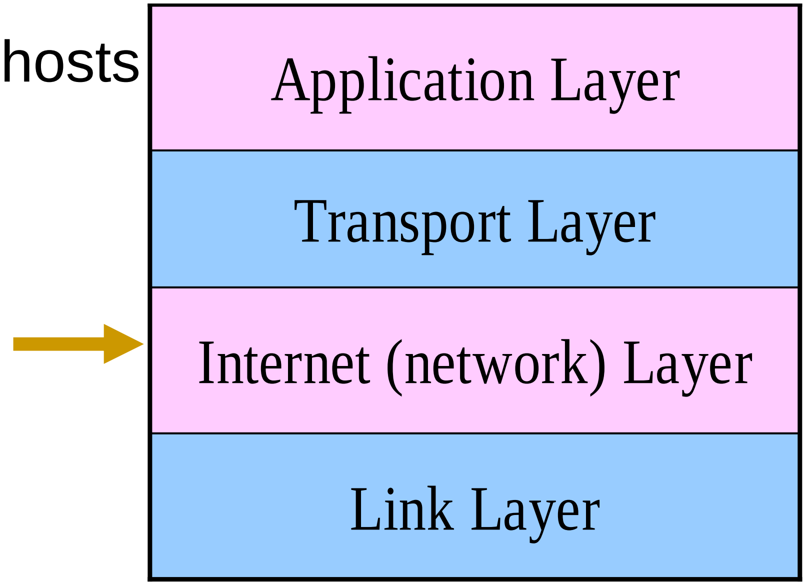
Few words about…
S/MIME – Secure E-Mail

- MIME – Multi-purpose Internet Mail Extensions (message + attached files)
- S/MIME services:
  - Non-repudiation of origin
  - Authentication and integrity (signatures)
  - Confidentiality (encryption)
- Message parts: signature, encrypted shared key, encrypted data (using shared key)
- X.509 certificates (also CRLs) sent with message
  - Problem: PKI not in place for public applications
- APIs for communicating via S/MIME
- Widely deployed standard; available e.g. in Open-SSL

Adding Security
Alternative 2: IP Security

Pros:

- Protect all applications, data (IP header, addresses)
- No change to applications
- Gateway can protect many hosts
- Anti-clogging mechanisms
- Implemented by operating systems, Routers, …
- Standard



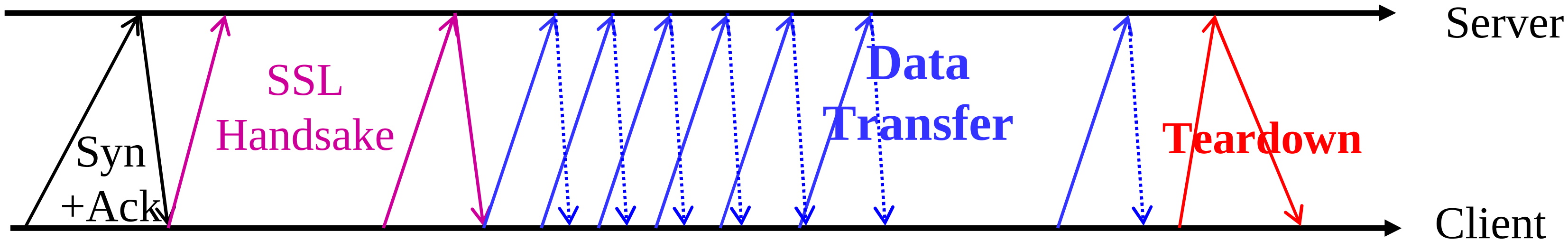
- Cons:
  - Implementation, interoperability, availability
  - Application awareness/control is difficult

Agenda – Transport Layer Security

- Example: SSL payments
- Evolution of SSL and TLS
- Layer and alternatives
  - Few words about S/MIME
- SSL Protocol
  - SSL phases and services
  - Sessions and connections
  - SSL Handshake
  - SSL protocols and layers
  - SSL Record protocol / layer
- Secure use of SSL
  - Designing SSL applications
  - Client & server authentication
  - Web spoofing attacks
- Cryptographic issues in SSL and TLS
  - Key derivation (PRF)
  - Order of Encryption/Auth
  - Chosen ciphertext attack
- DOS attacks on Servers
- SSL payments: problems
- Conclusions

SSL Operation Phases (high level)

- TCP Connection
- Handshake
  - Negotiate (agree on) algorithms, methods
  - Authenticate server and optionally client
  - Establish keys
- Data transfer
- SSL Secure Teardown (why is this necessary?)

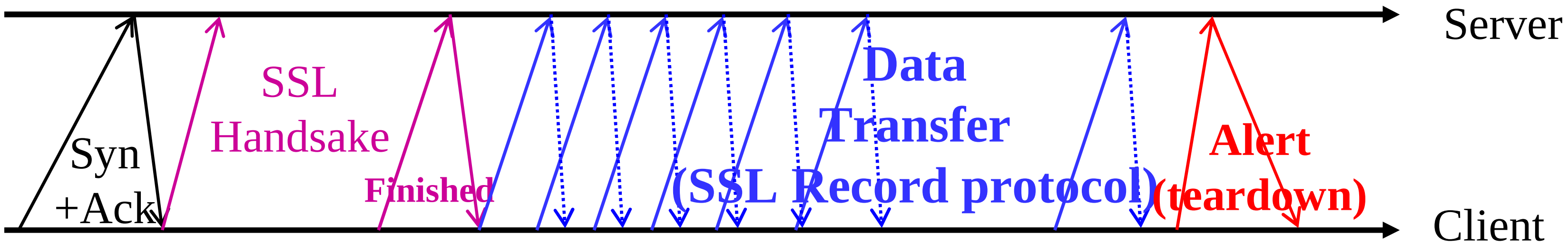


SSL Services

- Server Authentication (mandatory)
- Client Authentication (optional - if required by server)
- Secure connection:
  - Confidentiality (Encryption) – optional, possibly weak (export)
  - Message Authentication
  - Reliability: prevent re-ordering, truncating etc.
- Efficiency: allow resumption of SSL session in new connection (no need to re-do handshake)

SSL Operation Phases

- Client uses SSL API to open connection
- SSL Handshake protocol:
  - For efficiency – resume `session` if possible
  - If not (session not kept, new connection, override)
    - Establish session - algorithms and master keys
  - Establish connection (keys, etc.)
- Data transfer (SSL Record protocol)
- Teardown – use Alert protocol:
  - By application closing connection
  - Or due to error (by handshake or record protocols)



SSL Sessions and Connections

- Connection:
  - TCP/IP connection – send/receive secure messages
  - Reliable: ensures Delivery, Matching, FIFO
  - Independent, different keys for each connection
- SSL Session:
  - May span multiple connections for efficiency
  - Agree on algorithms and options
    - Client specifies possibilities, server chooses or rejects
  - Use public keys to Establish shared *MasterSecret* key
  - Server sets `session_id` so connection can resume (use existing session, for efficiency)
    - Client, server may discard session
    - Recommended (in RFC): keep session at most 24 hours

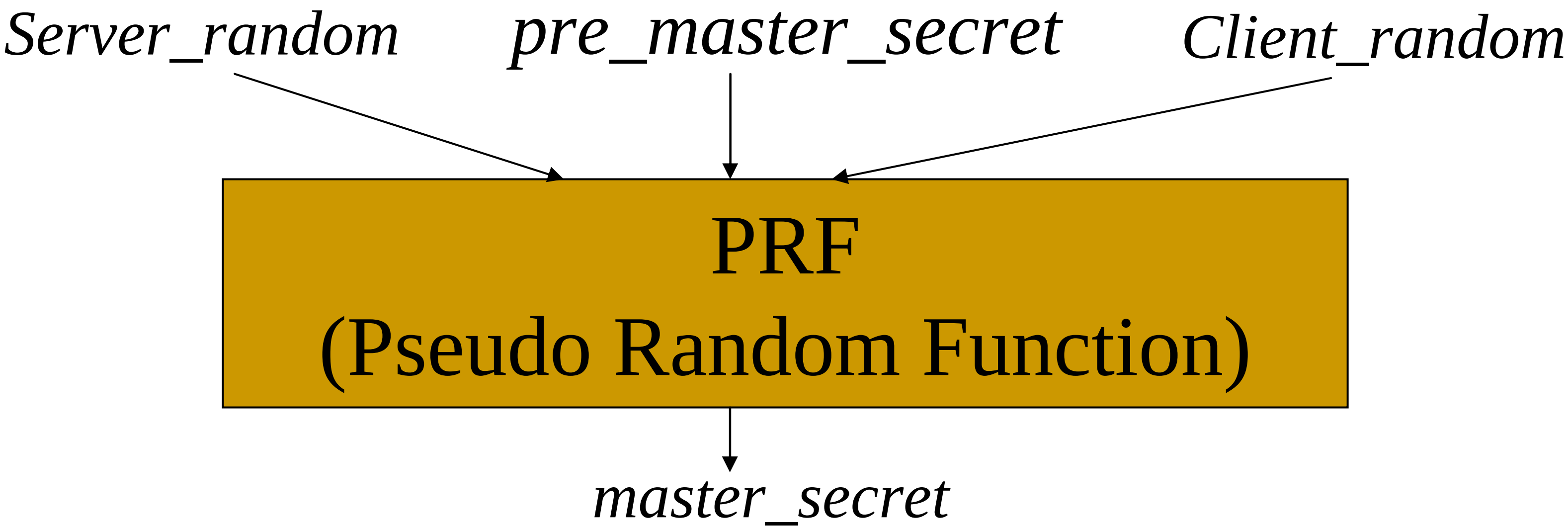
SSL Session State Variables

- Session ID: 32 bytes selected by server
- Peer certificate (X.509 v3)
- Compression method
- Cipher spec (encryption, MAC, etc.)
- Is Resumable: flag: allow new connections
- *master_secret*: 48 bytes, known to both
  - Derived from 48 bytes *pre_master_secret* (from DH key exchange / sent encrypted by RSA)
  - Using random numbers chosen by server and client at 1st connection of session
  - Using Pseudo-Random Function (PRF)
  - How?

Deriving *master_secret* Key

$$master\_secret = PRF_{pre\_master\_secret}(\text{“master secret"} \,||\, Client\_random \,||\, Server\_random)$$

PRF is based on MD5 and SHA-1; design differs btw SSL & TLS, see later



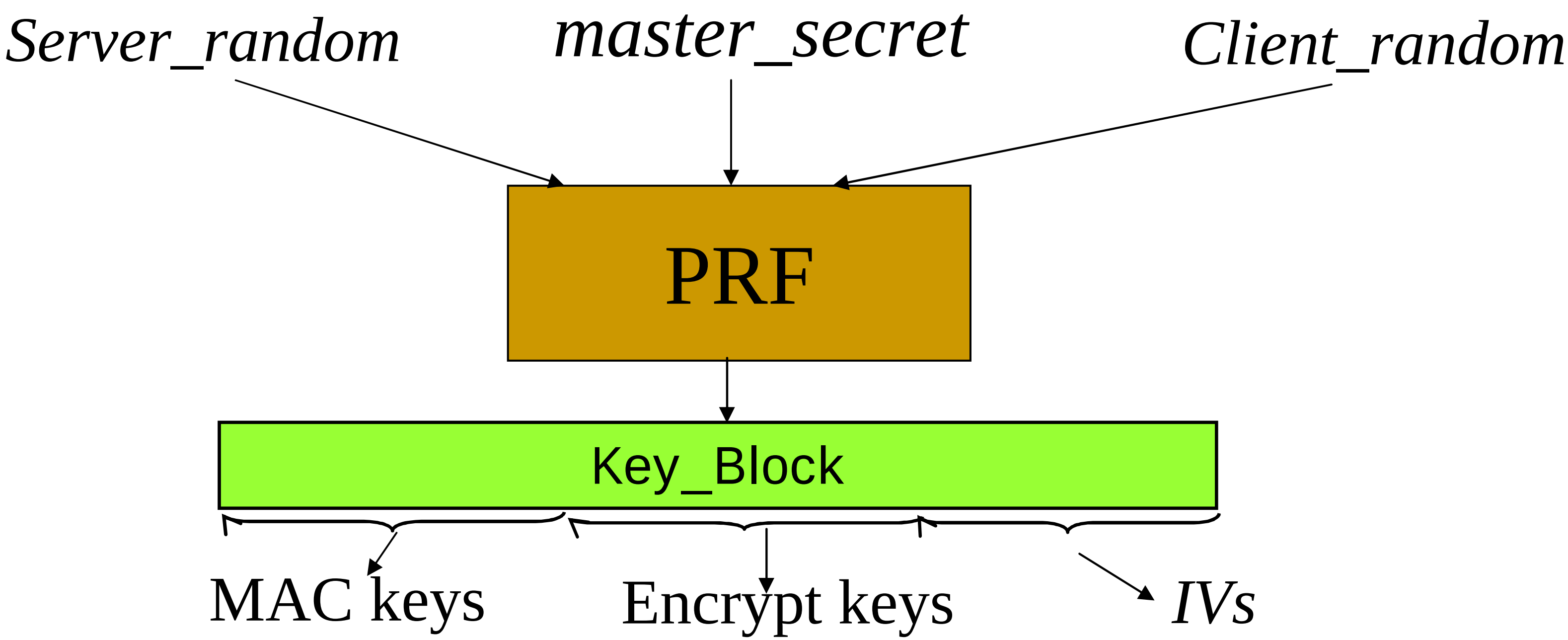
SSL Connection State Variables

- Session ID: 32 bytes selected by server
- Server and client sequence numbers
- *Server_random, client_random:* 32 bytes
  - Unique to each connection!
- Cryptographic keys and Initialization Vectors (IV)
  - Unique to each connection (why?)
  - Distinct encryption and authentication (MAC) keys (why?)
  - Distinct keys for client to server and server to client packets (why?)
  - How?

Deriving Connection Keys, IVs

Key_Block = *PRF* $_{master\_secret}$ *("key expansion"||*
Server_random ||Client_random)

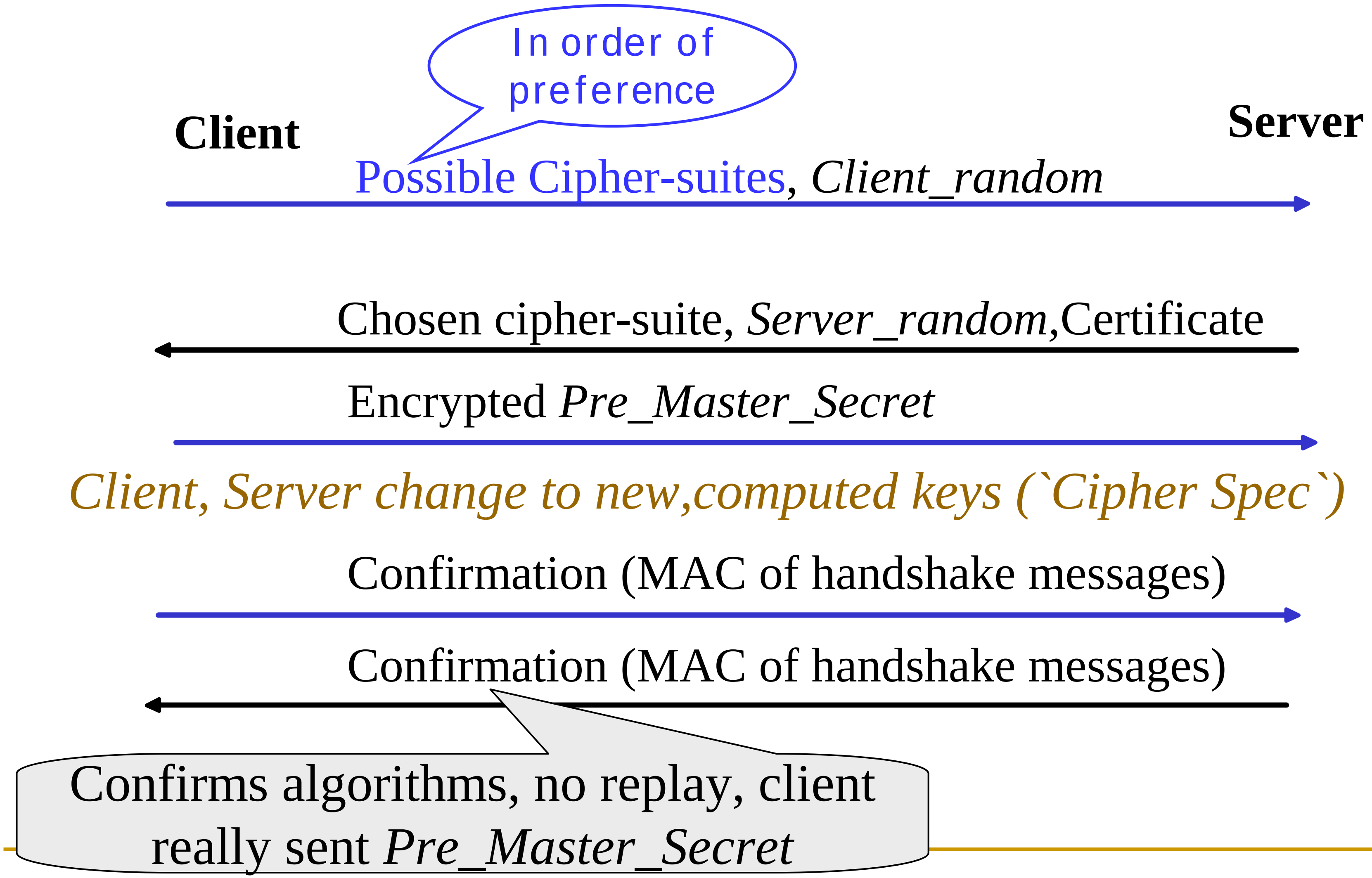
Split *Key_Block* to *ClientMACKey*, *serverMACKey*, *ClientEncryptKey*,…(using fixed order)



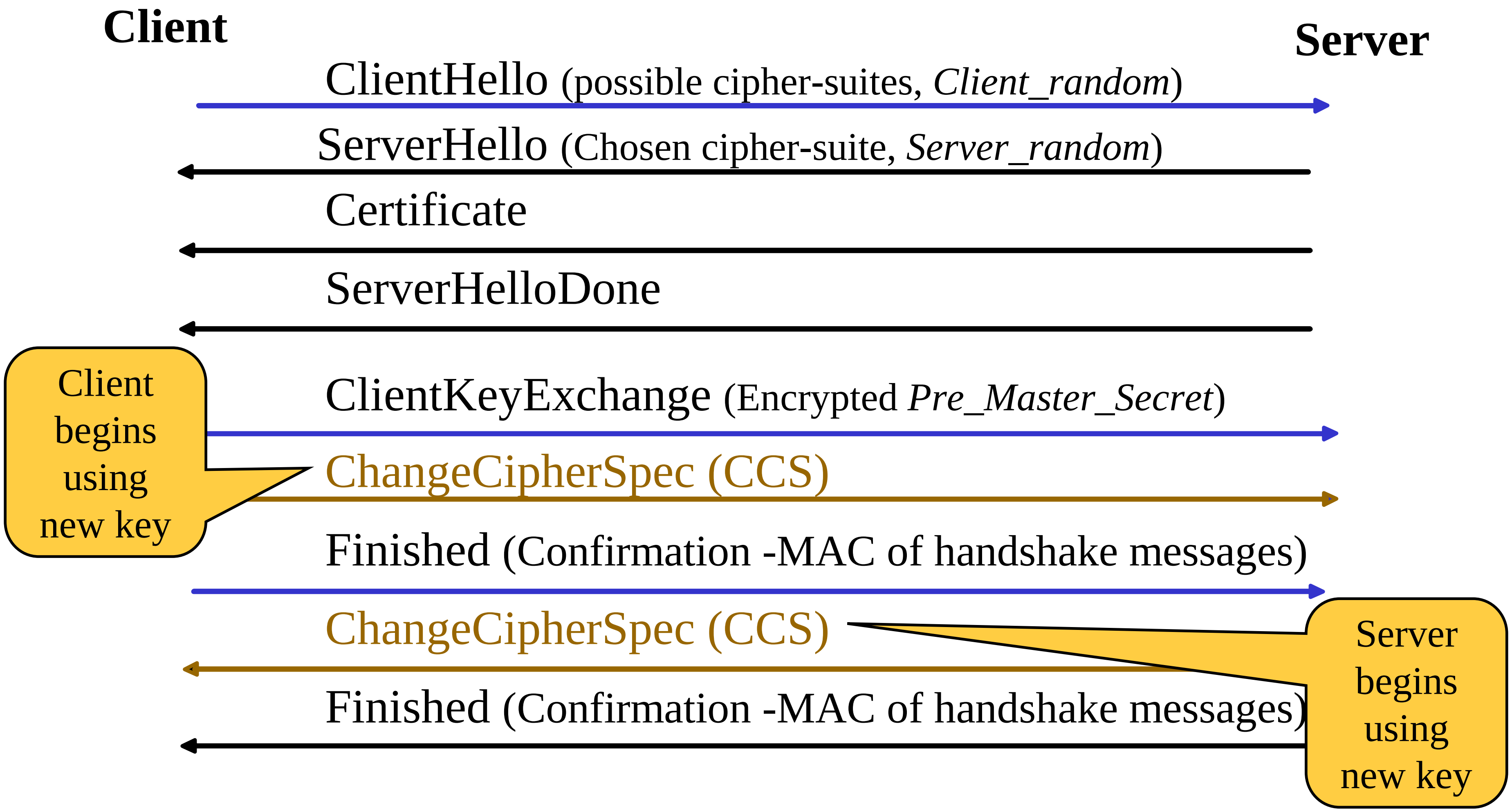
SSL Handshake Protocol

- Agree on *cipher suite*: algorithms and options:
  - Symmetric and Asymmetric Encryption
  - Signature and MAC
  - Compression
  - Options: client authentication, export (weak) versions,…
- Exchange random values
- Check for session resumption.
- Send certificate(s)
- Establish shared keys.
- Authenticate server
- Optionally authenticate client
- Confirm synchronization with peer

SSL Handshake – Overview



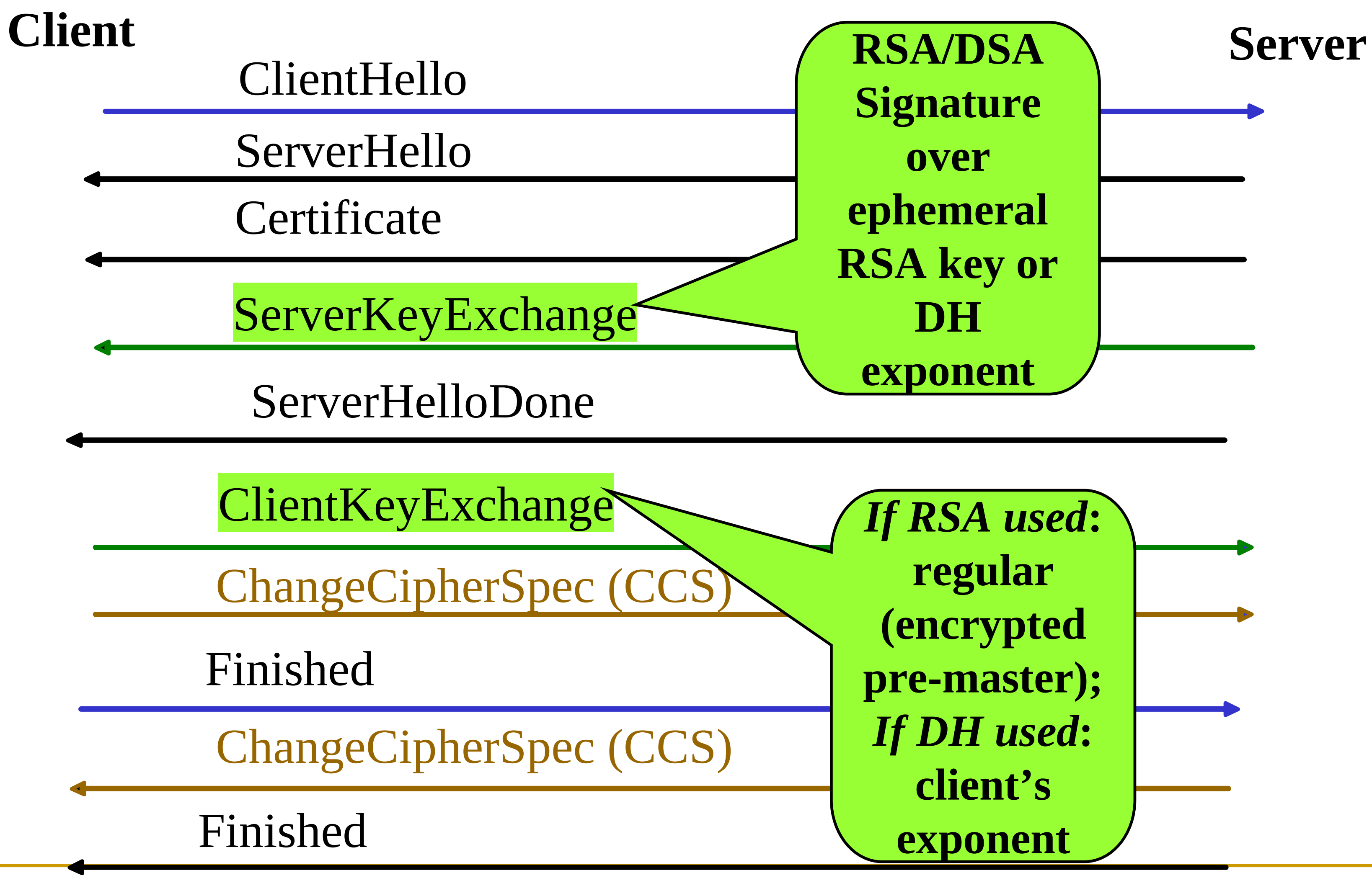
SSL Typical Handshake Messages



Advanced Handshake Features

- Session resumption
- Client authentication
- Ephemeral public keys
  - For forward security – (usually?) using Diffie-Hellman
  - Support for DH, with DSS signatures, is mandatory in TLS
  - Or, for using weak encryption public keys for export reasons (signed by strong public key) – Often with RSA
  - RSA key generation is expensive – often same ephemeral (and short, 512 bits) key used for multiple clients/sessions

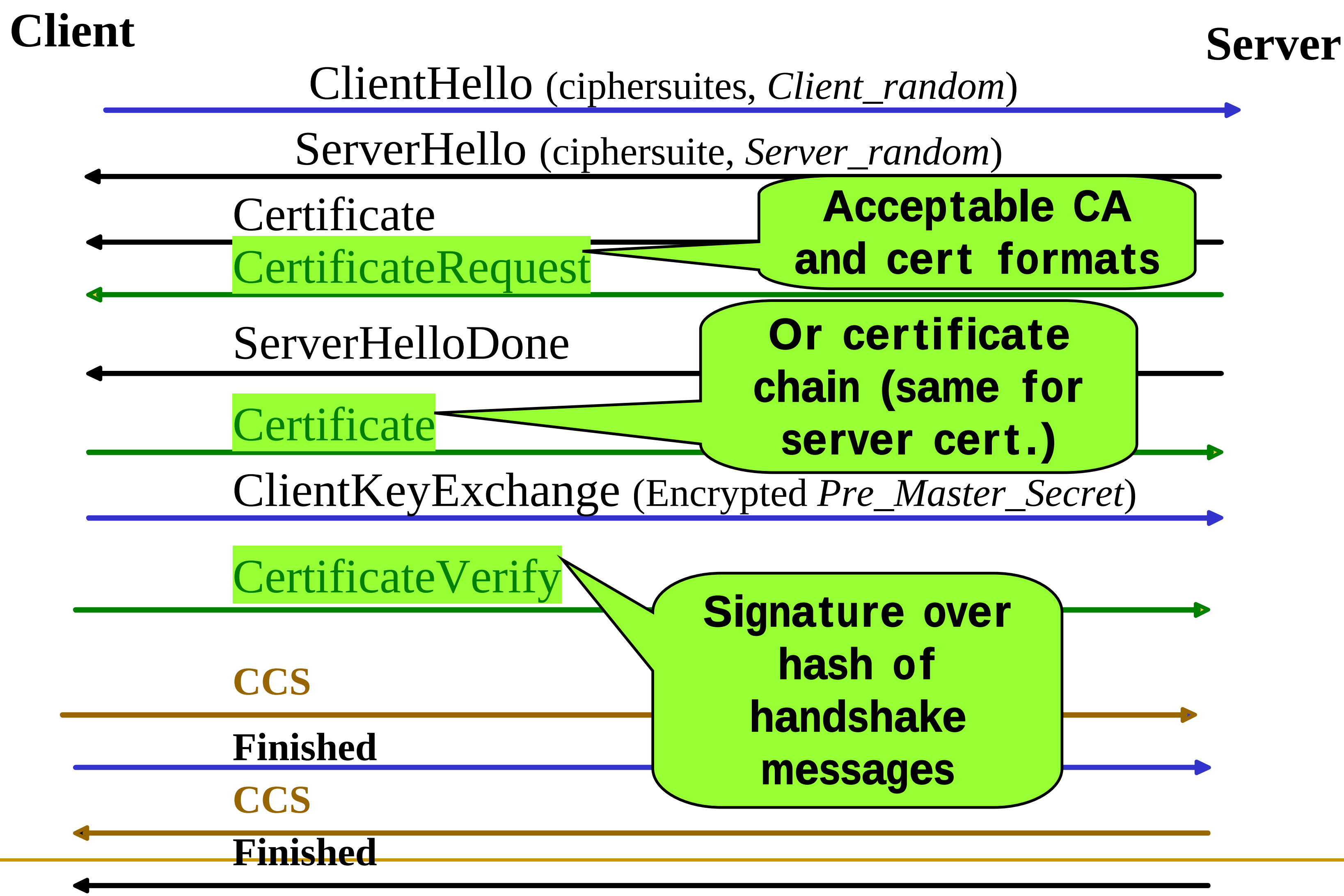
Handshake with Ephemeral public keys



SSL Client Authentication

- Usually, only the server has a certificate
  - Client can authenticate the server
  - Client sends some identification info (e.g. username, password) to server using the SSL tunnel – after it is established
- SSL also supports authentication with client certificates
  - Server requires certificate from client
  - Server signals acceptable Certificate Authorities (CAs) and certificate formats, options etc.
  - Client returns appropriate certificate (chain)
  - Client authenticates by signing using certified public key
- Client authentication using certificates is used mostly within organizations, communities – more on this later

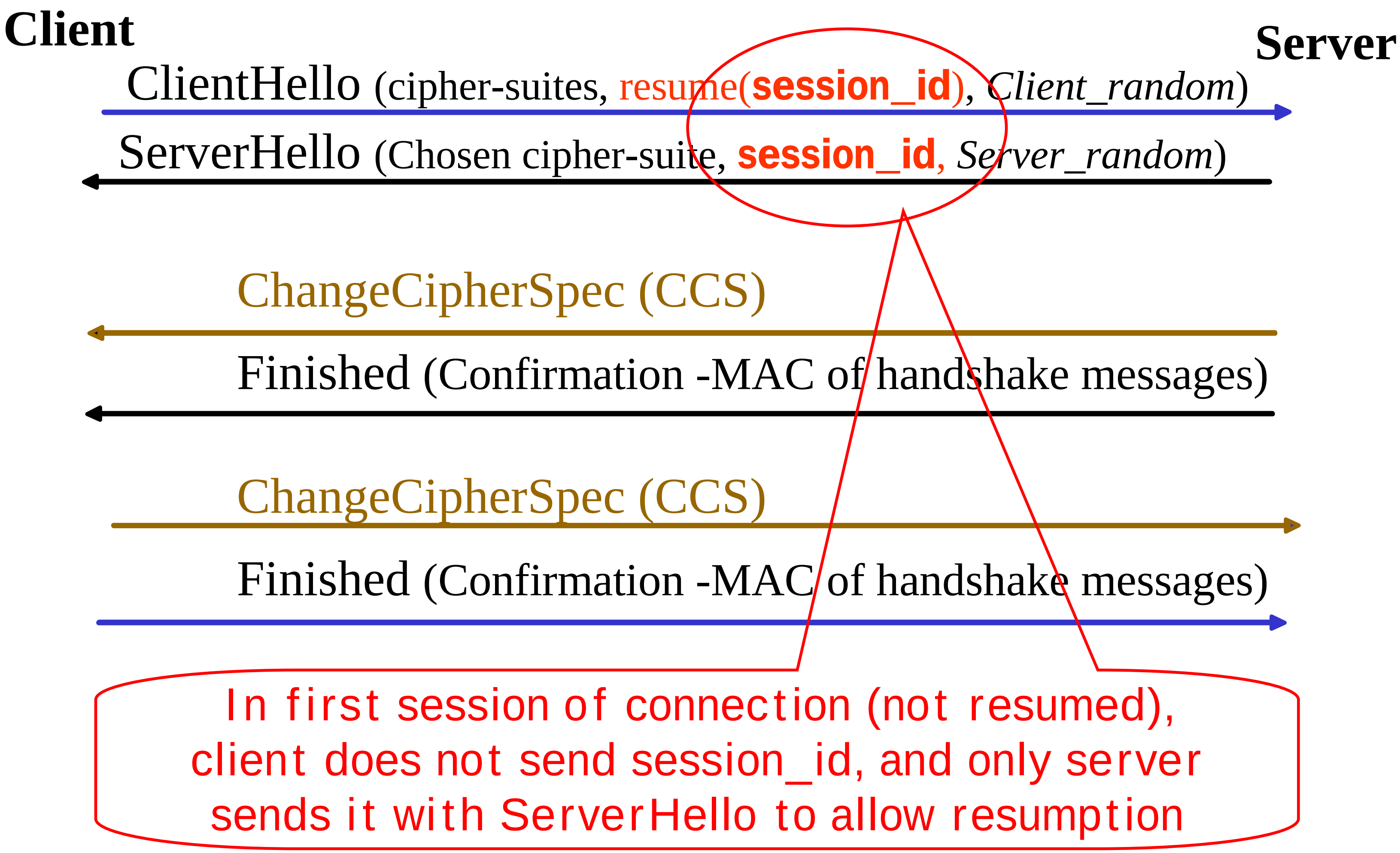
Client Authentication Handshake



SSL Session Resumption

- SSL session setup has substantial overhead
  - Randomness generation (both)
  - Transmission of certificates (both)
  - RSA encryption of Pre-Master-sercret (client)
  - RSA decryption of Pre-Master-secret (server)
  - Derivation of master secret and key block (both)
- Problems:
  - Significant performance penalty (mainly on server)
  - Server vulnerable to clogging (DOS) attacks
- Session resumption:
  - If client makes many connections to same server…
  - Server, client can re-use Pre-Master-secret from last connection
  - How? By identifying a session using *session ID*

Session Resumption Handshake



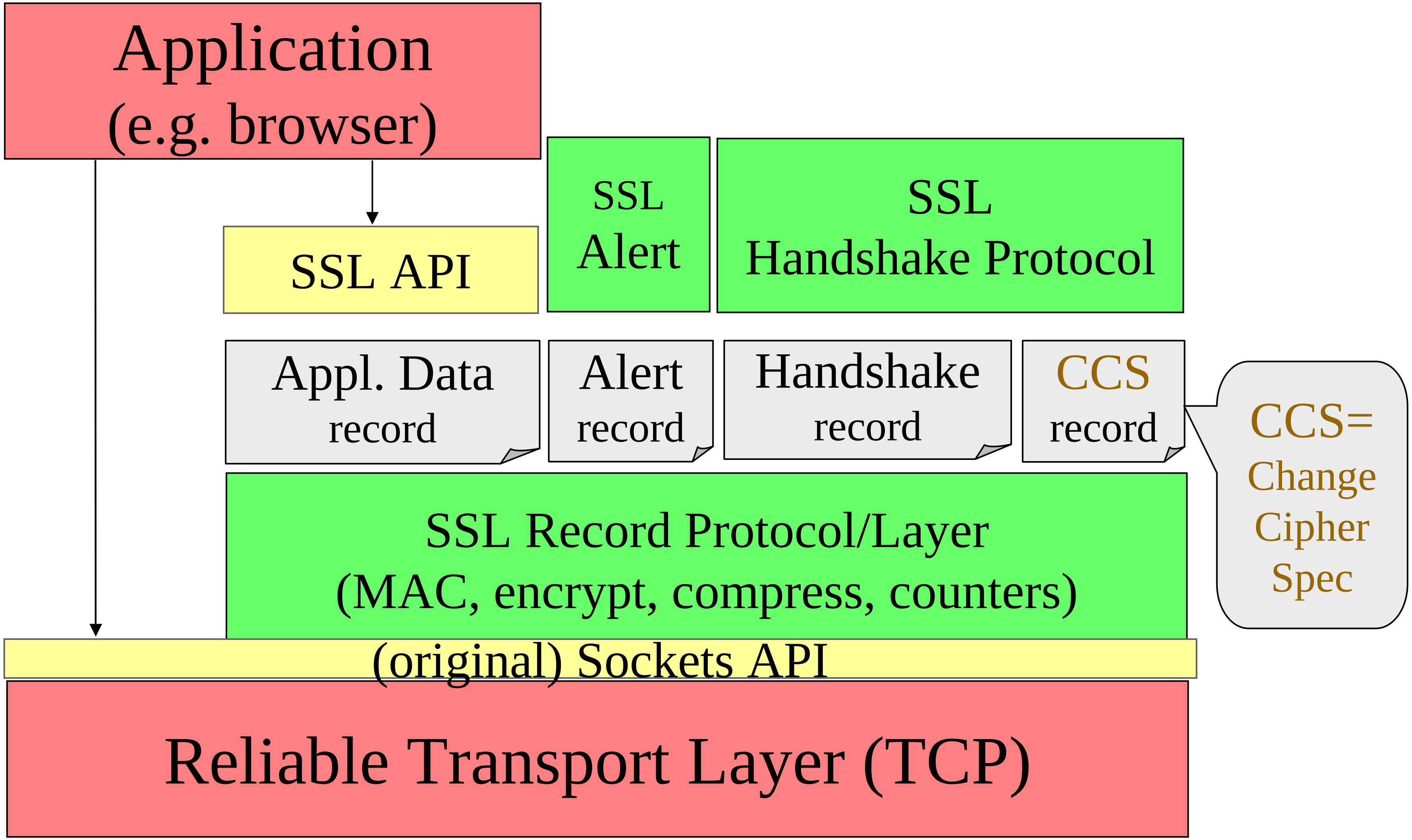
Session Resumption Issues

- Caching requires considerable server resources
  - Result: cache usually kept for only few minutest, not 24 hrs
- Resumption conflicts with replicated (cluster) servers
  - TCP connections routed to arbitrary server in cluster
  - Solution 1: server in cluster determined by client IP address → but requests from many clients may use same NAT IP addr
  - Solution 2: shared storage of session information → not easy!
  - Solution 3: SSL-session aware connection routing
  - Solution 4: Client side session caching – encrypted, authenticated cache; a non-standard SSL/TLS extension
- Session resumption helps only for repeating connections
  - SSL payments involve one (or few) connections → not much help
- Other possible optimizations (not standardized)
  - Client caching of certificates and other server info (`fast track`)
  - Encrypt using ephemeral, short server keys
  - Server encrypts Pre-Master-Secret using Client’s public key

Handshake Protocol Messages

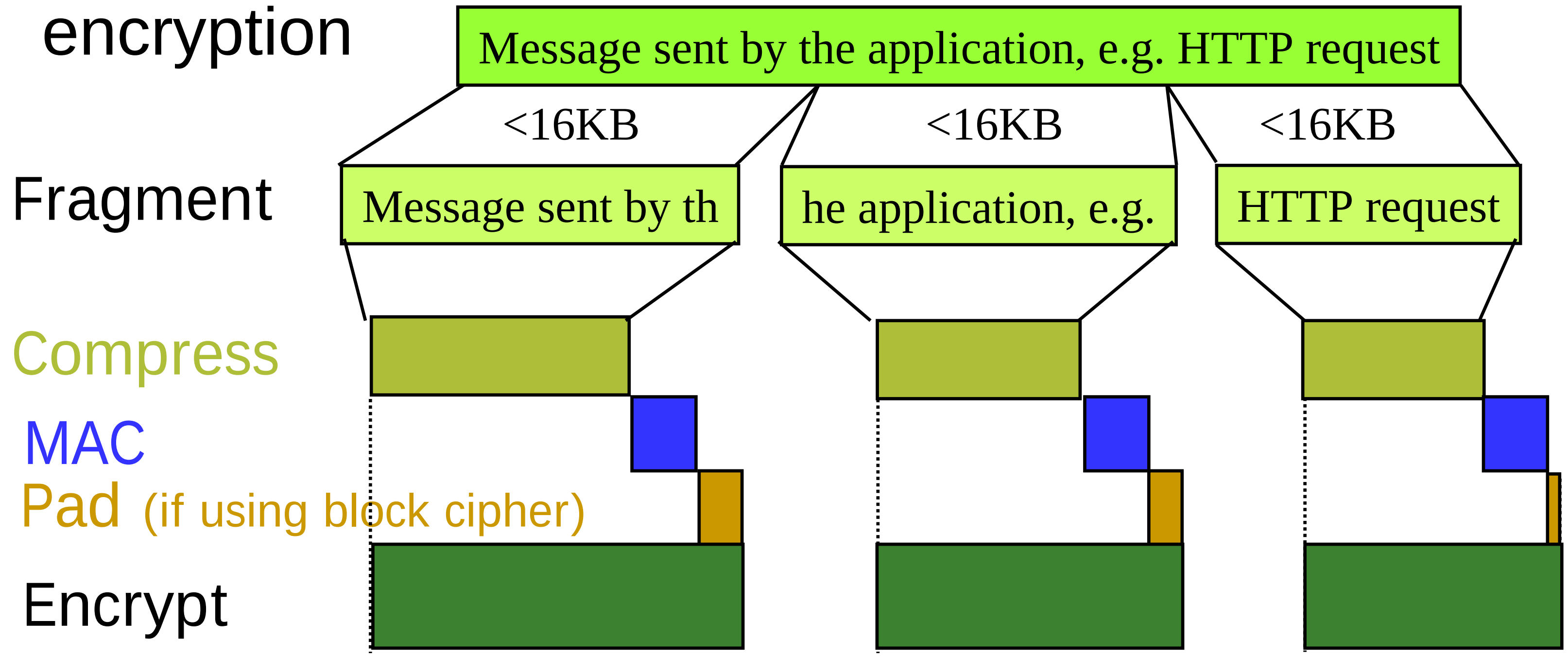
Message	M?	From	Meaning/Contains
HelloReq.	O	Srvr	Inform client to begin
ClientHello	M	Clnt	Version, *client_random, session_ID,* algorithms
ServerHello	M	Srvr	Version, *server_random, session_ID,* algorithms
Certificate	O	Both	X.509 certificate
ServerKeyExchng	O	Srvr	Ephemeral server pub key (this session only)
Cert. Request	O	Srvr	Cert. type (RSA/DSS,Sign/DH), CAs
ClientKeyExchang	M	Clnt	Encrypted *pre_master_key*
Cert. verify	O	Clnt	Sign previous messages
Finished	M	Both	MAC on entire handshake

SSL Protocols, Layers and Records



SSL Record Layer

- Assumes underlying reliable communication (TCP)
- Fragmentation, compression, authentication, encryption



Send each fragment via TCP

SSL Record Protocol

1. Fragments data – 16KB in a fragment
2. Compress each fragment; Compression must be lossless and never increase length (up to 1KB Ok)
3. Authenticate by appending MAC
   - Key: MAC_write_secret (from *master_secret)*
   - MAC computed over *counter* || *length* || *content*
   - Use *counter* (64 bits) to prevent replay in SSL session
   - The *counter* value is only input to MAC, not sent
     - Since we assume SSL is over TCP which ensures FIFO
     - So why SSL adds counter to MAC at all?
4. Padding to complete block (if using block cipher)
5. Encrypt fragment (including MAC)

Alert Protocol and Record

- Signal state changes and indicate errors
- Invoked by:
  - Application - to close connection *(close_notify)*
    - Connection should close with *close_notify*
    - This allows detection of *truncation attack* (dropping of last messages)
    - Notice: *close_notify* is normal, not failure alert!
  - Handshake protocol – in case of problem
  - Record protocol – e.g. if MAC is not valid
    - Notice: easy to tear-down (denial of service)
- Alert record carries alerts

Agenda – Transport Layer Security

- Example: SSL payments
- Evolution of SSL and TLS
- Layer and alternatives
  - Few words about S/MIME
- SSL Protocol
  - SSL phases and services
  - Sessions and connections
  - SSL Handshake
  - SSL protocols and layers
  - SSL Record protocol / layer
- Secure use of SSL
  - Designing SSL applications
  - Client & server authentication
  - Web spoofing attacks
- Cryptographic issues in SSL and TLS
- Conclusions

Secure Usage of SSL

- Designing Secure Applications using SSL API
- Validating Certificate (or certificates chain)
- Server Access Control (client authentication)
  - Using client certificates
  - Using username and password, etc.
- Client Access Control (server authentication)
- Site spoofing attacks on browsers

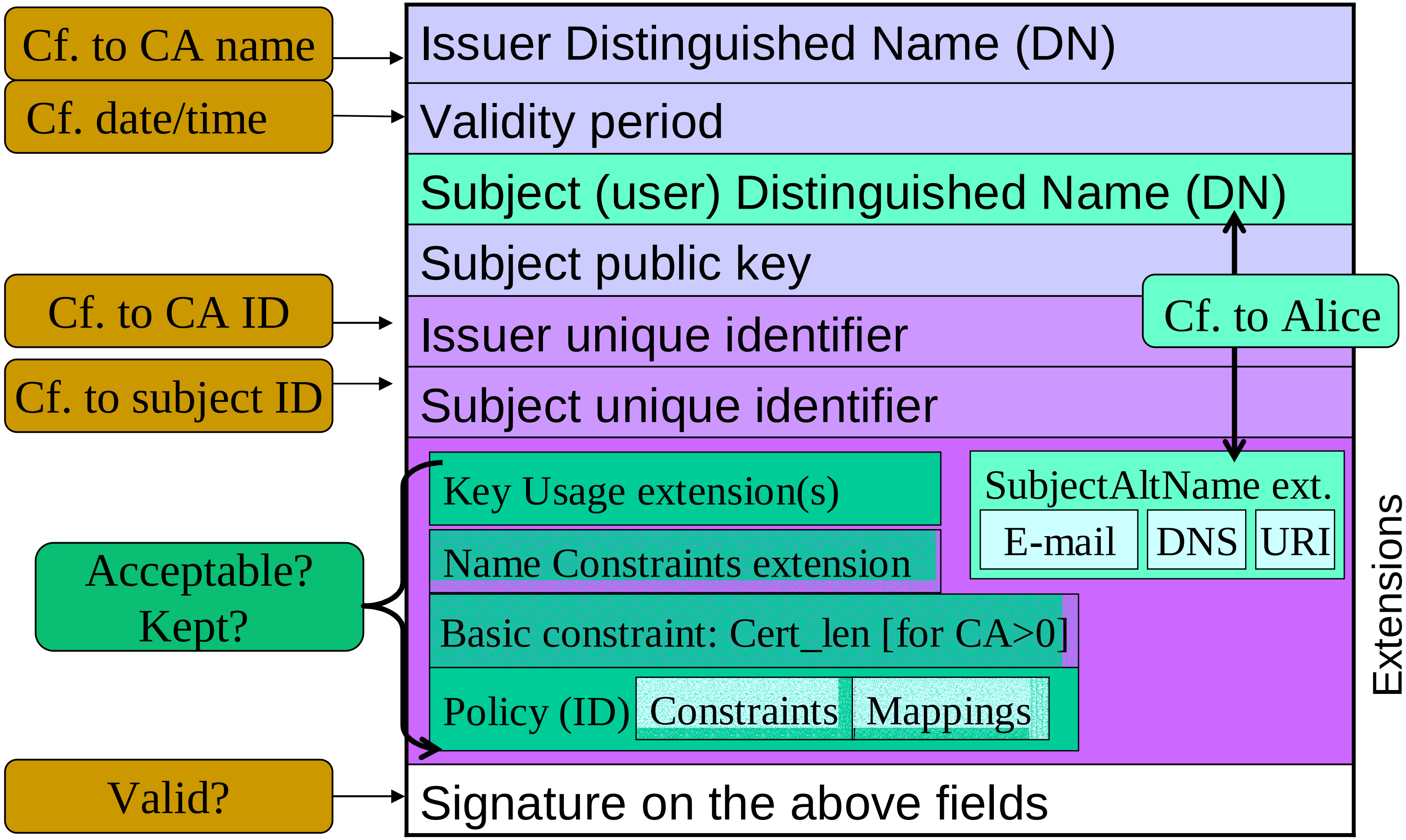
Designing Applications using SSL API

- Several SSL toolkits (e.g. OpenSSL); slightly different APIs
- Initialization tasks:
  - Load CA's certificates (at clients; servers: only if using client auth)
  - Load keys and certificates
  - Seed random number generator (use collected noise)
  - Load allowed cipher suites
    - Most toolkits allow adding new (more secure?) cipher suites
  - In server: generate/load ephemeral DH and/or RSA keys (if used)
- Connection API calls
  - Very similar to standard TCP (Sockets) API
  - But returns server (and optionally client) certificate
  - Need to validate certificate
  - Close (tear-down) connection - to identify truncation attacks

Validating Certificates

- Validation done by application, not SSL!!
- Verify root CA is trusted
  - Predefined list of `trusted CAs` in application
    - E.g. look in your browser…
  - Do we really trust all of them?
- Validate certificate (chain)
  - Validate signature(s)
  - Check validity/expiration dates
  - Check identities, constraints, key usage…
  - Check for revocations – SSL does not carry CRLs; application must collect by itself if CRL's are used.
- Reminder…

Recall: X.509 Certificate Validation



After Validating Certificates: Access Control

- Application (e.g. browser or server):
  - Verify root CA is trusted
  - Validate certificate (chain):
    - Validity, expiration, revocation
    - Identities, constraints, key-usage, …
  - Extract name/ID from Distinguished Name, subjectAltName…
- Client access control (after server authentication):
  - Is this the server the client wanted to connect to ?
  - Is this the *kind of server* the client had in mind? (e.g. Visa-authorized merchant)
  - Done by client application (e.g. browser) and client (manually)
- Server access control (after client authentication)
  - Is this an authorized client/customer?
  - What are his permissions?

Client Authentication with Cert's (Server Access Control)

- Typically X.509 certificates are *identity certificates*
- Client certificates: identity should be known to server…
- Problem: no global, unique namespace ("John Smith12"…)
- Personal certificates from General-purpose CA's (e.g. Verisign) are not very useful, and very uncommon
- Result: each server/community use their own certificates, naming
- Client has to chose certificate for each server → inconvenient
- Server must be able to identify names of authorized clients

Server Access Control (Client Authentication) Methods

- Using client certificates…
  - High level of security
  - Requires issuing (buying?) certificates to each client
  - Browsers prompt user to select certificate (hassle)
  - If based on identity, requires database of clients in server
- Using Username-Password authentication
  - Browser sends password as argument of a form
    - Possibly filled by browser (`wallet` function: passport, ECML)
  - Relies on SSL security (encryption+server authentication)
  - Better but non-standard: use password as key of MAC (never send password – don't expose to spoofed server)
  - Inconvenience: typing/approving password per request

Secure Session

- Goal: authenticate <u>once</u> per application session
- How? Few options…
  - Application session = SSL session
    - Requires session identification – usually available in API
    - But session retention is limited (browsers, servers)
  - Or: identify application session… how?
    - Cookie contains application session id (and/or password)
    - Send cookie with each request/response:
      - Automated cookie mechanisms in browsers
      - Or: encode cookie as part of URLs
    - Risks: exposure, forgery, privacy
      - Exercise: design of secure cookie mechanism

Server Authentication

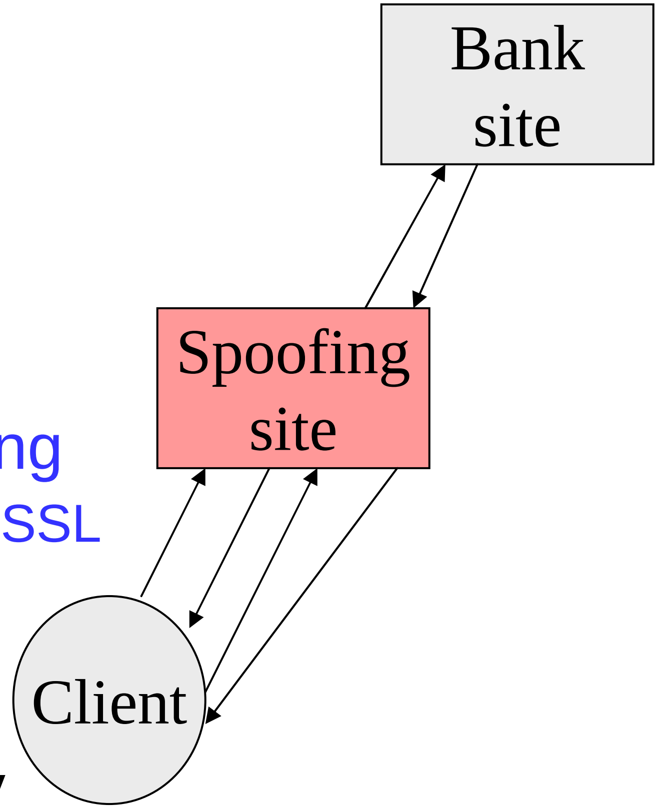
- Critical – e.g. when user enters secrets (password, cc#,…)
- Based on Server's X.509 *identity certificates*
- Certificate (chain) must pass validation
  - Responsibility of application
  - Browsers pre-configured with many CA's and don't test chain well
  - Usually CA validates ownership of site… using insecure DNS
  - You can remove untrusted CA's from browser (but few do this)
- Server identity:
  - Typically (e.g. in browsers): DNS name, e.g. www.citibank.com
  - Not IP address since it is not meaningful and may change
- No standard mapping of DNS to Distinguished Name
  - *Usually* use dNSName field in subjectAltName extension
- User must specify or at least know and understand:
  - If connection is secure, server authenticated
  - What is the (DNS?) name of the server

Indicating Secure Connection and Server Identity

- Ensure user is aware of server's identity
- Ensure user is aware of (in)secure connection
- The user should identify the server
  - Give same DNS Name as in certificate
  - Notice: the same server may host multiple sites (e.g. ISP)
  - Solution: must have certificate for each hosted site
- Spoofing attacks on browsers: directing user to spoofed site
  - Changing link (URL) in referring site…
    - Visible, but unnoticed by (most) users, or
    - Advanced spoofing: (almost?) non-visible – screen emulation
  - Security degrading attacks

Site-Spoofing Attacks on Browsers

- User visits spoofing site, site becomes proxy
- User browsing is thru proxy
- User is not aware
  - Most users don't look at URLs
  - Or: spoof sends phony certificate
  - Or: spoof *emulates* normal browsing
    - JavaScript: same window, fake URL, SSL indicator
    - Java: emulated window (supports interaction)
  - Or: spoof selects weakest security offered by client, E.g. SSL ver. 2, PCT, DES,…



Agenda – Transport Layer Security

- Example: SSL payments
- Evolution of SSL and TLS
- Layer and alternatives
  - Few words about S/MIME
- SSL Protocol
  - SSL phases and services
  - Sessions and connections
  - SSL Handshake
  - SSL protocols and layers
  - SSL Record protocol / layer
- Secure use of SSL
  - Designing SSL applications
  - Client & server authentication
  - Web spoofing attacks
- Cryptographic issues in SSL and TLS
- Conclusions

Cryptographic Issues in SSL & TLS

- Much research and security improvements in evolution of SSL & TLS
- We do not cover the (critical!) fixes to SSLv1, v2
  - See e.g. in Rescola's book (`SSL and TLS`).
  - SSLv2 is enabled by default in many browsers
- TLS improves security cf. to SSLv3:
  - Cryptanalysis-tolerance
  - In particular: passes US FIPS-140 criteria
  - Internal design of MAC, hash functions, etc.
- Details: in `extras`…

Conclusion

- SSL / TLS is the most widely deployed security protocol, standard
  - Easy to implement, deploy and use; widely available
  - Flexible, supports many scenarios and policies
  - Mature cryptographic design
- But SSL is not always the best tool…
  - Use IP-Sec e.g. for anti-clogging, broader protection
  - Use application security, e.g. s/mime, for non-repudiation, store-and-forward communication (not online)
- Beware of host-spoofing and web-spoofing
  - Many browsers allow hard-to-detect spoofing
  - Many users will not detect simple spoofing (similar URL)

Extras…

Crypto in SSL & TLS: Key Derivation

- Key derivation in SSL, TLS:
  - *Key block* (block of connection keys) from *master_secret*
  - *master_secret* from *pre_master_secret*
- Critical for security
- Design based on hash functions
  - Why not on block ciphers e.g. AES? Not available when SSL designed; DES was already too weak, no other standard and free cipher
- Which hash function to use?
  - Two main candidates: MD5 and SHA1
  - SSLv2: use MD5; SSLv3 and TLS: use both!
- How to use the hash functions?
  - Different design for TLS and SSL
  - SSL design: intuitive
  - TLS design: Cryptanalysis-tolerant PRF

Key Derivation in SSLv3

- Based on HMAC: $HMAC\_h_k(m)=h(k\oplus opad \,||\, h(k\oplus ipad \,||\, m))$
- Intuition: output of HMAC should be unpredictable
- Idea: modify HMAC to use both MD5 and SHA-1
- SSL modifications:
  - Use SHA for the `internal` hash, MD5 for the `external`
  - Prepend different strings to generate enough output
  - Slightly different for master secret and key block (not sure why)
- *pms=PreMasterSecret, cr=Client_random, sr=Server_random*
- *ms=Master_secret= MD5(pms||SHA("A"||pms||cr||sr))|| MD5(pms||SHA("BB"||pms||cr||sr))|| MD5(pms||SHA("CCC"||pms||cr||sr))*
- *Key_block= MD5(ms||SHA("A"||ms||sr||cr))|| MD5(ms||SHA("BB"||ms||sr||cr))|| MD5(ms||SHA("CCC"||ms||sr||cr))||…*

Key Derivation in SSLv3 - Criticism

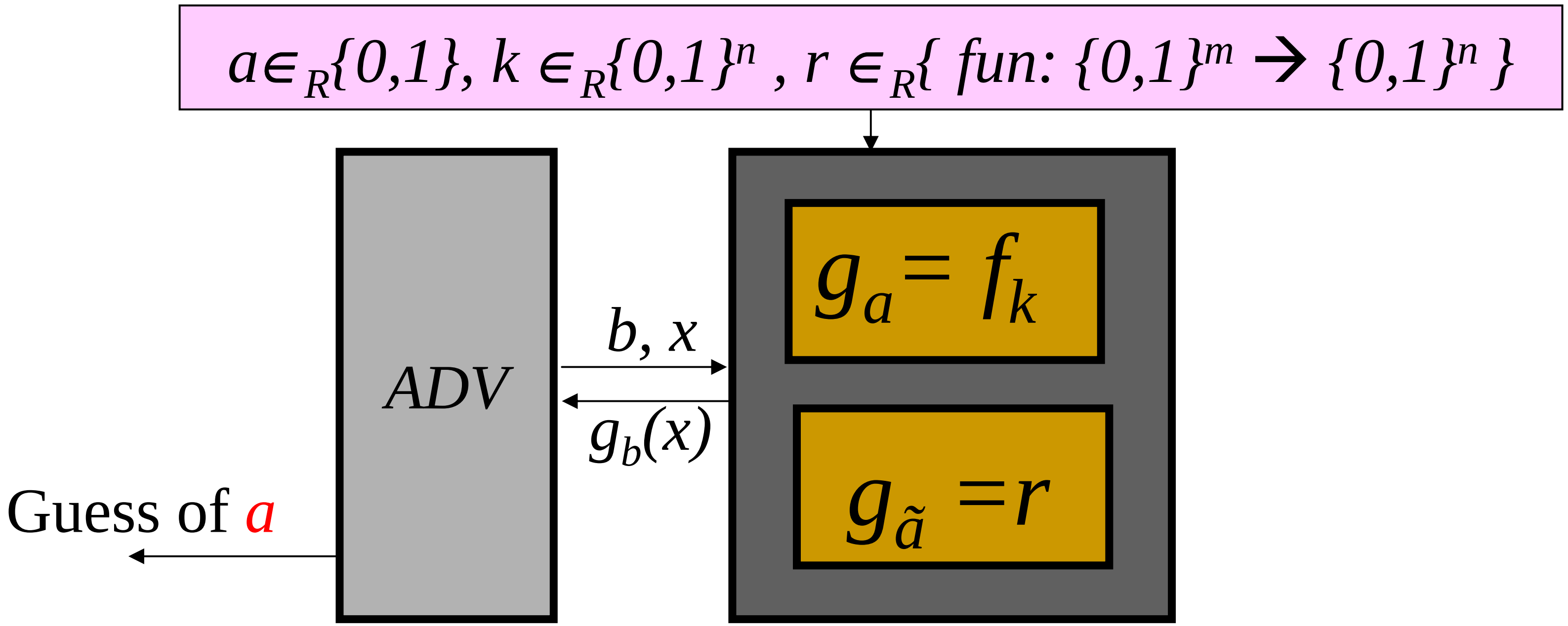
- Recall *Key_block* (same argument for *MasterSecret*):
  - *Let ms=MasterSecret, cr=Client_random, sr=Server_random*
  - *Key_block= MD5(ms||SHA("A"||ms||sr||cr))||*
    MD5(ms||SHA("BB"||ms||sr||cr))||…
- Completely intuitive, no justification / analysis
- HMAC analysis/proof depend on *both* internal and external hash having security properties:
  - Internal hash: Collision-resistant-only VIL MAC
  - External hash: Fixed-Input Length secure MAC
- If either MD5 or SHA is weak, derivation may be weak
- *No cryptanalysis-tolerance!*
- *Fails FIPS-140: security should depend only on FIPS-approved cryptographic mechanisms*

Key Derivation in TLS: use PRF

- Idea: the \`standard\` secure mechanism for key derivation is a Pseudo-Random Function (PRF)
- For example, using master key k and PRF f_k:
  - To derive an encryption key: $EncKey=f_k(\text{“encrypt”})$
  - To derive authentication key from client to server, use: $C2SAuthKey=f_k(\text{“auth, client to server”})$
  - To use different encryption keys in each connection, (using same master key): $EncKey=f_k(\text{“encrypt”}, random)$
  - Or, in TLS: derive one long *Key_block*, then split it and use different (fixed) parts of it for keys for encryption, authentication, and IV, in each direction
- How? Recall Pseudo-Random Function (PRF)…

Pseudo-Random Functions (PRF)

- An *m to n* FIL-PRF is a collection of efficient functions $\{f_k:\{0,1\}^m \rightarrow \{0,1\}^n\}$, such that no adversary can efficiently distinguish between f_k, for random key *k,* and a random function *r* from $\{0,1\}^m$ to $\{0,1\}^n$



Key Derivation: Two Steps…

- Step 1: FIL→VIL (Fixed→Variable Input Length)
  - SHA's output is 160bits, MD5 output is 128bit… and more bits are needed anyway
  - Transform FIL PRF $HMAC\_h_k$ to VIL PRF_h_k
  - h is <u>either</u> SHA <u>or</u> MD5
- Step 2: cryptanalysis-tolerant VIL PRF composition: given VIL PRF_MD5_k and PRF_SHA_k , design VIL PRF_k to be secure as long as either PRF_MD5_k or PRF_SHA_k is secure

Step 1: FIL PRF → VIL PRF

- Assume: $HMAC\_h_k$ is a FIL PRF
- Design of VIL PRF_h: concatenate outputs, using different `labels` $A(i)$:
  $PRF\_h_k(r)=HMAC\_h_k(A\_h(1)||r)$
  $|| HMAC\_h_k(A\_h(2)||r) || \ldots$
- Labels $A\_h(i)$ derived by HMAC:
  $A\_h(i)=HMAC\_h_{secret}(A\_h(i\text{-}1)); A\_h(0)=cr||sr$
  - Simpler design $A\_h(i)=i$ is also secure (assuming $HMAC\_h_k$ is a FIL PRF)
  - But more complex design above is (almost) as efficient, and seems more robust to `typical` attacks against $HMAC\_h_k$ (e.g. attack that finds $HMAC\_h_k(2)$ given $HMAC\_h_k(1)$)

Step 2: Cryptanalysis Tolerance

- Given two candidate VIL PRFs: *PRF_MD5*, *PRF_SHA*
- Intuition: cryptanalysis-tolerant composition: $PRF_k(r)=PRF\_MD5_k(r)\oplus PRF\_SHA_k(r)$
- Question/exercise: is this composition cryptanalysis-tolerant?

Cryptanalysis-Tolerant PRF: 1st try...

- Consider any two PRF-candidates f, g
- Define $P_k(m)= f_k(m)\oplus g_k(m)$
- *Question:* assume either f or g is a PRF. Is then P a PRF?
- *Answer: NO.*
- Trivial examples: $f_k(m)= g_k(m), f_k(m)= \sim g_k(m)$
- Intuition may hold for `independent` $f, g\ldots$ (e.g. MD5 and SHA?)
- Making input different, e.g. $f_k(1||m)\oplus g_k(0||m)$, does not help (why?)
- Idea: use different *keys* !

TLS: Cryptanalysis-Tolerant PRF

- Define $P_{k1,k2}(m)= f_{k1}(m)\oplus g_{k2}(m)$
- *Claim:* if either f or g is a PRF, then P a PRF.
- *Proof sketch:* assume g is a PRF but P is not a PRF. Namely there is an algorithm *A,* that can distinguish between a box computing $P_{k1,k2}(\ )$ and a box computing a random function.
- Assume now we are given a box computing either $g_{k2}(m)$ or a random function. We use it to compute $P_{k1,k2}(m)= f_{k1}(m)\oplus g_{k2}(m)$ (selecting k_1 ourselves). Now we use *A* to distinguish between this and random.
- This is what is done in TLS!

PRF in TLS – Details

- PRF keys (*PreMasterSecret*, *MasterSecret*) are 48B
- Use only half of it (24 bytes) for each PRF-candidate (PRF_MD5 and PRF_SHA)
- $TLS\_PRF_k(r)=PRF\_MD5_{k[48\ldots25]}(r)\oplus PRF\_SHA_{k[1\ldots24]}(r)$
- Deriving as many bytes as necessary
  - E.g. 48 bytes for Master Secret
- To derive Master Secret:
  - Let m_{MS}= *"master secret"||client_random||server_random*
  - $MasterSecret=TLS\_PRF_{PreMasterSecret}(m_{MS})$
- To derive Key Block:
  - Let m_{KB}= *"key expansion"||client_random||server_random*
  - $KeyBlock=TLS\_PRF_{MasterSecret}(m_{KB})$

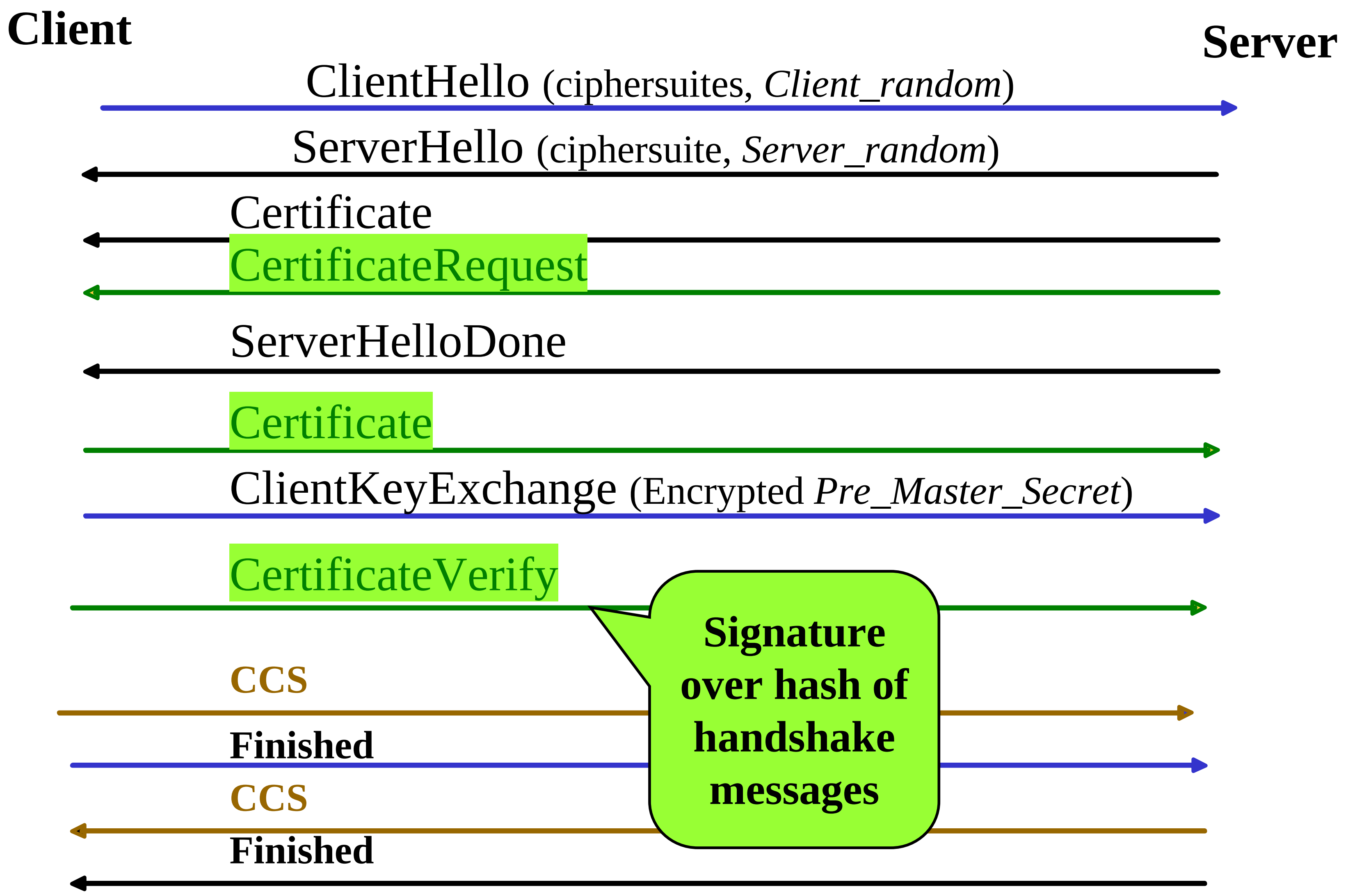
Cryptographic Issues in SSL & TLS: Finished Message Computation

- Finished message is sent at end of handshake:
  - From client to server and vice verse
- Goal: to authenticate entire handshake using *master_secret*
- Authentication uses both MD5 and SHA (for cryptanalysis-tolerance)
- Computation differs between SSL and TLS
- SSL: for both $h=MD5$ and $h=SHA$, send $h(master\_secret \,||\, opad \,||\, h(messages \,||\, Sender \,||master\_secret||ipad))$
- This differs from HMAC: $h(k\oplus opad \,||\, h(k \oplus ipad \,||m))$
- Motivation for difference: key (*master_secret*) defined just at Finish…
- But consider hash design (Merkle-Damgard), this may be insecure!
- TLS is simpler and more secure: send 12 bytes from output of $PRF_{master\_secret}(label||MD5(messages)||SHA(messages))$
  - Label is either “server” or “client”

Cryptographic Issues in SSL & TLS: Client Certificate Verification

- Recall client authentication handshake

Client Authentication Handshake

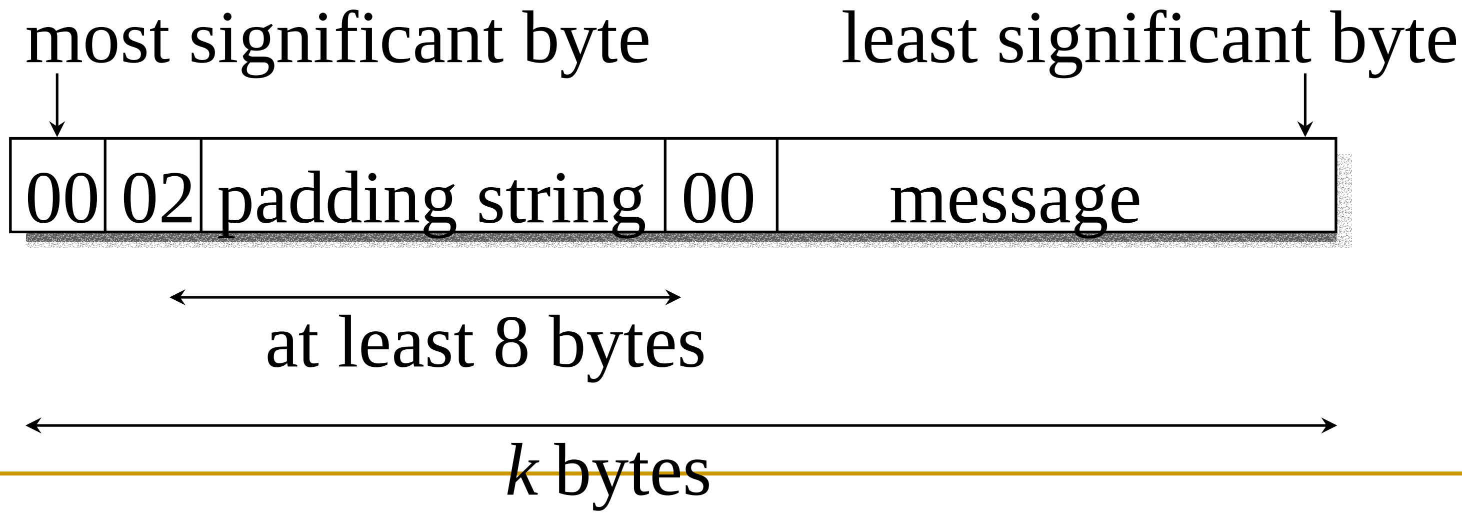


CertificateVerify Message

- Sent from client to server to authenticate client
- Contains signature over hash of handshake *messages*
  - Using RSA: both MD5 hash and SHA hash (for cryptanalysis-tolerance)
  - Using DSA: only SHA hash
- Hash computation differs between SSL and TLS:
  - SSL: *h(master_secret || h(messages || master_secret || pad))*
  - TLS: *h(messages)*
- Why?
  - Unnecessary complication in SSL; messages are not secret, hashing is (supposed to be) collision-resistant
  - Possible, unnecessary exposure of *master_secret*
  - This is the only place it is used directly as key (of MAC...)

Cryptographic Issues in SSL & TLS: RSA Encryption Format (PKCS#1)

- SSL and TLS are using PKCS #1 Version 1.5
- Recall: Subject to Feedback-only Chosen-Ciphertext Attack (CCA) [Bleichenbacher'98]
- Attack is practical against some SSL, TLS implementations (see later…)



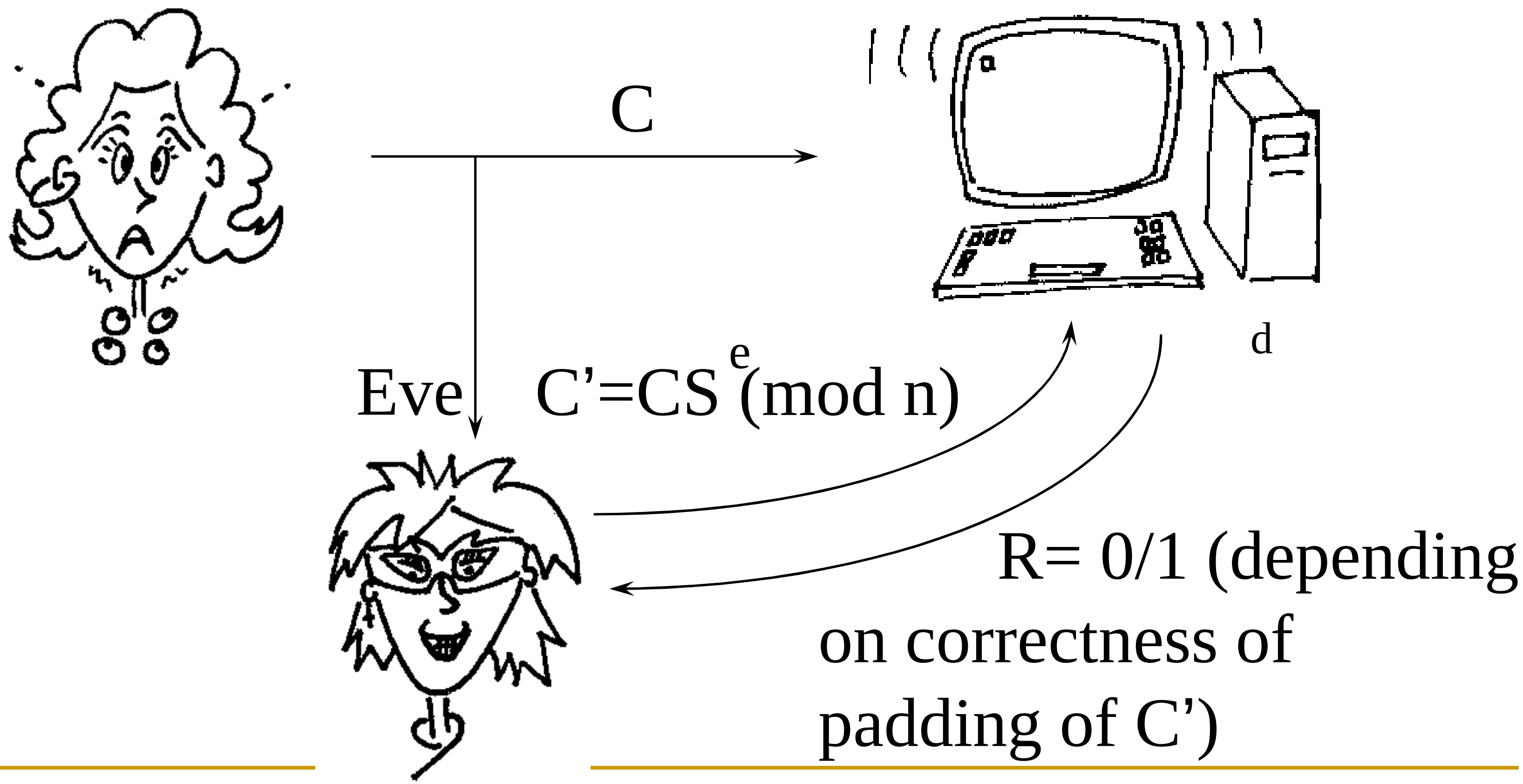
Reminder: Feedback-only Chosen-Ciphertext Attack[Bleichenbacher'98]

Alice

PK:(n=pq,e)

Bob

SK:(p,q,d: ed=1 mod $\varphi(n)$)



Preventing CCA Attack

- Some SSL, TLS implementations send specific alert immediately on detecting bad PKCS#1 format
- Helps attacker; need only 1 million trials (chosen ciphertexts) to decrypt message
- Prevention is easy…
  - Send same alert if pre-master-secret is not formatted correctly, attacker needs about 2^{40} trials → not practical
  - RFC224 recommendation: don't send alerts, use random pre-master-secret → will fail in Finish message validation
  - USE PKCS#1 version 2 (OAEP) or another format secure against CCA

Cryptographic Issues in SSL & TLS: order of Auth / Encrypt

- SSL authenticates, then encrypts:
  - *A=MAC(m), C=Enc(m,A),* send *C*
- IPSEC encrypts, then authenticates:
  - *C=Enc(m), A=MAC(C),* send *(C,A)*
- Which is better? Does it matter?

Question: Order of Auth / Encrypt

- SSL authenticates, then encrypts *(AtE)*:
  - *A=MAC(m), C=Enc(m,A),* send *C*
- IPSEC encrypts, then authenticates *(EtA)*:
  - *C=Enc(m), A=MAC(C),* send *(C,A)*
- Which is better? Does it matter?
  - *Enc(m,A)* may be harder to cryptanalyze cf. to *Enc(m),* so *AtE* seems to strengthen encryption
  - But we should use secure encryption, not depend on *A=MAC(m)* to fix it!

Question: Order of Auth/Encrypt

- SSL authenticates, then encrypts *(AtE):*
  - *A=MAC(m), C=Enc(m,A),* send *C*
- IPSEC encrypts, then authenticates *(EtA)*:
  - *C=Enc(m), A=MAC(C),* send *(C,A)*
- EtA seems better:
  - EtA resistant to clogging (verify MAC before decrypt)
  - EtA allows to authenticate (also) public data
    - E.g. extend to multiple recipients (multicast)
  - AtE subject to attack if attacker knows if authentication failed or not
    - Although not with standard encryption – OTP, CBC
    - Recall attack from day 6, `Authentication`…

Feedback-only Chosen-Ciphertext Attack on Authenticate-then-Encrypt

Advanced!

- Assume: attacker can choose ciphertext, and whether it passes or fails authentication validation
- Define the following cipher *E* based on One Time Pad (OTP) (or a pseudo-random generator):
  - $E_k(x)=Transform(x) \oplus k$ *[bit-wise XOR]*
  - *Transform* each bit of the plaintext to two bits:
    - Zero bits (0) are transformed to two zeros (00)
    - One bits (1) are transformed to (01) or (10) randomly
- *E* indistinguishable under chosen plaintext attack
- We show an attack on *auth-then-encrypt* when using E
- *Attack:* flip first two bits of ciphertext.
  - If authentication is still valid, first plaintext bit is 1
  - If authentication fails, first plaintext bit is zero.