Chapter 17

Security at the Transport Layer:
SSL and TLS

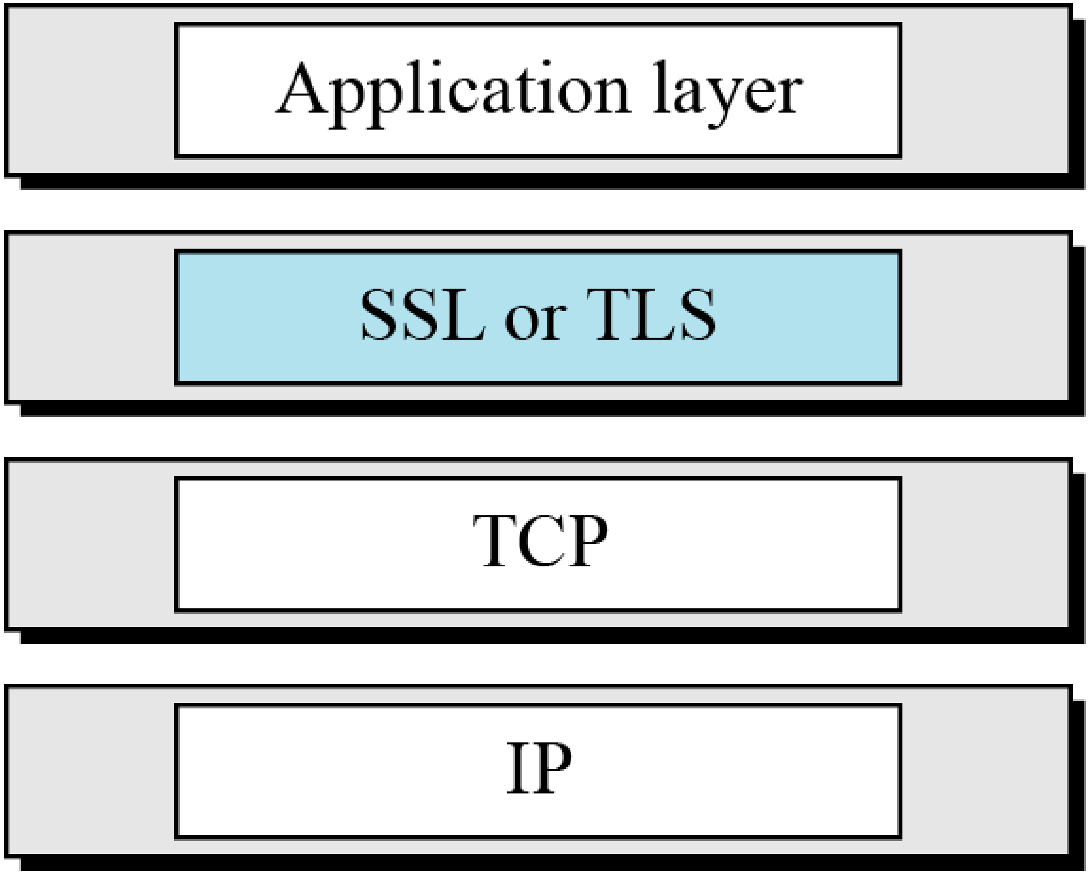
Chapter 17

Objectives

- ❑ To discuss the need for security services at the transport layer of the Internet model
- ❑ To discuss the general architecture of SSL
- ❑ To discuss the general architecture of TLS
- ❑ To compare and contrast SSL and TLS

17 Continued

Figure 17.1 *Location of SSL and TLS in the Internet model*



17-1 SSL ARCHITECTURE

SSL is designed to provide security and compression services to data generated from the application layer.

Topics discussed in this section:

17.1.1 Services
17.1.2 Key Exchange Algorithms
17.1.3 Encryption/Decryption Alogrithms
17.1.4 Hash Algorithms
17.1.5 Cipher Suite
17.1.6 Compression Algorithms
17.1.7 Crypography Parameter Generation
17.1.8 Session and Connections

17.1.1 Services

Fragmentation

Compression

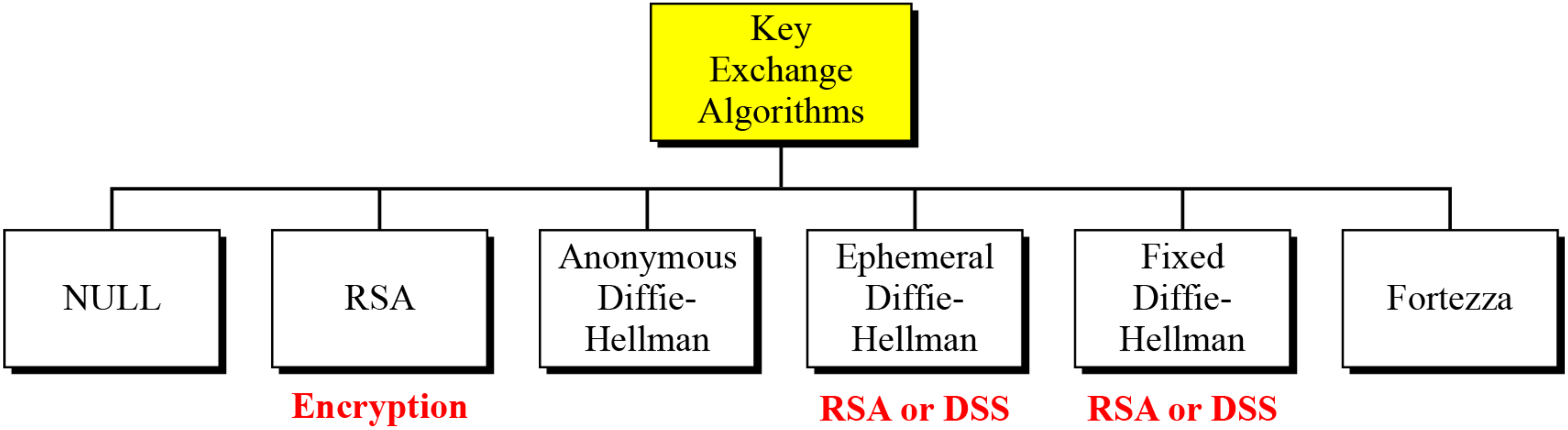
Message Integrity

Confidentiality

Framing

17.1.2 Key Exchange Algorithms

Figure 17.2 ***Key-exchange methods***



17.1.2 Continued

Null

There is no key exchange in this method. No pre-master secret is established between the client and the server.

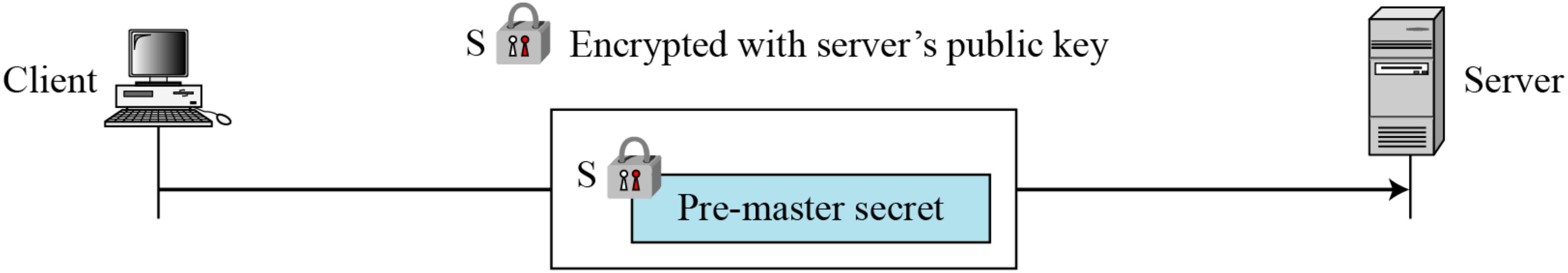
Note

Both client and server need to know the value of the pre-master secret.

17.1.2 Continued

RSA

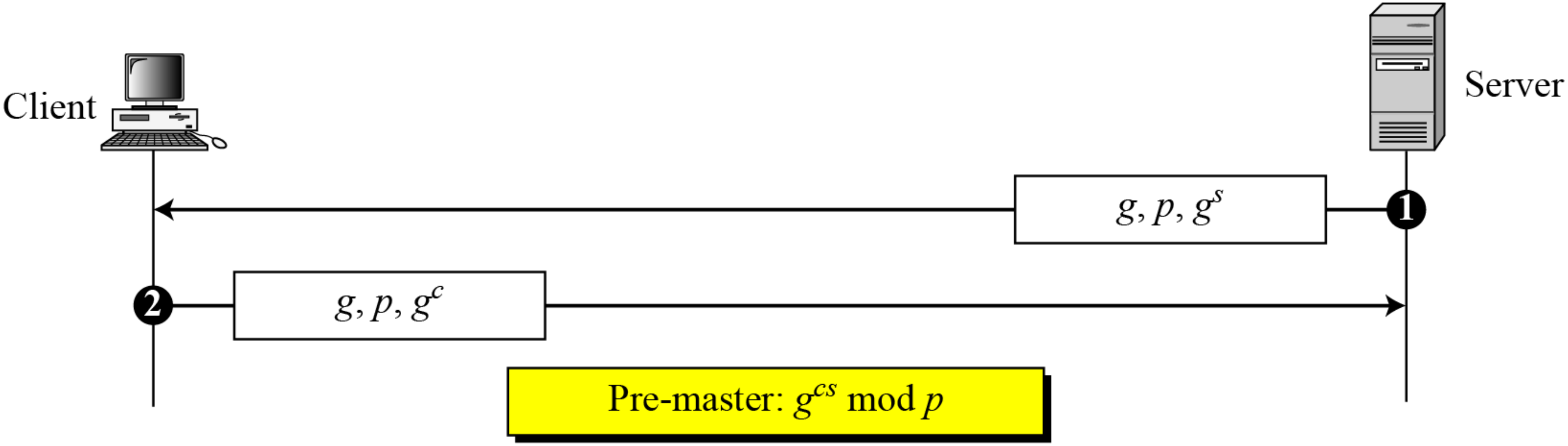
Figure 17.3 ***RSA key exchange; server public key***



17.1.2 *Continued*

Anonymous Diffie-Hellman

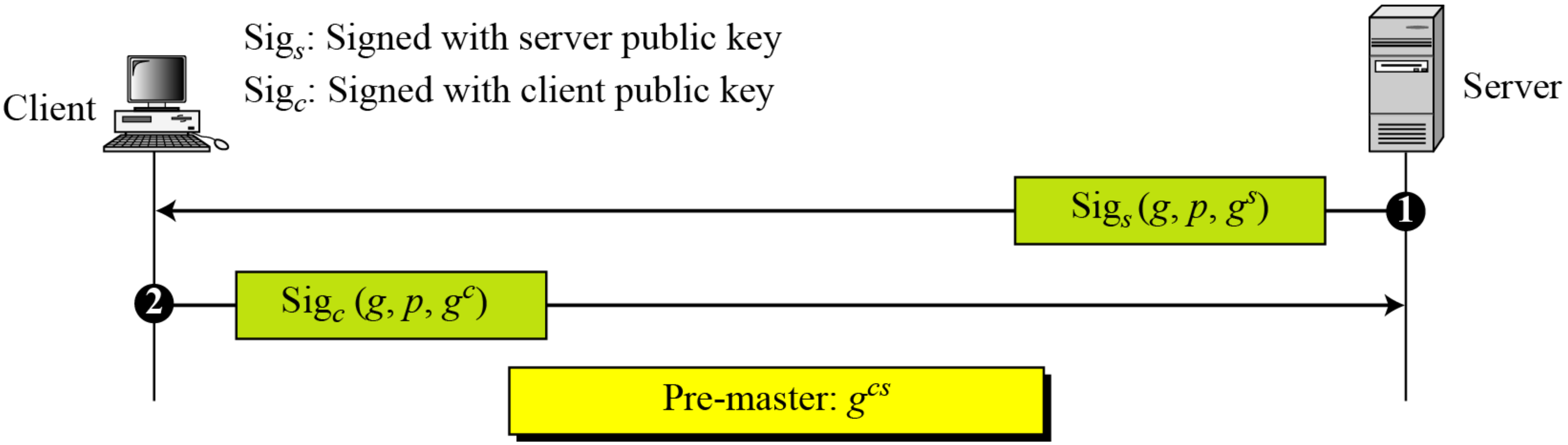
Figure 17.4 ***Anonymous Diffie-Hellman key exchange***



17.1.2 *Continued*

Ephemeral Diffie-Hellman key exchange

Figure 17.5 ***Ephemeral Diffie-Hellman key exchange***



Sig$_s$: Signed with server public key
Sig$_c$: Signed with client public key
Client
Server
1
Sig$_s$ (g, p, g^s)
2
Sig$_c$ (g, p, g^c)
Pre-master: g^{cs}

17.1.2 Continued

Fixed Diffie-Hellman

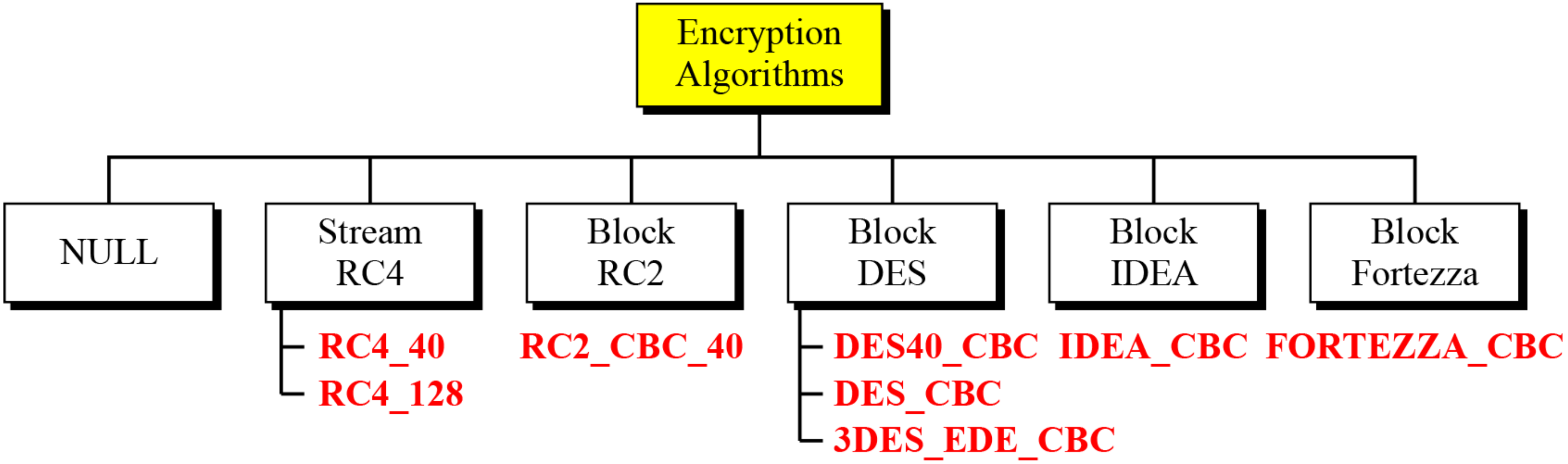
Another solution is the fixed Diffie-Hellman method. All entities in a group can prepare fixed Diffie-Hellman parameters (g and p).

Fortezza

Fortezza is a registered trademark of the U.S. National Security Agency (NSA). It is a family of security protocols developed for the Defense Department.

17.1.3 Encryption/Decryption Algorithms

Figure 17.6 ***Encryption/decryption algorithms***



17.1.3 Continued

NULL

The NULL category simply defines the lack of an encryption/decryption algorithm.

Stream RC

Two RC algorithms are defined in stream mode.

Block RC

One RC algorithm is defined in block mode.

DES

All DES algorithms are defined in block mode.

17.1.3 Continued

IDEA

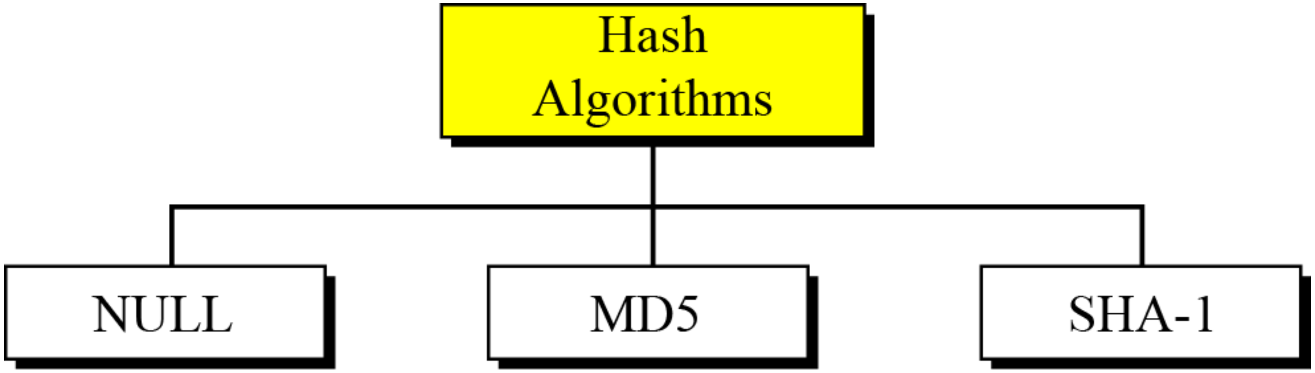
The IDEA algorithm defined in block mode is IDEA_CBC, with a 128-bit key.

Fortezza

The one Fortezza algorithm defined in block mode is FORTEZZA_CBC.

17.1.4 Hash Algorithm

Figure 17.7 ***Hash algorithms for message integrity***



17.1.4 Continued

NULL

The two parties may decline to use an algorithm. In this case, there is no hash function and the message is not authenticated.

MD5

The two parties may choose MD5 as the hash algorithm. In this case, a 128-key MD5 hash algorithm is used.

SHA-1

The two parties may choose SHA as the hash algorithm. In this case, a 160-bit SHA-1 hash algorithm is used.

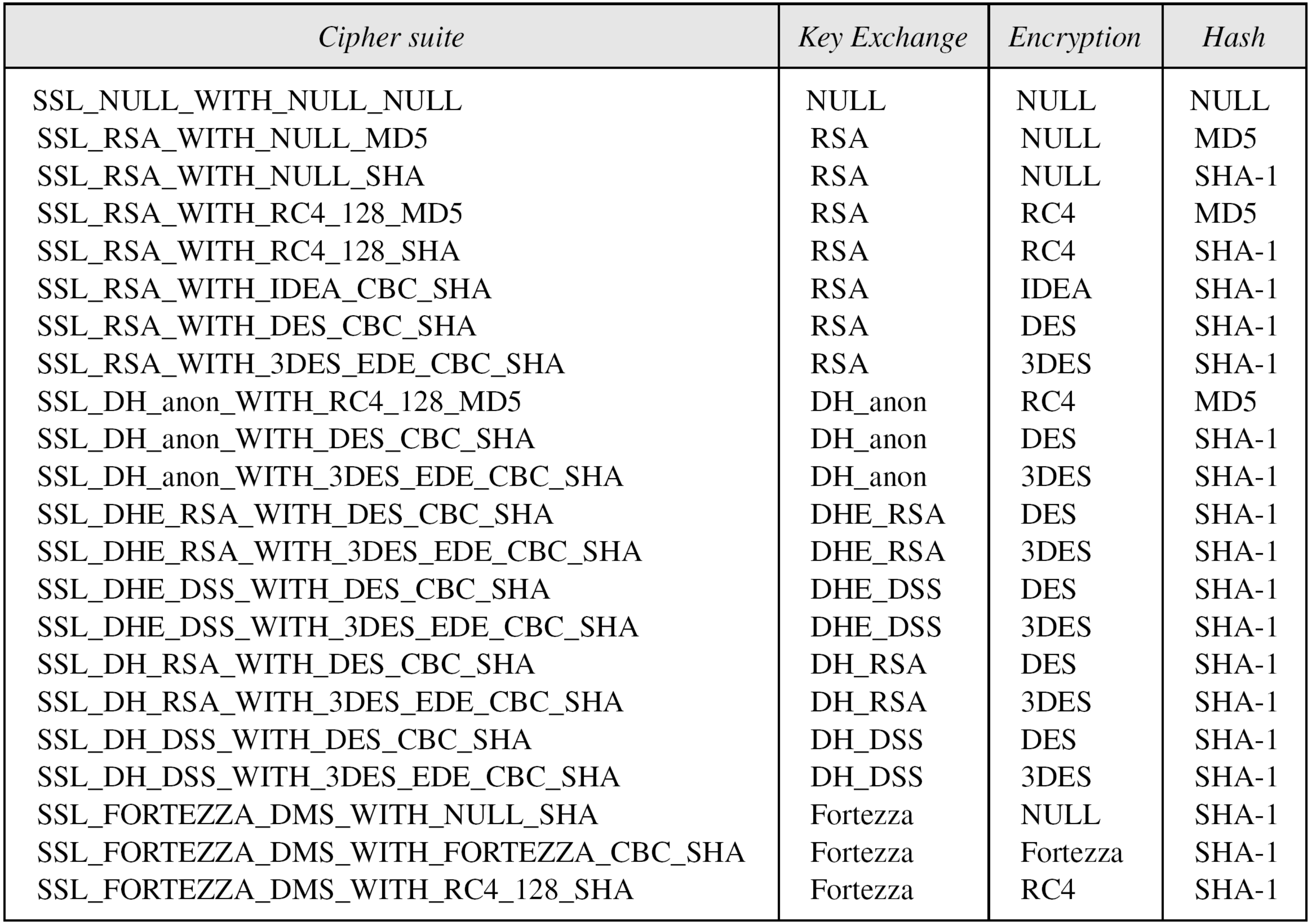
17.1.5 Cipher Suite

The combination of key exchange, hash, and encryption algorithms defines a cipher suite for each SSL session.

SSL_DHE_RSA_WITH_DES_CBC_SHA

17.1.5 Continued

Table 17.1 *SSL cipher suite list*



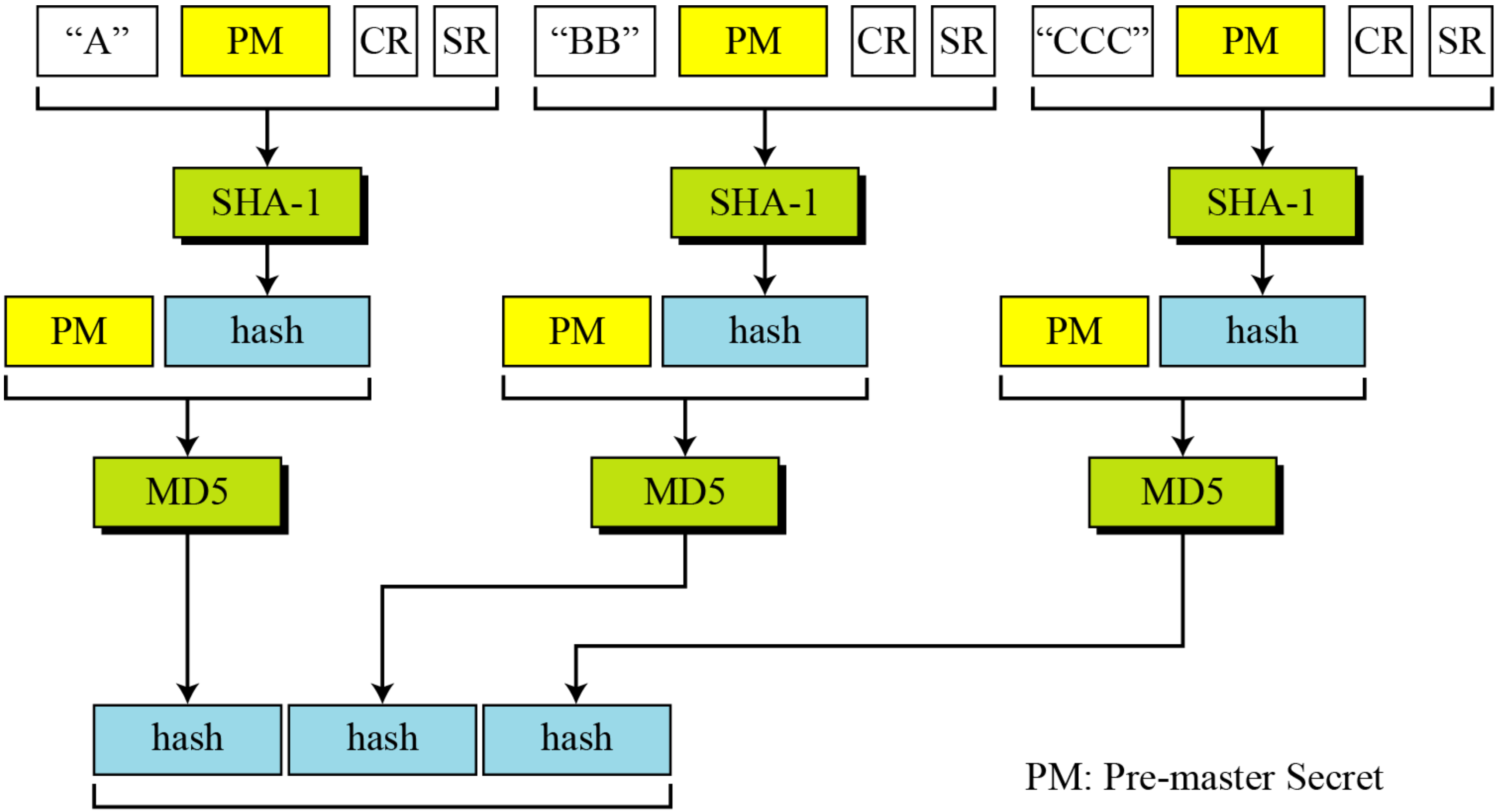
Cipher suite	*Key Exchange*	*Encryption*	*Hash*
SSL_NULL_WITH_NULL_NULL	NULL	NULL	NULL
SSL_RSA_WITH_NULL_MD5	RSA	NULL	MD5
SSL_RSA_WITH_NULL_SHA	RSA	NULL	SHA-1
SSL_RSA_WITH_RC4_128_MD5	RSA	RC4	MD5
SSL_RSA_WITH_RC4_128_SHA	RSA	RC4	SHA-1
SSL_RSA_WITH_IDEA_CBC_SHA	RSA	IDEA	SHA-1
SSL_RSA_WITH_DES_CBC_SHA	RSA	DES	SHA-1
SSL_RSA_WITH_3DES_EDE_CBC_SHA	RSA	3DES	SHA-1
SSL_DH_anon_WITH_RC4_128_MD5	DH_anon	RC4	MD5
SSL_DH_anon_WITH_DES_CBC_SHA	DH_anon	DES	SHA-1
SSL_DH_anon_WITH_3DES_EDE_CBC_SHA	DH_anon	3DES	SHA-1
SSL_DHE_RSA_WITH_DES_CBC_SHA	DHE_RSA	DES	SHA-1
SSL_DHE_RSA_WITH_3DES_EDE_CBC_SHA	DHE_RSA	3DES	SHA-1
SSL_DHE_DSS_WITH_DES_CBC_SHA	DHE_DSS	DES	SHA-1
SSL_DHE_DSS_WITH_3DES_EDE_CBC_SHA	DHE_DSS	3DES	SHA-1
SSL_DH_RSA_WITH_DES_CBC_SHA	DH_RSA	DES	SHA-1
SSL_DH_RSA_WITH_3DES_EDE_CBC_SHA	DH_RSA	3DES	SHA-1
SSL_DH_DSS_WITH_DES_CBC_SHA	DH_DSS	DES	SHA-1
SSL_DH_DSS_WITH_3DES_EDE_CBC_SHA	DH_DSS	3DES	SHA-1
SSL_FORTEZZA_DMS_WITH_NULL_SHA	Fortezza	NULL	SHA-1
SSL_FORTEZZA_DMS_WITH_FORTEZZA_CBC_SHA	Fortezza	Fortezza	SHA-1
SSL_FORTEZZA_DMS_WITH_RC4_128_SHA	Fortezza	RC4	SHA-1

17.1.6 Compression Algorithms

Compression is optional in SSLv3. No specific compression algorithm is defined for SSLv3. Therefore, the default compression method is NULL.

17.1.7 Cryptographic Parameter Generation

Figure 17.8 *Calculation of master secret from pre-master secret*

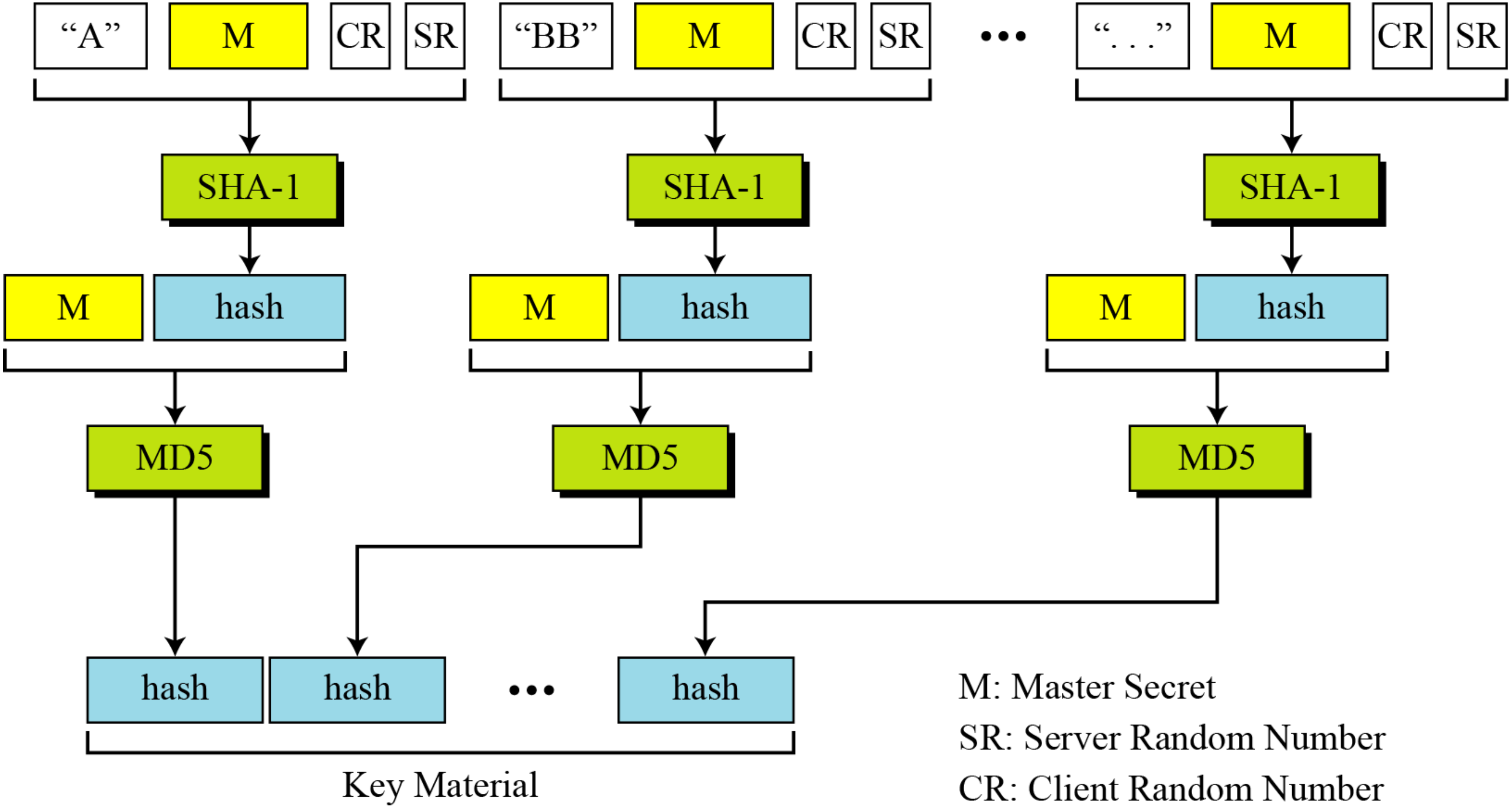


Master secret
(48 bytes)

PM: Pre-master Secret
SR: Server Random Number
CR: Client Random Number

17.1.7 Continued

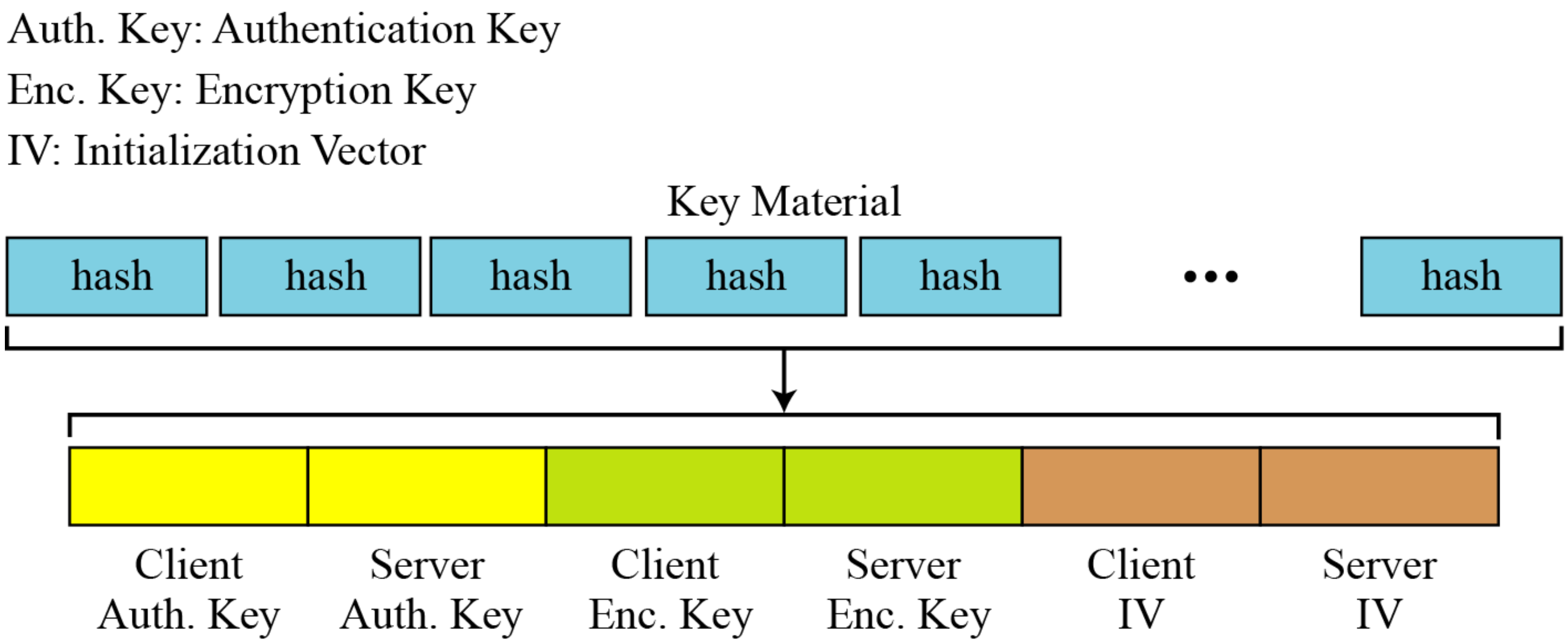
Figure 17.9 *Calculation of key material from master secret*



M: Master Secret
SR: Server Random Number
CR: Client Random Number

17.1.7 Continued

Figure 17.10 ***Extractions of cryptographic secrets from key material***



Auth. Key: Authentication Key

Enc. Key: Encryption Key

IV: Initialization Vector

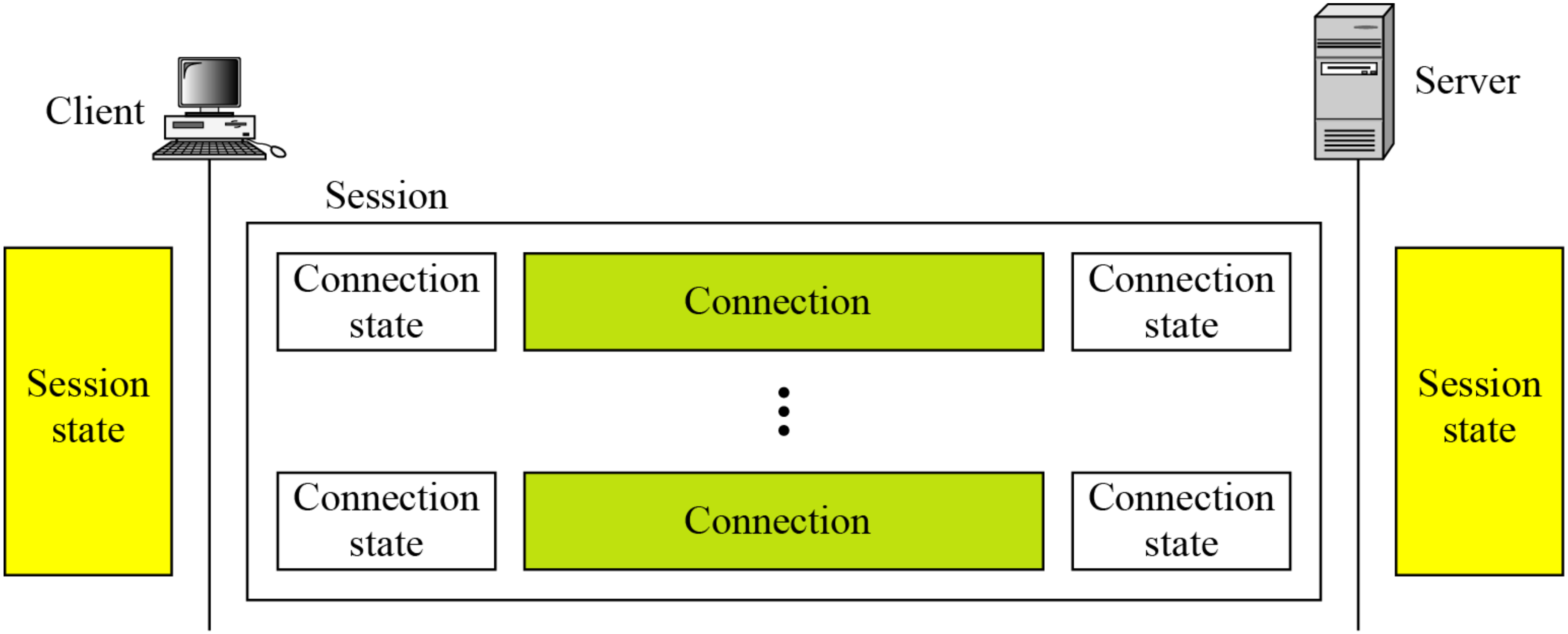
17.1.8 Sessions and Connections

Note

**In a session, one party has the role of a client and the other the role of a server;
in a connection, both parties have equal roles, they are peers.**

17.1.8 Continued

Figure 17.11 *A session and connections*



17.1.8 Continued

Session State

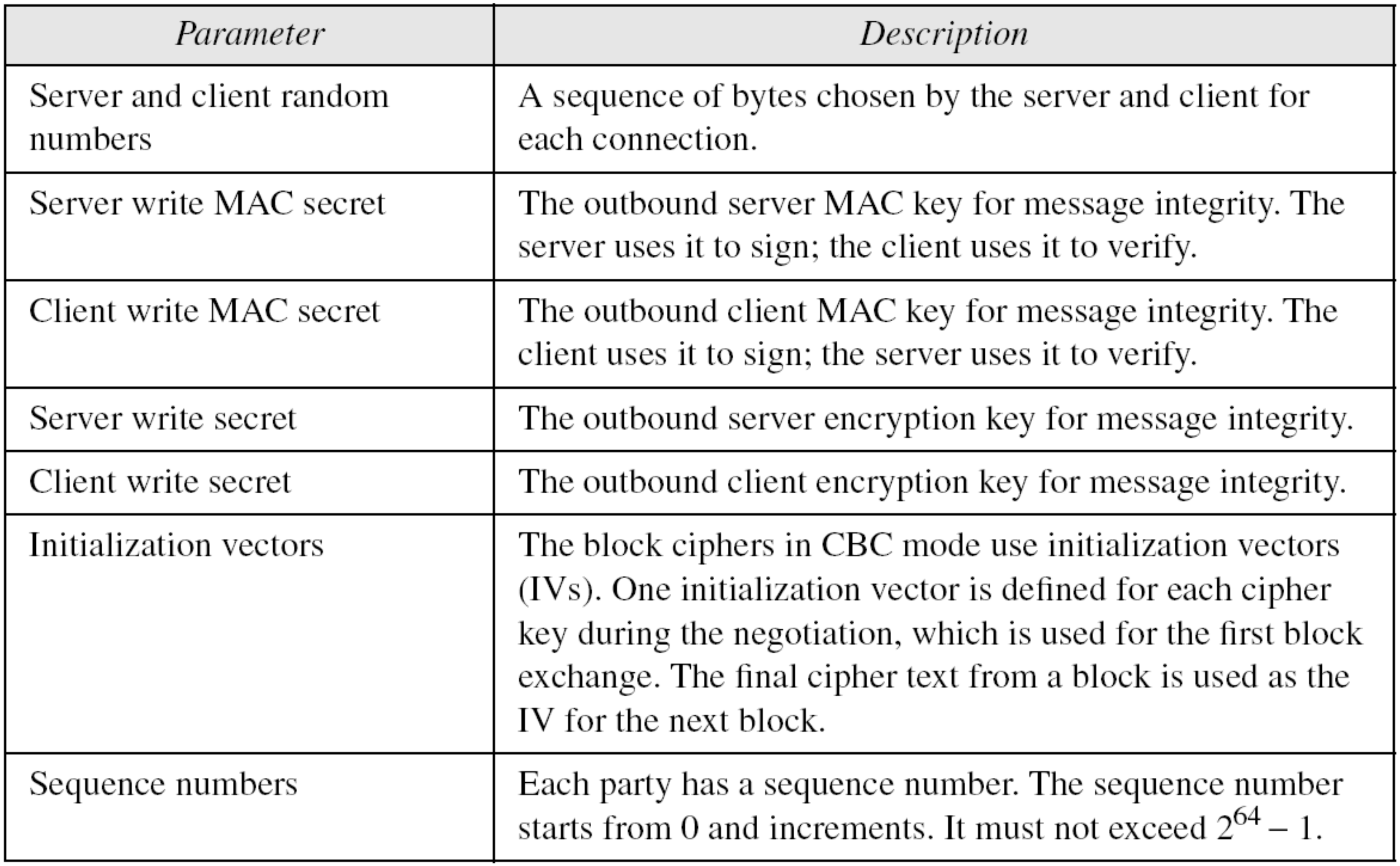
Table 17.2 ***Session state parameters***

Parameter	*Description*
Session ID	A server-chosen 8-bit number defining a session.
Peer Certificate	A certificate of type X509.v3. This parameter may by empty (null).
Compression Method	The compression method.
Cipher Suite	The agreed-upon cipher suite.
Master Secret	The 48-byte secret.
Is resumable	A yes-no flag that allows new connections in an old session.

17.1.8 Continued

Connection State

Table 17.3 ***Connection state parameters***



Parameter	*Description*
Server and client random numbers	A sequence of bytes chosen by the server and client for each connection.
Server write MAC secret	The outbound server MAC key for message integrity. The server uses it to sign; the client uses it to verify.
Client write MAC secret	The outbound client MAC key for message integrity. The client uses it to sign; the server uses it to verify.
Server write secret	The outbound server encryption key for message integrity.
Client write secret	The outbound client encryption key for message integrity.
Initialization vectors	The block ciphers in CBC mode use initialization vectors (IVs). One initialization vector is defined for each cipher key during the negotiation, which is used for the first block exchange. The final cipher text from a block is used as the IV for the next block.
Sequence numbers	Each party has a sequence number. The sequence number starts from 0 and increments. It must not exceed $2^{64} - 1$.

17.1.8 Continued

Note

**The client and the server have six different cryptography secrets: three read secrets and three write secrets.
The read secrets for the client are the same as the write secrets for the server and vice versa.**

17-2 Four Protocols

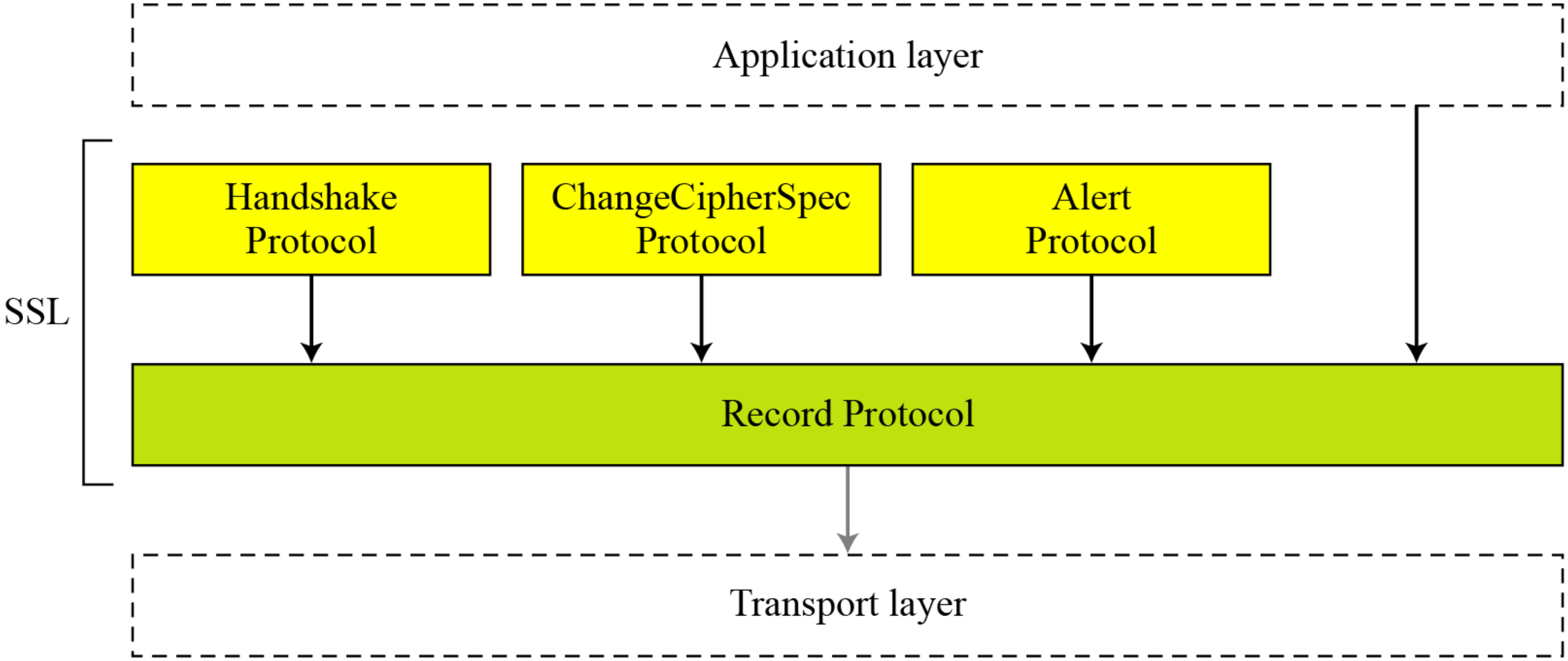
We have discussed the idea of SSL without showing how SSL accomplishes its tasks. SSL defines four protocols in two layers, as shown in Figure 17.12.

Topics discussed in this section:

17.2.1 Handshake Protocol
17.2.2 ChangeCipher Spec Protocol
17.2.3 Alert Protocol
17.2.4 Record Protocol

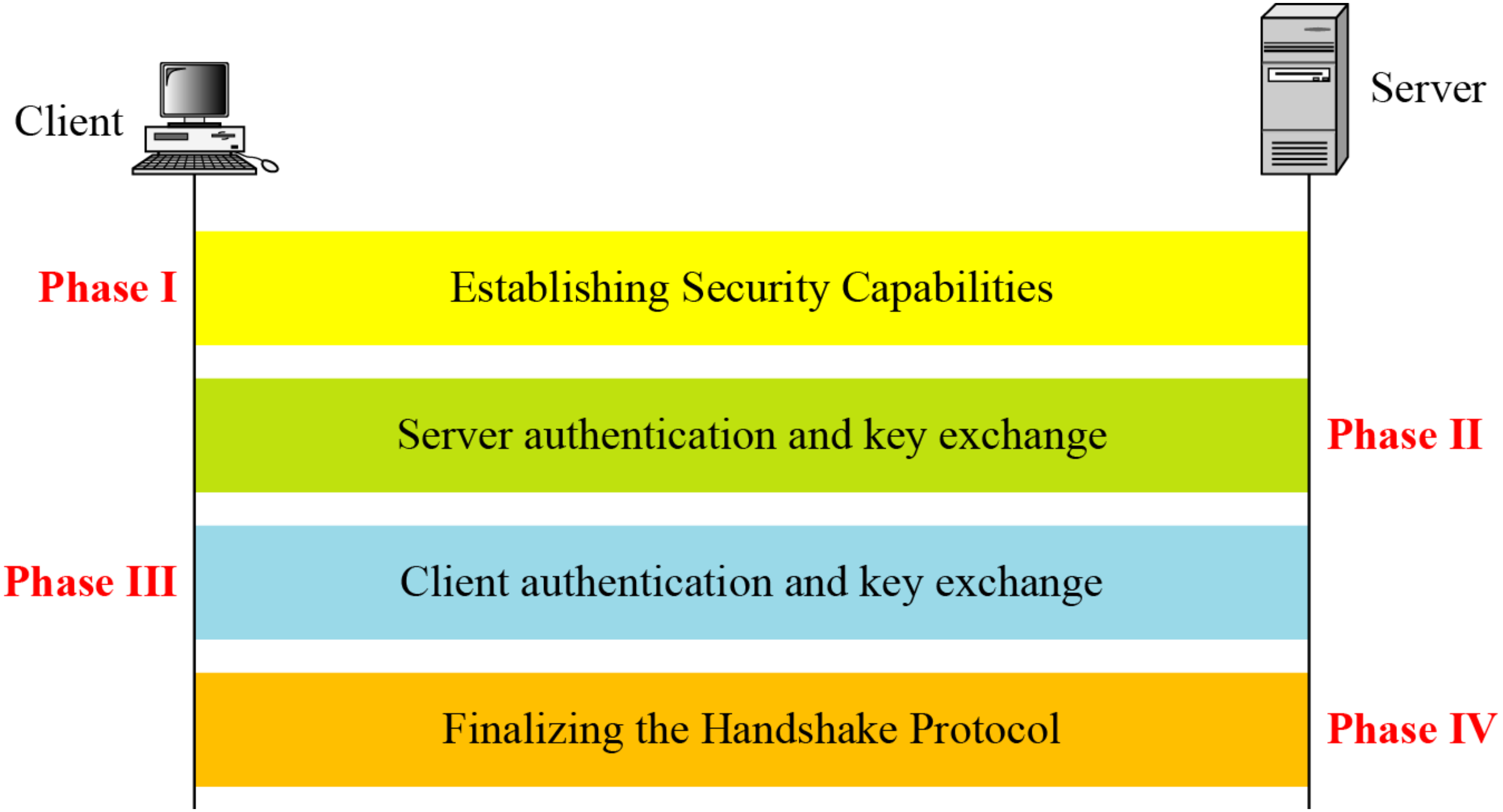
17.2. Continued

Figure 17.12 *Four SSL protocols*



17.2.1 Handshake Protocol

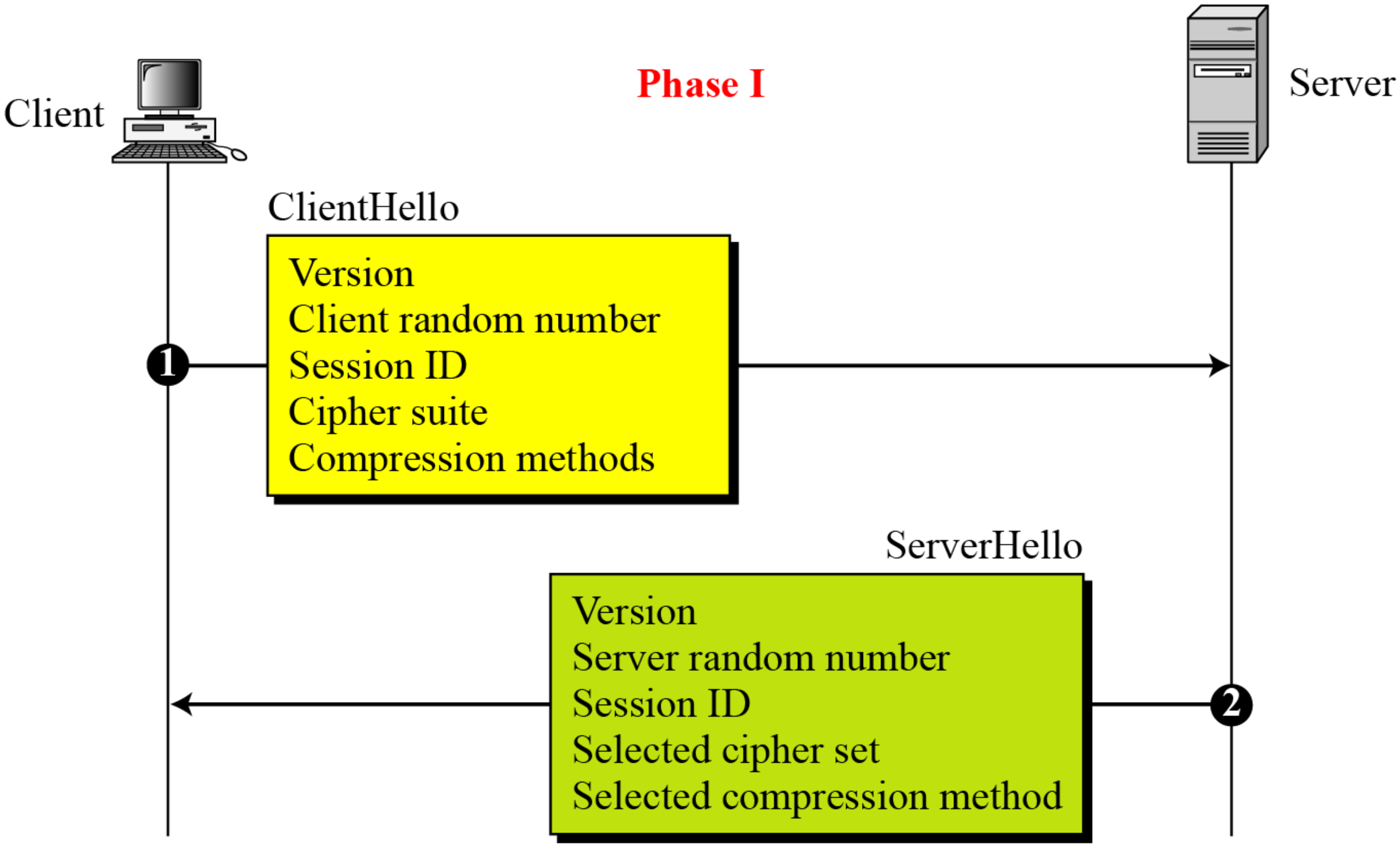
Figure 17.13 *Handshake Protocol*



Client
Server
Phase I
Establishing Security Capabilities
Server authentication and key exchange
Phase II
Phase III
Client authentication and key exchange
Finalizing the Handshake Protocol
Phase IV

17.2.1 Continued

Figure 17.14 *Phase I of Handshake Protocol*



ClientHello:

- Version
- Client random number
- Session ID
- Cipher suite
- Compression methods

ServerHello:

- Version
- Server random number
- Session ID
- Selected cipher set
- Selected compression method

17.2.1 Continued

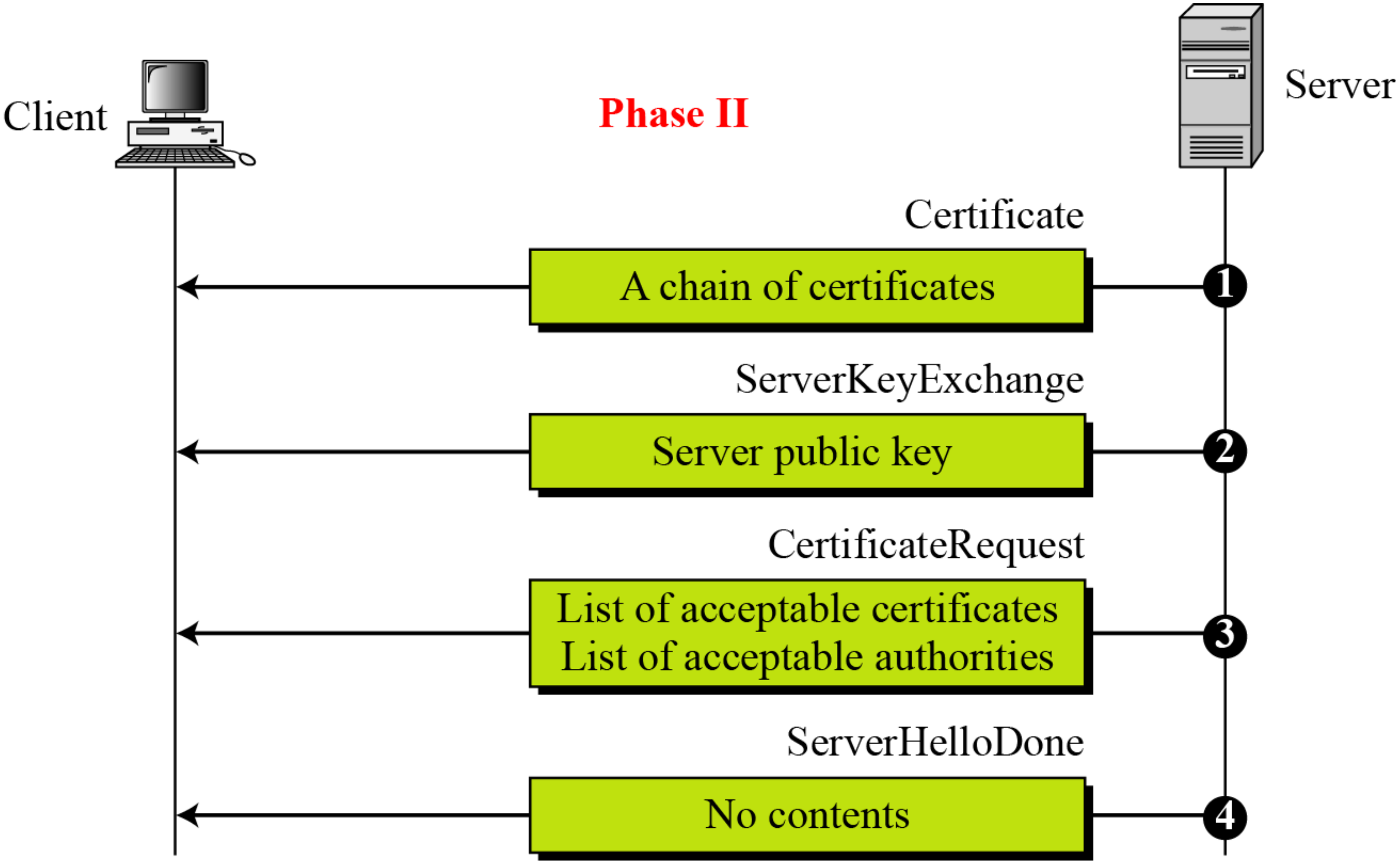
Note

After Phase I, the client and server know the following:

- ❑ **The version of SSL**
- ❑ **The algorithms for key exchange, message authentication, and encryption**
- ❑ **The compression method**
- ❑ **The two random numbers for key generation**

17.2.1 Continued

Figure 17.15 *Phase II of Handshake Protocol*



17.2.1 Continued

Note

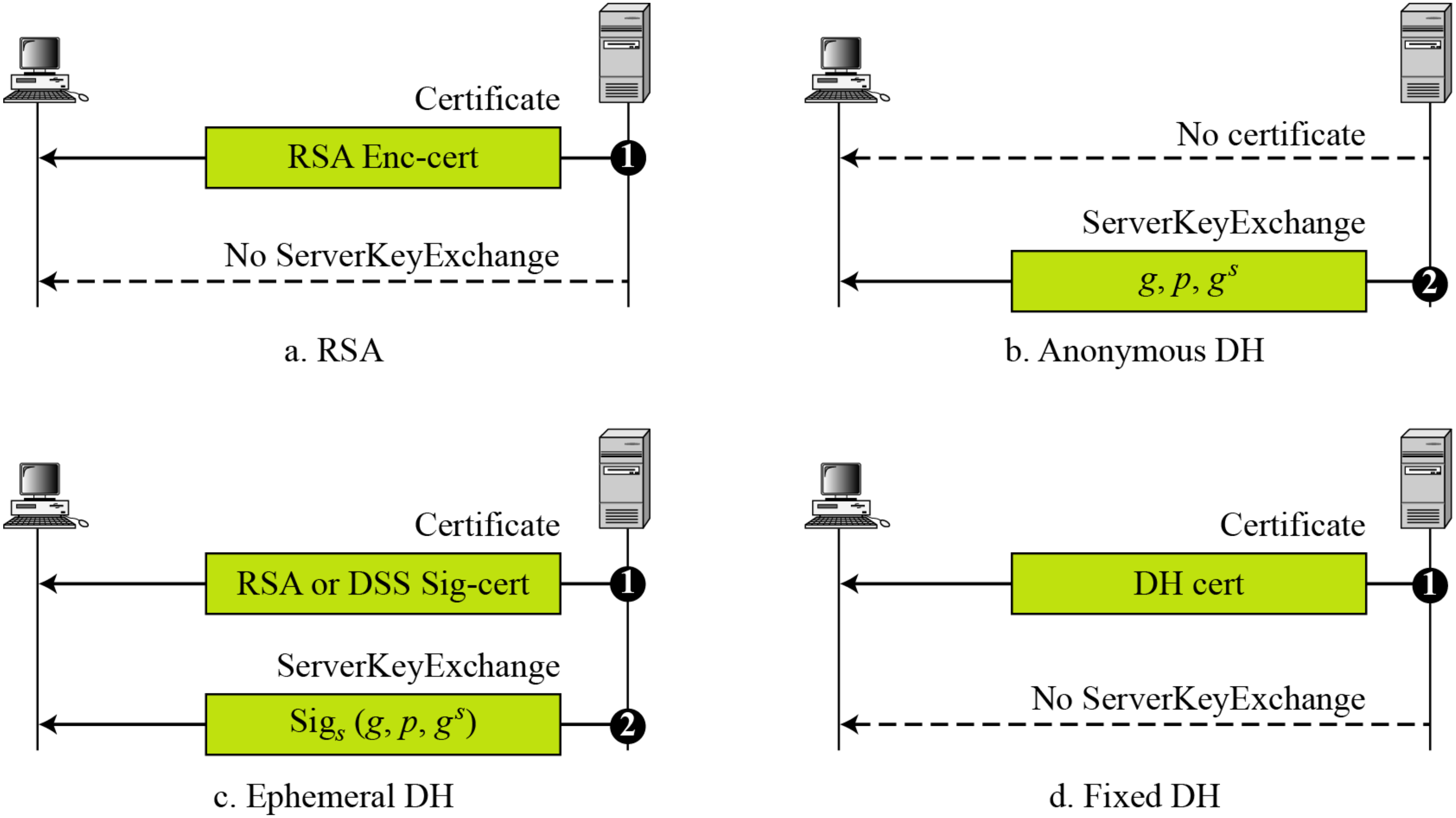
After Phase II,

❑ The server is authenticated to the client.

❑ The client knows the public key of the server if required.

17.2.1 Continued

Figure 17.16 ***Four cases in Phase II***



a. RSA

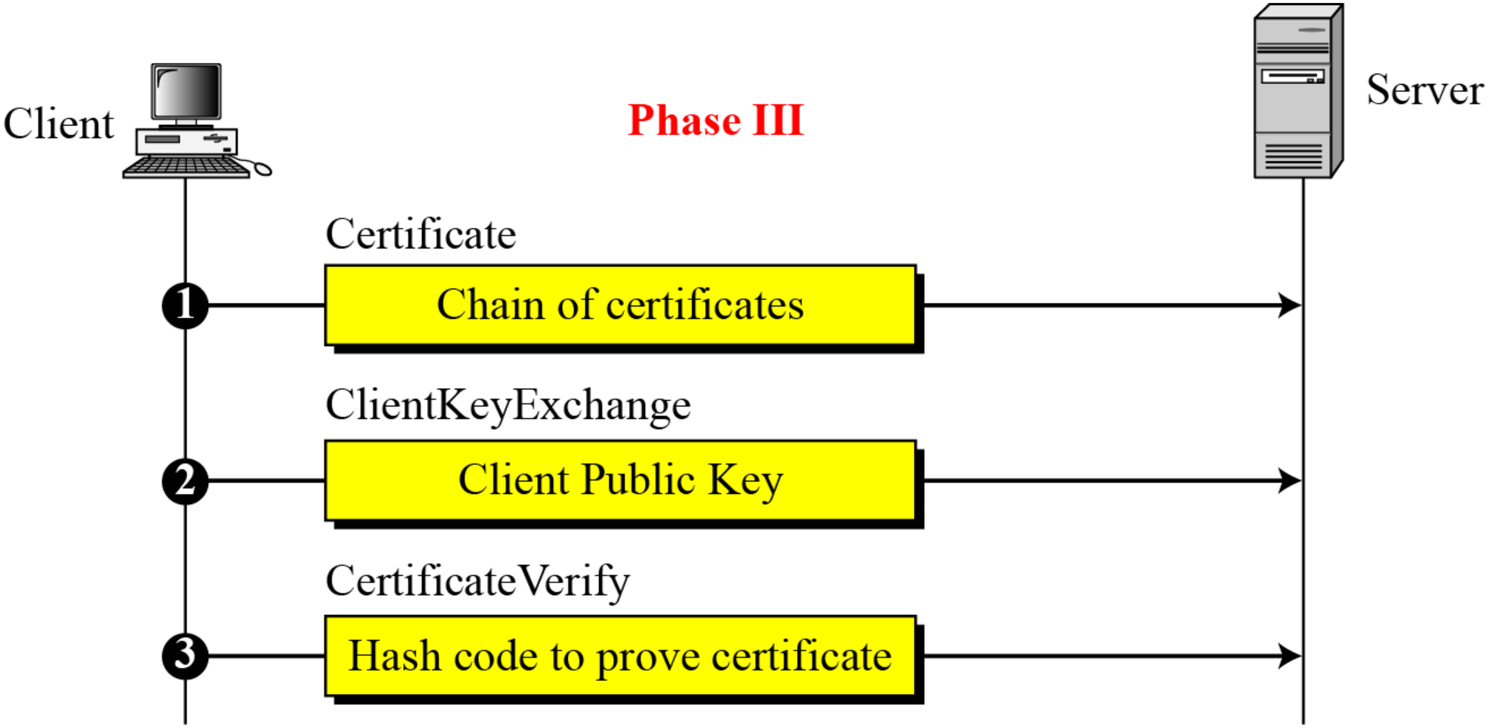
b. Anonymous DH

c. Ephemeral DH

d. Fixed DH

17.2.1 Continued

Figure 17.17 ***Phase III of Handshake Protocol***



17.2.1 Continued

Note

After Phase III,

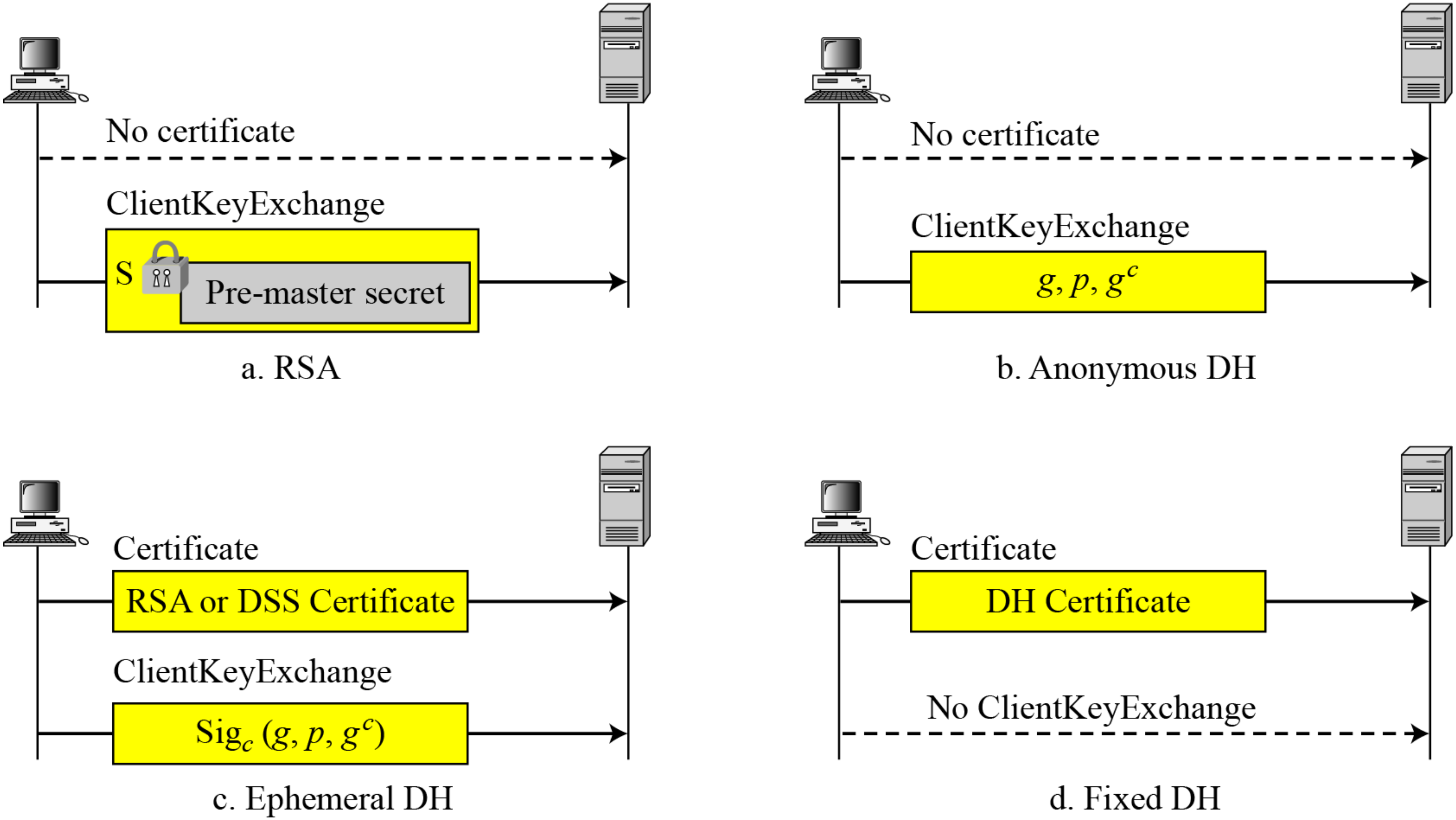
- ❑ **The client is authenticated for the server.**
- ❑ **Both the client and the server know the pre-master secret.**

17.2.1 Continued

Figure 17.18 *Four cases in Phase III*

S 🔒ncrypted with server’s public key

Sig_c: Signed with client’s public key



a. RSA

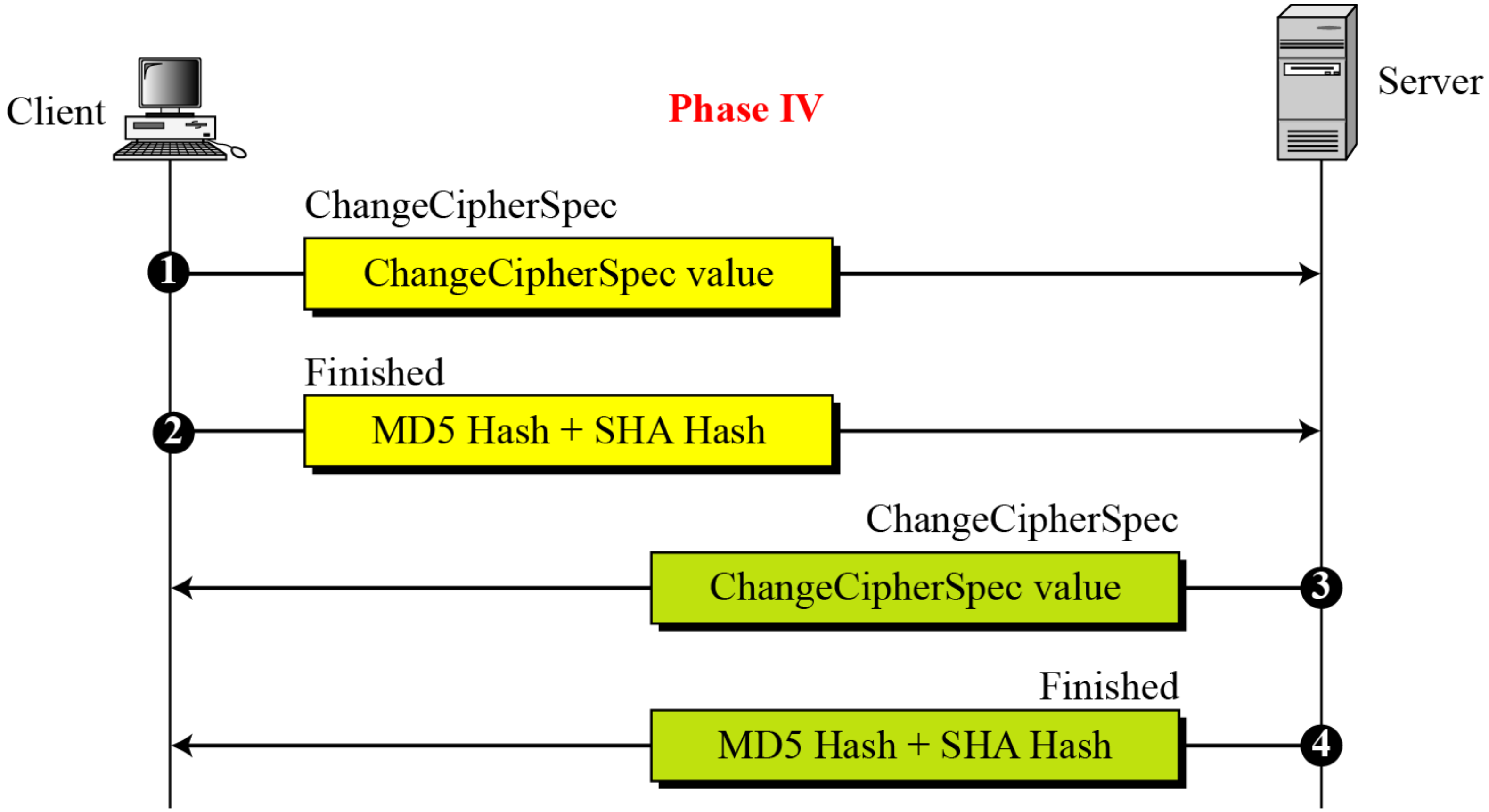
b. Anonymous DH

c. Ephemeral DH

d. Fixed DH

17.2.1 Continued

Figure 17.19 *Phase IV of Handshake Protocol*



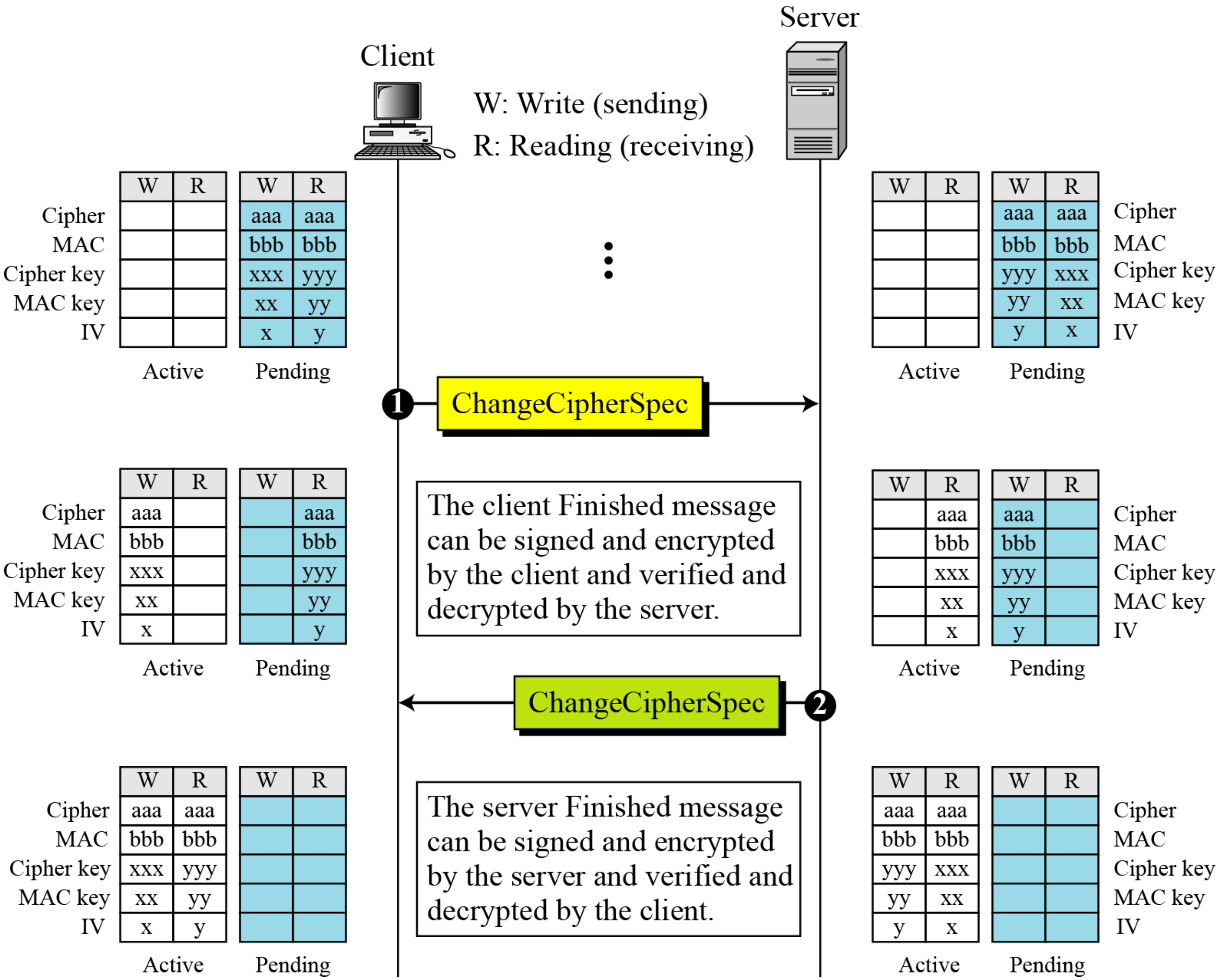
17.2.1 Continued

Note

After Phase IV, the client and server are ready to exchange data.

17.2.2 ChangeCipherSpec Protocol

Figure 17.20 ***Movement of parameters from pending state to active state***



Client:

	Active		Pending	
	W	R	W	R
Cipher			aaa	aaa
MAC			bbb	bbb
Cipher key			xxx	yyy
MAC key			xx	yy
IV			x	y

Server:

	Active		Pending	
	W	R	W	R
Cipher			aaa	aaa
MAC			bbb	bbb
Cipher key			yyy	xxx
MAC key			yy	xx
IV			y	x

Client:

	Active		Pending	
	W	R	W	R
Cipher	aaa			aaa
MAC	bbb			bbb
Cipher key	xxx			yyy
MAC key	xx			yy
IV	x			y

The client Finished message can be signed and encrypted by the client and verified and decrypted by the server.

Server:

	Active		Pending	
	W	R	W	R
Cipher		aaa	aaa	
MAC		bbb	bbb	
Cipher key		xxx	yyy	
MAC key		xx	yy	
IV		x	y	

Client:

	Active		Pending	
	W	R	W	R
Cipher	aaa	aaa		
MAC	bbb	bbb		
Cipher key	xxx	yyy		
MAC key	xx	yy		
IV	x	y		

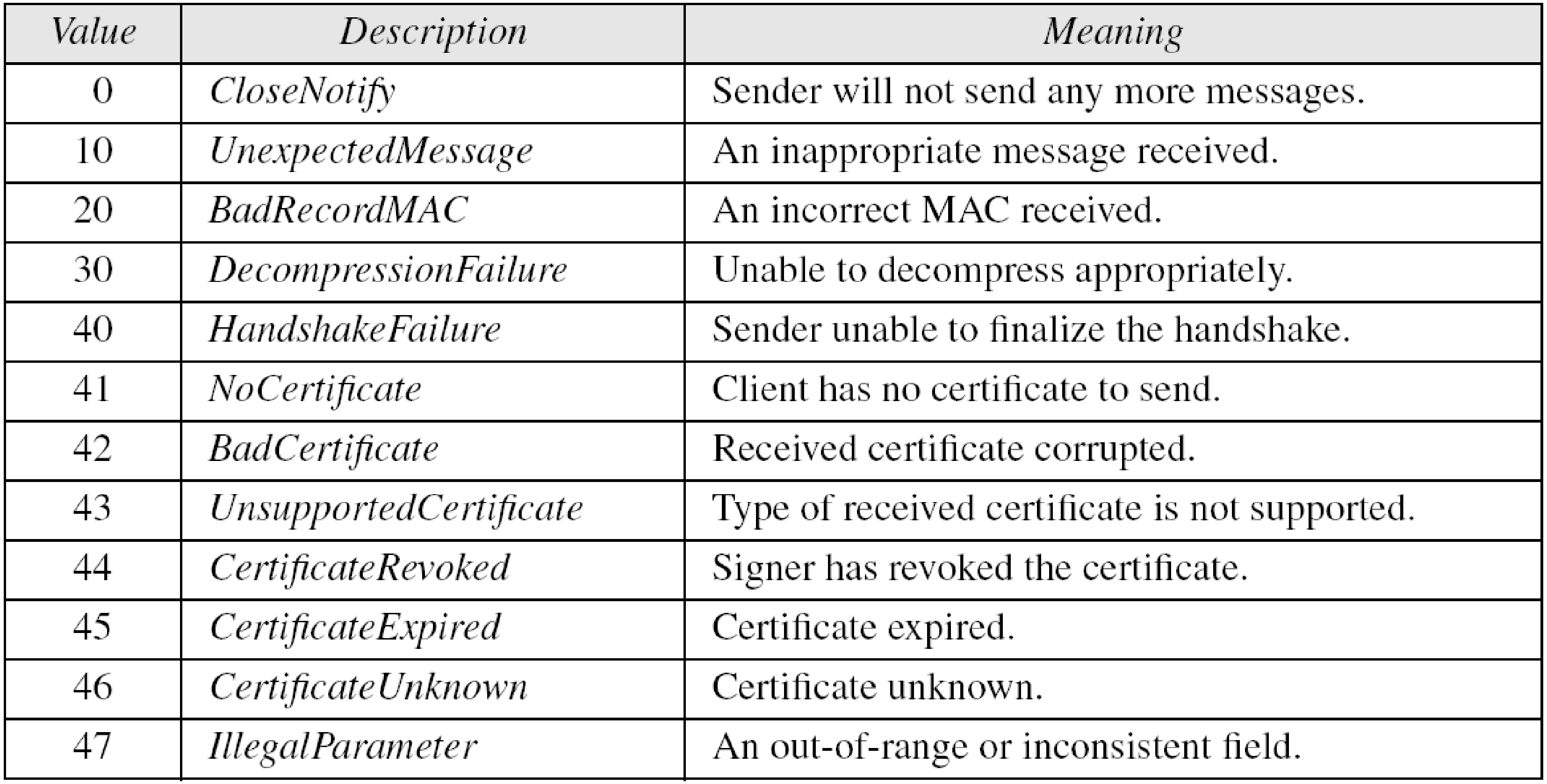
The server Finished message can be signed and encrypted by the server and verified and decrypted by the client.

Server:

	Active		Pending	
	W	R	W	R
Cipher	aaa	aaa		
MAC	bbb	bbb		
Cipher key	yyy	xxx		
MAC key	yy	xx		
IV	y	x		

17.2.3 Alert Protocol

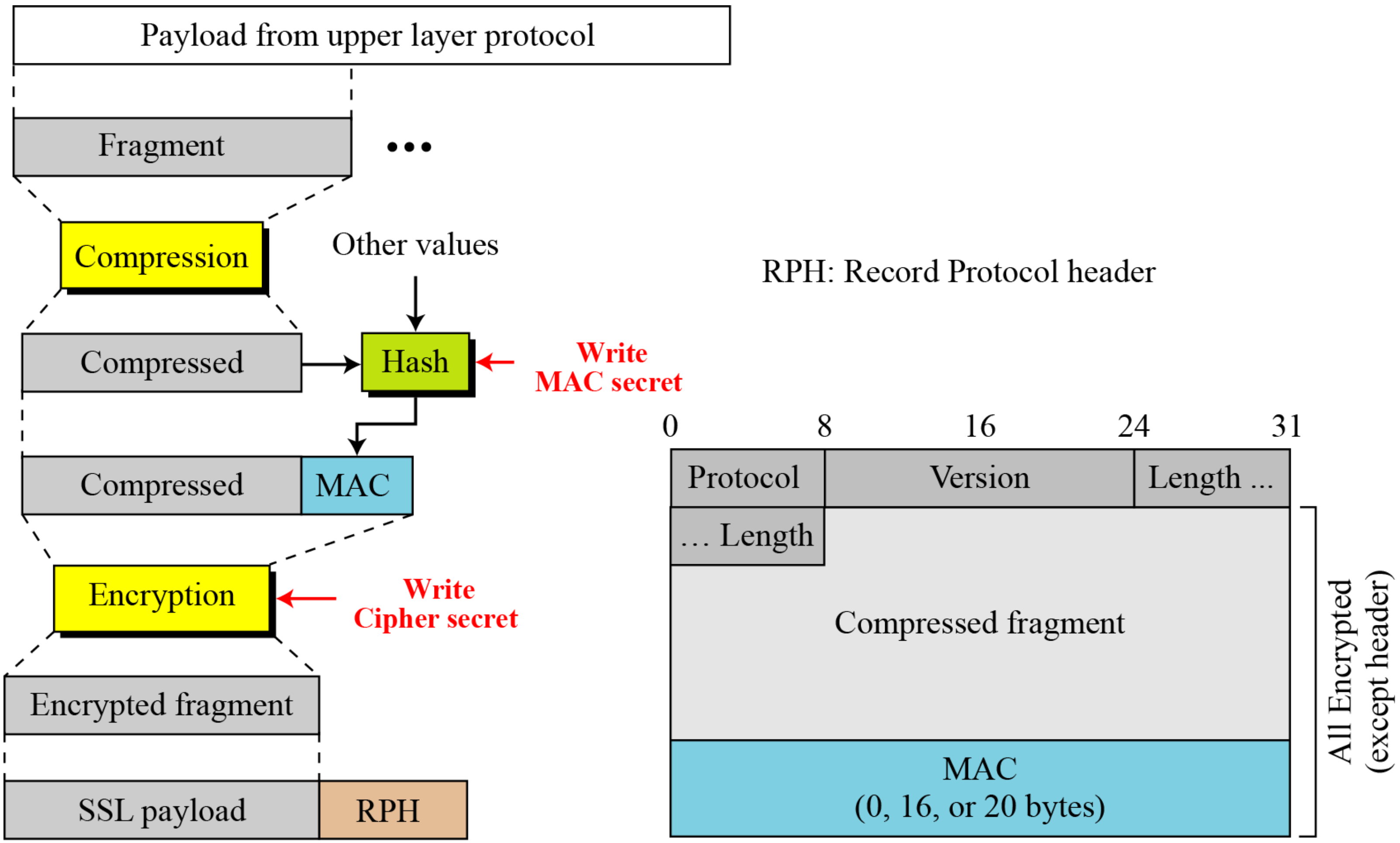
Table 17.4 ***Alerts defined for SSL***



Value	*Description*	*Meaning*
0	*CloseNotify*	Sender will not send any more messages.
10	*UnexpectedMessage*	An inappropriate message received.
20	*BadRecordMAC*	An incorrect MAC received.
30	*DecompressionFailure*	Unable to decompress appropriately.
40	*HandshakeFailure*	Sender unable to finalize the handshake.
41	*NoCertificate*	Client has no certificate to send.
42	*BadCertificate*	Received certificate corrupted.
43	*UnsupportedCertificate*	Type of received certificate is not supported.
44	*CertificateRevoked*	Signer has revoked the certificate.
45	*CertificateExpired*	Certificate expired.
46	*CertificateUnknown*	Certificate unknown.
47	*IllegalParameter*	An out-of-range or inconsistent field.

17.2.4 Record Protocol

Figure 17.21 ***Processing done by the Record Protocol***



Payload from upper layer protocol

Fragment •••

Compression

Other values

Compressed → Hash

Write MAC secret

Compressed | MAC

Encryption

Write Cipher secret

Encrypted fragment

SSL payload | RPH

RPH: Record Protocol header

0	8	16	24	31
Protocol	Version		Length …	
… Length				
Compressed fragment				
MAC (0, 16, or 20 bytes)				

All Encrypted (except header)

a. Process

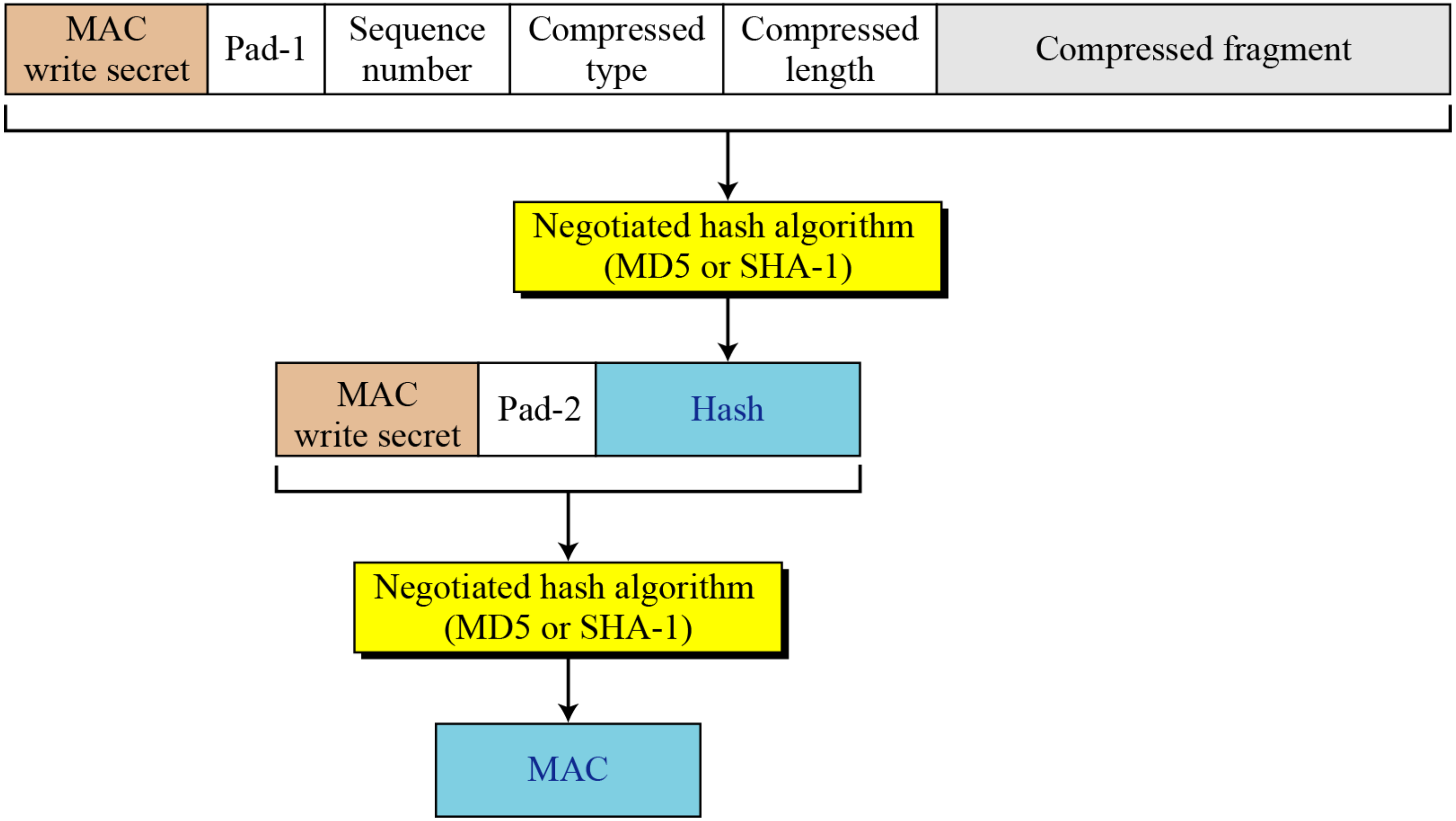
b. Encapsulation

17.2.4 Continued

Figure 17.22 *Calculation of MAC*

Pad-1: Byte 0x36 (00110110) repeated 48 times for MD5 and 40 times for SHA-1

Pad-2: Byte 0x5C (01011100) repeated 48 times for MD5 and 40 times for SHA-1



17-3 SSL MESSAGE FORMATS

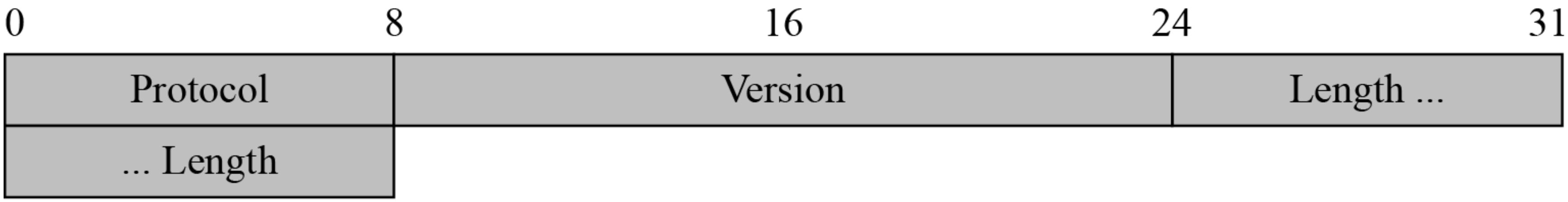
As we have discussed, messages from three protocols and data from the application layer are encapsulated in the Record Protocol messages.

Topics discussed in this section:

17.3.1 ChangeCipherSpec Protocol
17.3.2 Alert Protocol
17.3.3 Handshake Protocol
17.3.4 Application Data

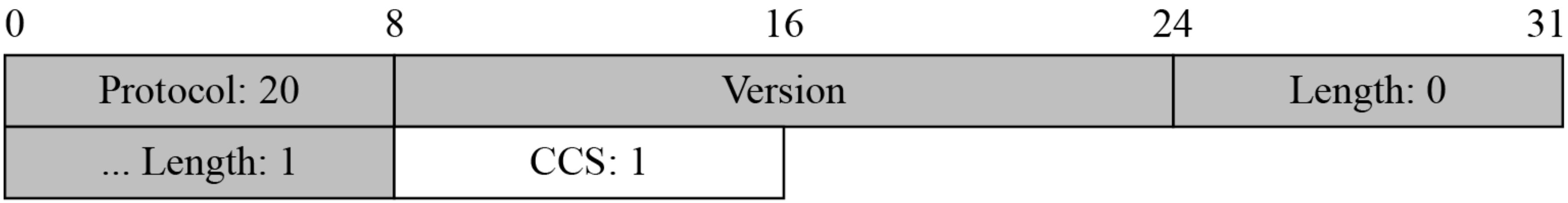
17.3 *Continued*

Figure 17.23 ***Record Protocol general header***



17.3.1 ChangeCipherSpec Protocol

Figure 17.24 *ChangeCipherSpec message*



Protocol: 20

Version

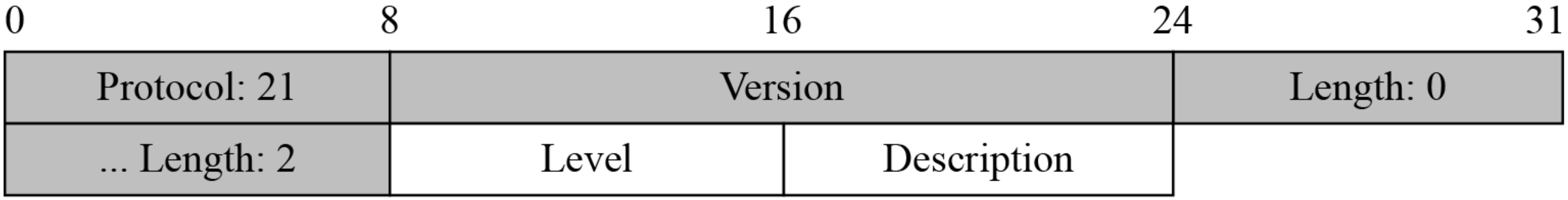
Length: 0

... Length: 1

CCS: 1

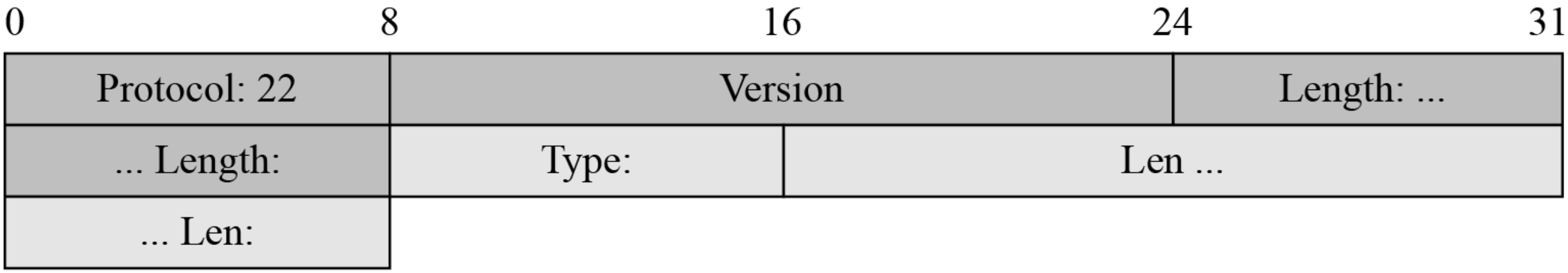
17.3.2 Alert Protocol

Figure 17.25 ***Alert message***



17.3.3 Handshake Protocol

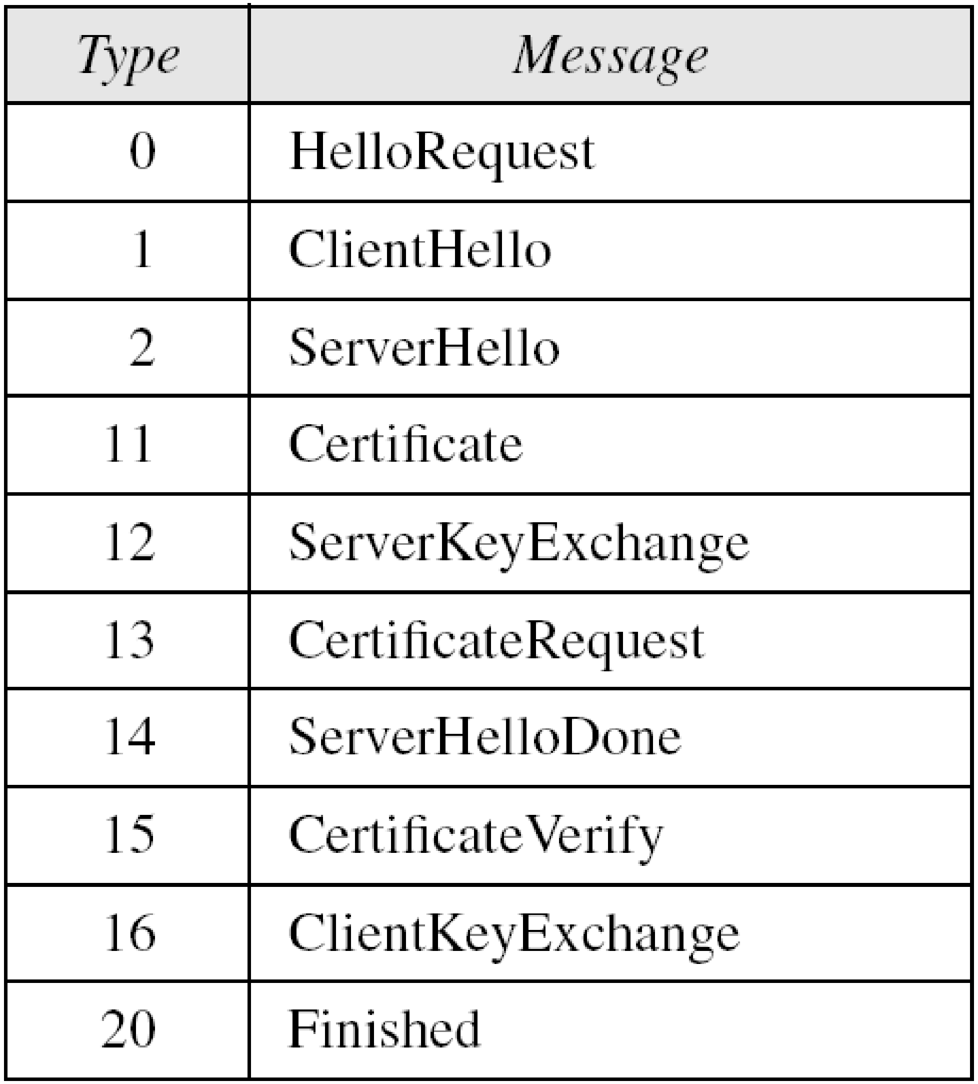
Figure 17.26 ***Generic header for Handshake Protocol***



Protocol: 22	Version		Length: ...
... Length:	Type:	Len ...	
... Len:			

17.3.3 Continued

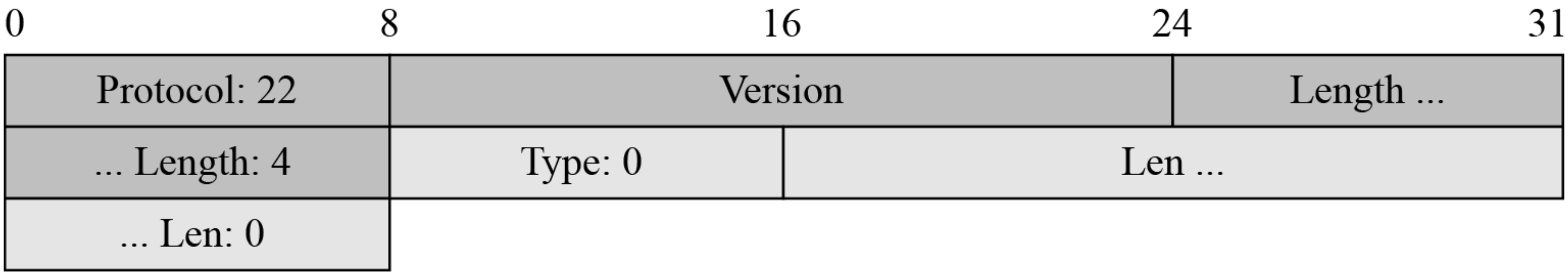
Table 17.5 *Types of Handshake messages*



Type	*Message*
0	HelloRequest
1	ClientHello
2	ServerHello
11	Certificate
12	ServerKeyExchange
13	CertificateRequest
14	ServerHelloDone
15	CertificateVerify
16	ClientKeyExchange
20	Finished

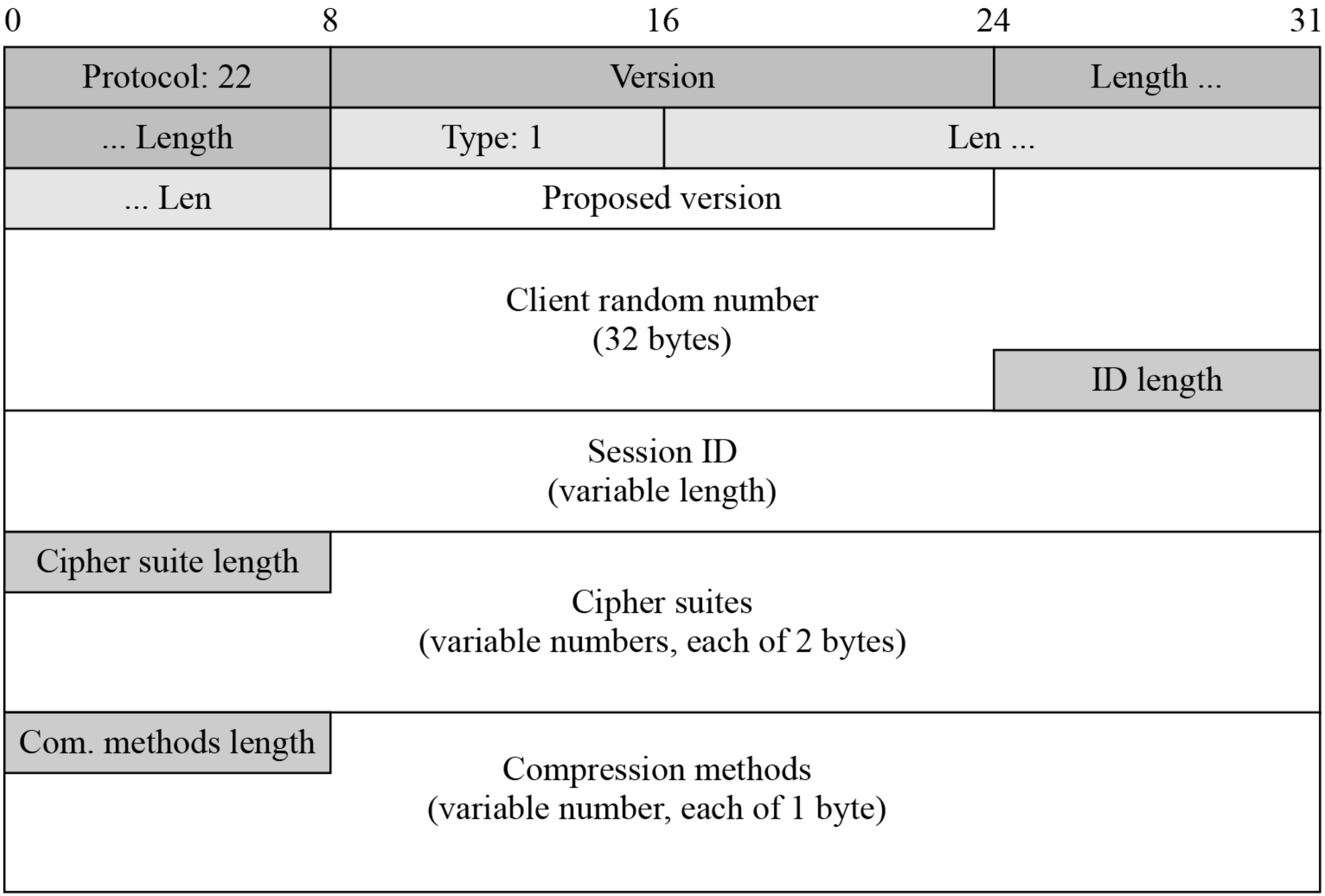
17.3.3 Continued

Figure 17.27 *Virtual tributary types*



17.3.3 Continued

Figure 17.28 *ClientHello message*



0 8 16 24 31

Protocol: 22

Version

Length ...

... Length

Type: 1

Len ...

... Len

Proposed version

Client random number
(32 bytes)

ID length

Session ID
(variable length)

Cipher suite length

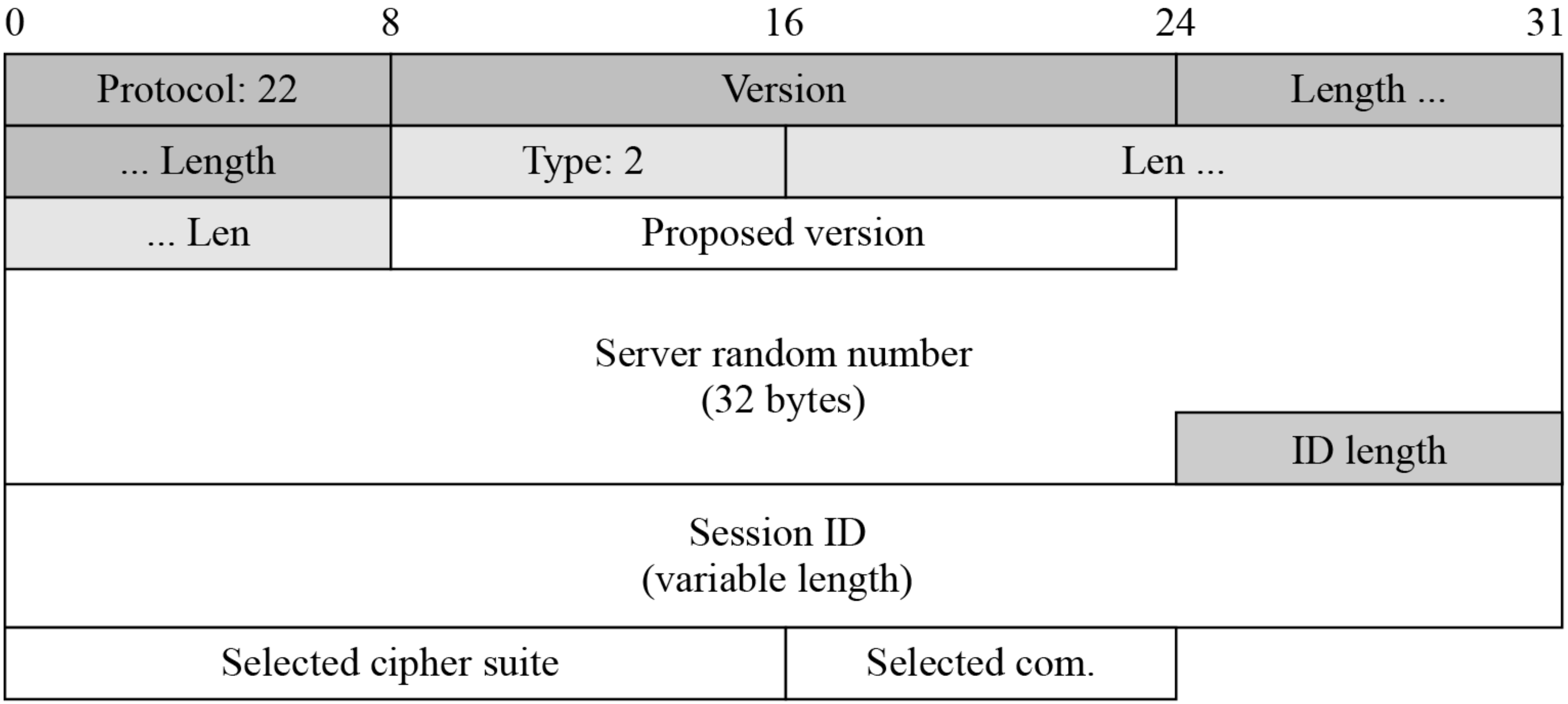
Cipher suites
(variable numbers, each of 2 bytes)

Com. methods length

Compression methods
(variable number, each of 1 byte)

17.3.3 Continued

Figure 17.29 ***ServerHello message***



0
8
16
24
31

Protocol: 22
Version
Length ...

... Length
Type: 2
Len ...

... Len
Proposed version

Server random number
(32 bytes)

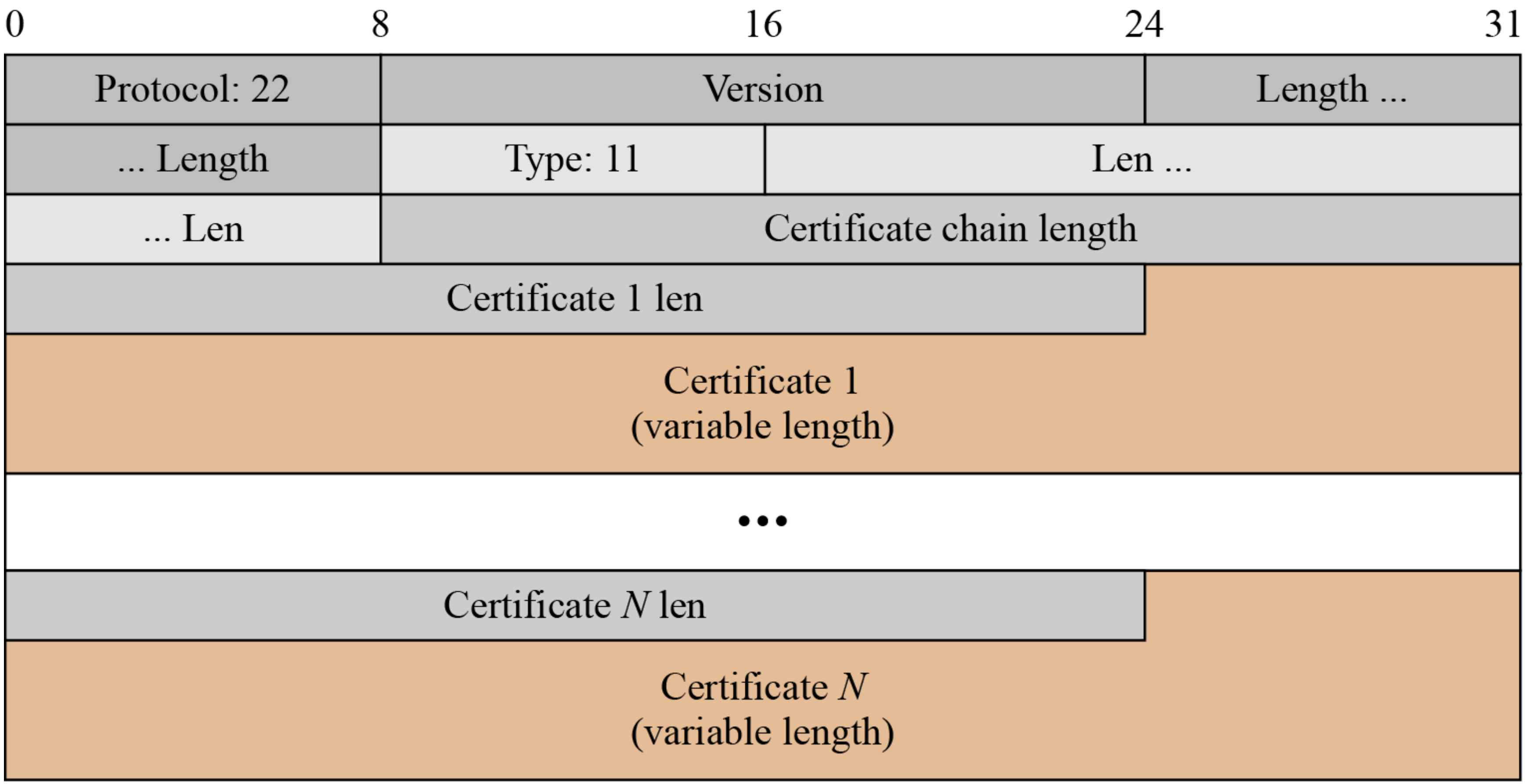
ID length

Session ID
(variable length)

Selected cipher suite
Selected com.

17.3.3 Continued

Figure 17.30 *Certificate message*



0 8 16 24 31

Protocol: 22 | Version | Length ...

... Length | Type: 11 | Len ...

... Len | Certificate chain length

Certificate 1 len

Certificate 1
(variable length)

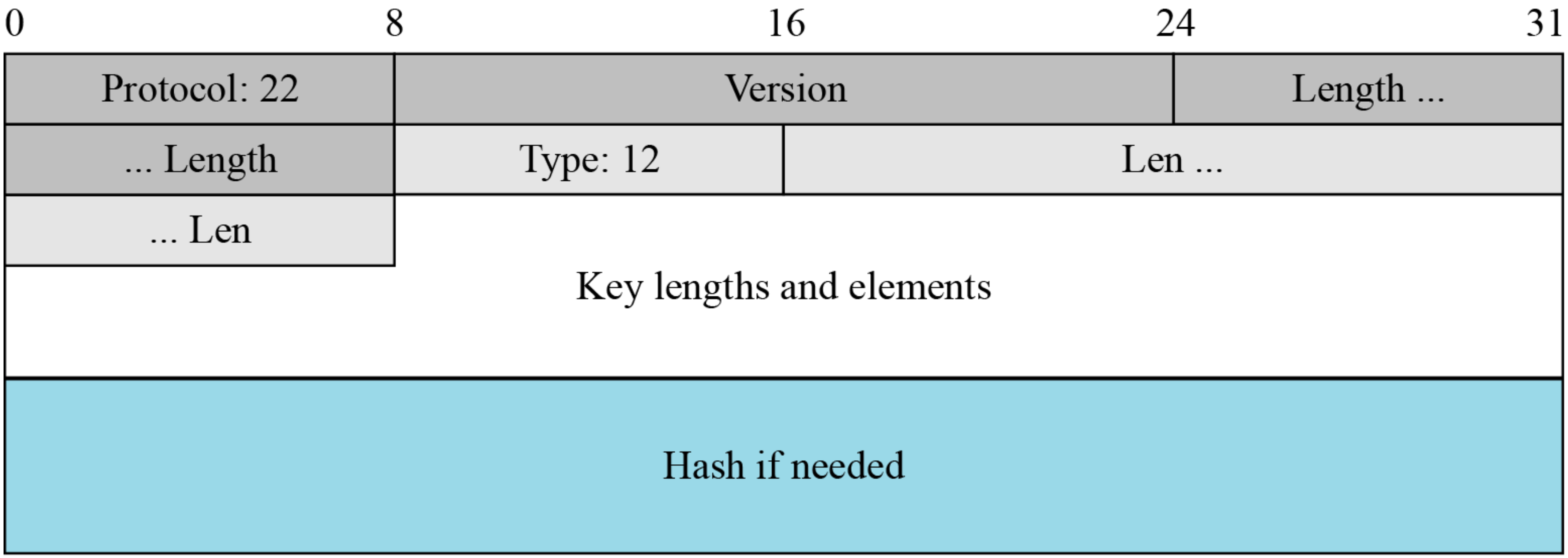
•••

Certificate *N* len

Certificate *N*
(variable length)

17.3.3 Continued

Figure 17.31 *ServerKeyExchange message*



0 8 16 24 31

Protocol: 22

Version

Length ...

... Length

Type: 12

Len ...

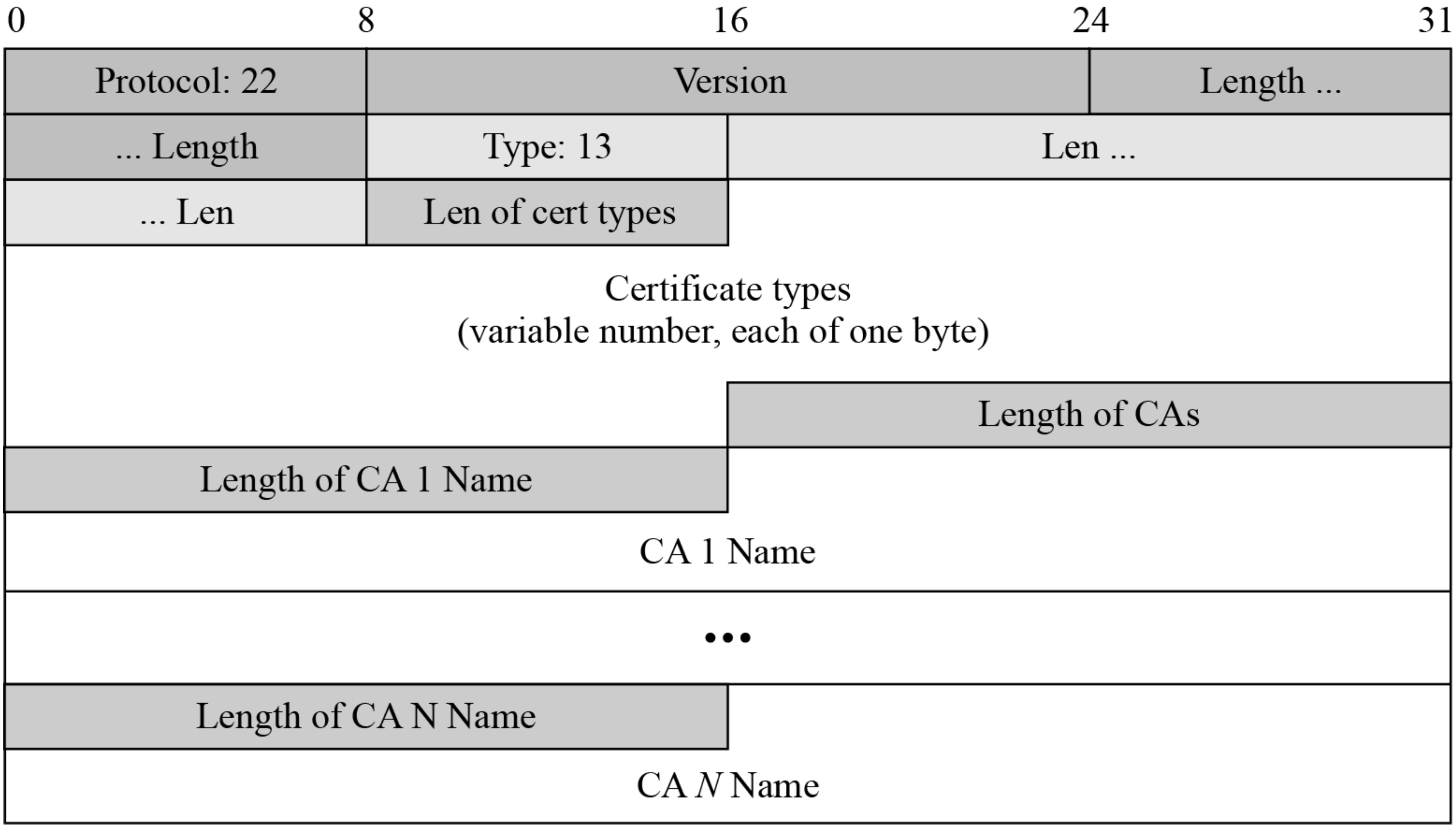
... Len

Key lengths and elements

Hash if needed

17.3.3 Continued

Figure 17.32 *CertificateRequest message*



0
8
16
24
31

Protocol: 22
Version
Length ...

... Length
Type: 13
Len ...

... Len
Len of cert types

Certificate types
(variable number, each of one byte)

Length of CAs

Length of CA 1 Name

CA 1 Name

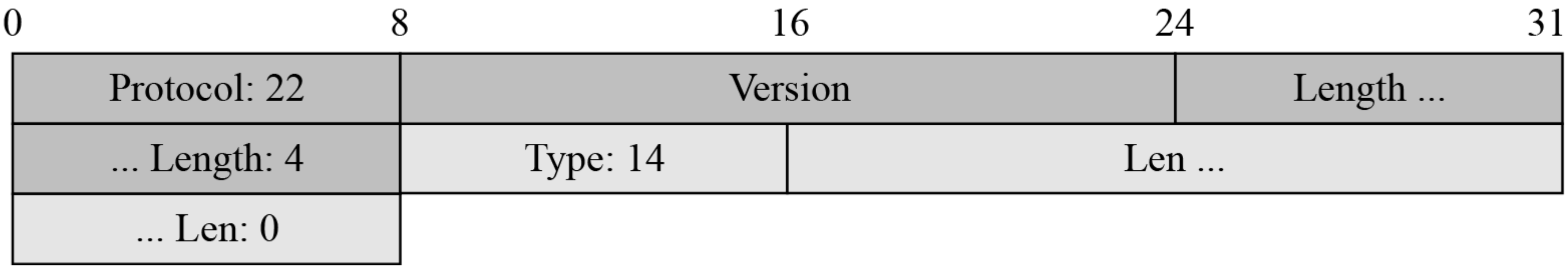
•••

Length of CA N Name

CA *N* Name

17.3.3 Continued

Figure 17.33 *ServerHelloDone message*

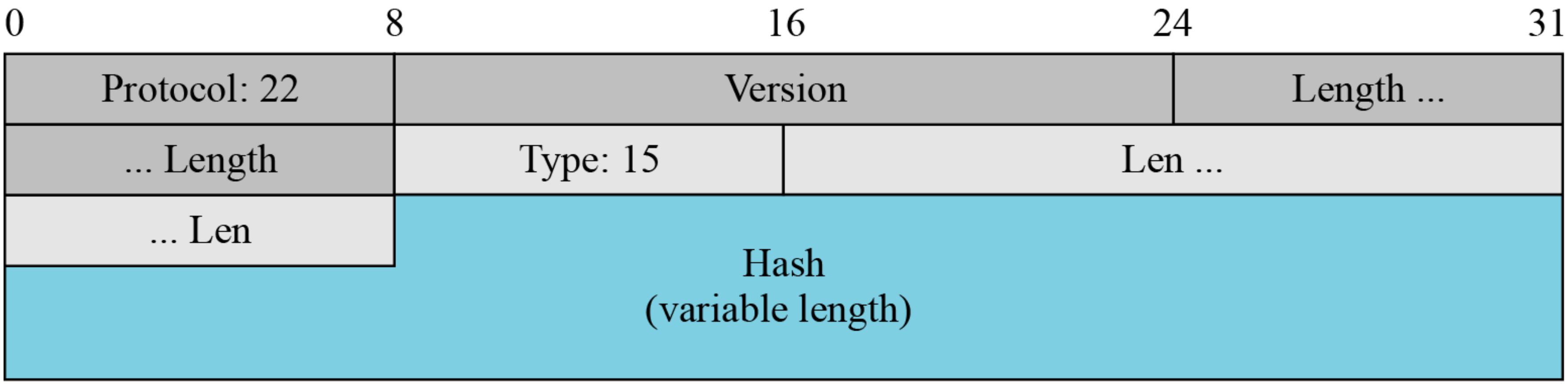


0
8
16
24
31

Protocol: 22
Version
Length ...
... Length: 4
Type: 14
Len ...
... Len: 0

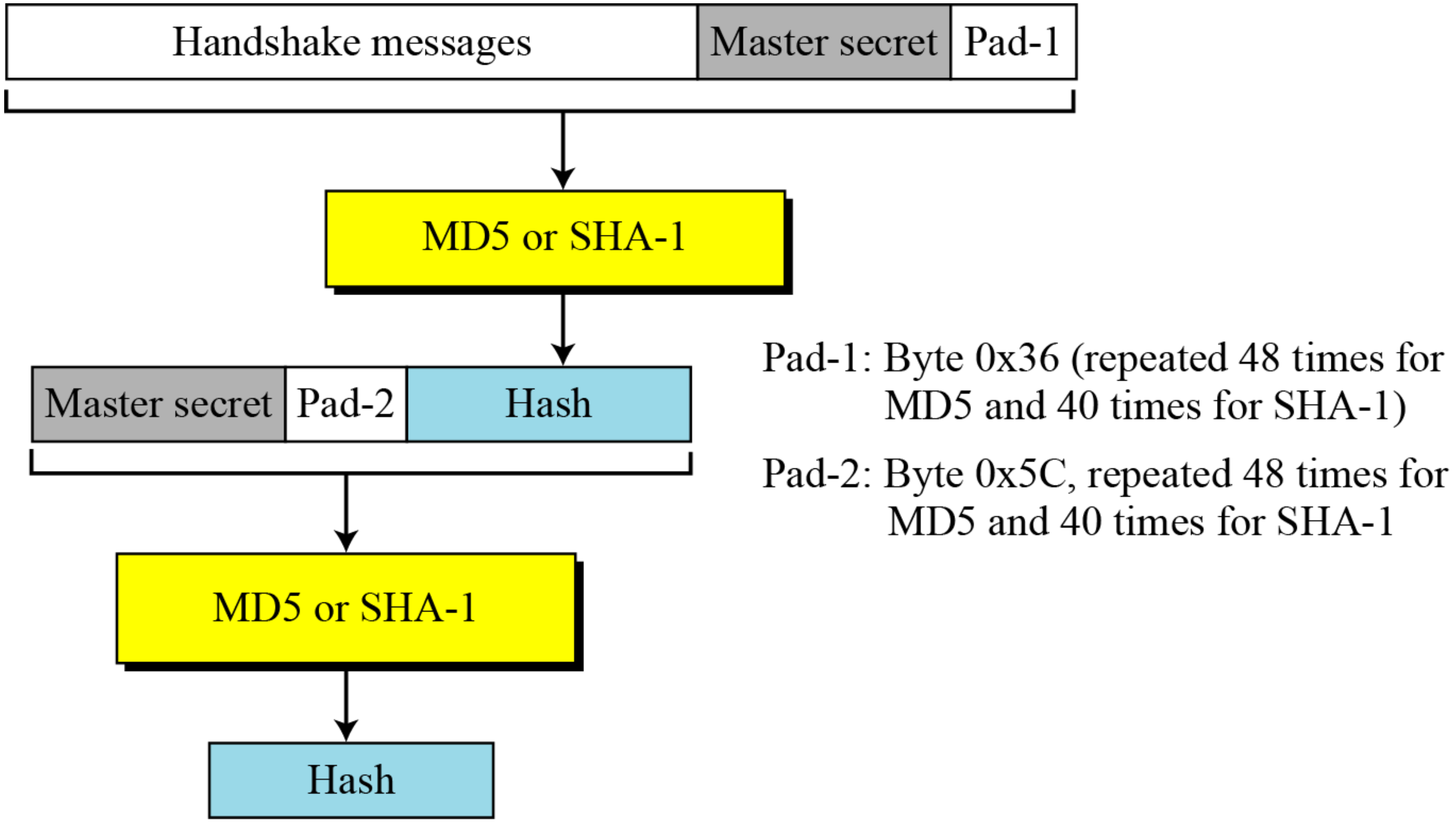
17.3.3 Continued

Figure 17.34 *CertificateVerify message*



17.3.3 Continued

Figure 17.35 *Hash calculation for CertificateVerify message*

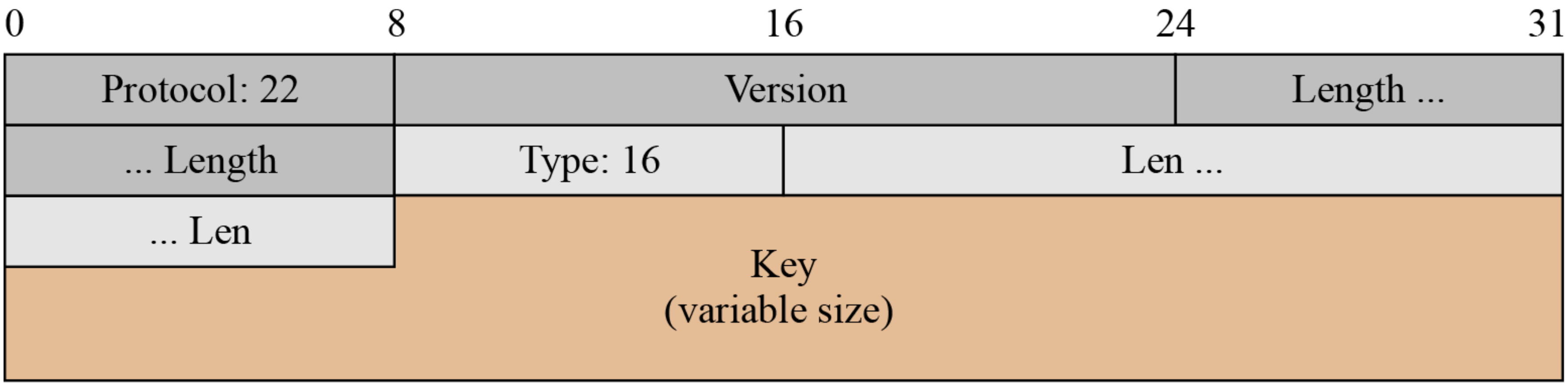


Pad-1: Byte 0x36 (repeated 48 times for MD5 and 40 times for SHA-1)

Pad-2: Byte 0x5C, repeated 48 times for MD5 and 40 times for SHA-1

17.3.3 Continued

Figure 17.36 *ClientKeyExchange message*



0 8 16 24 31

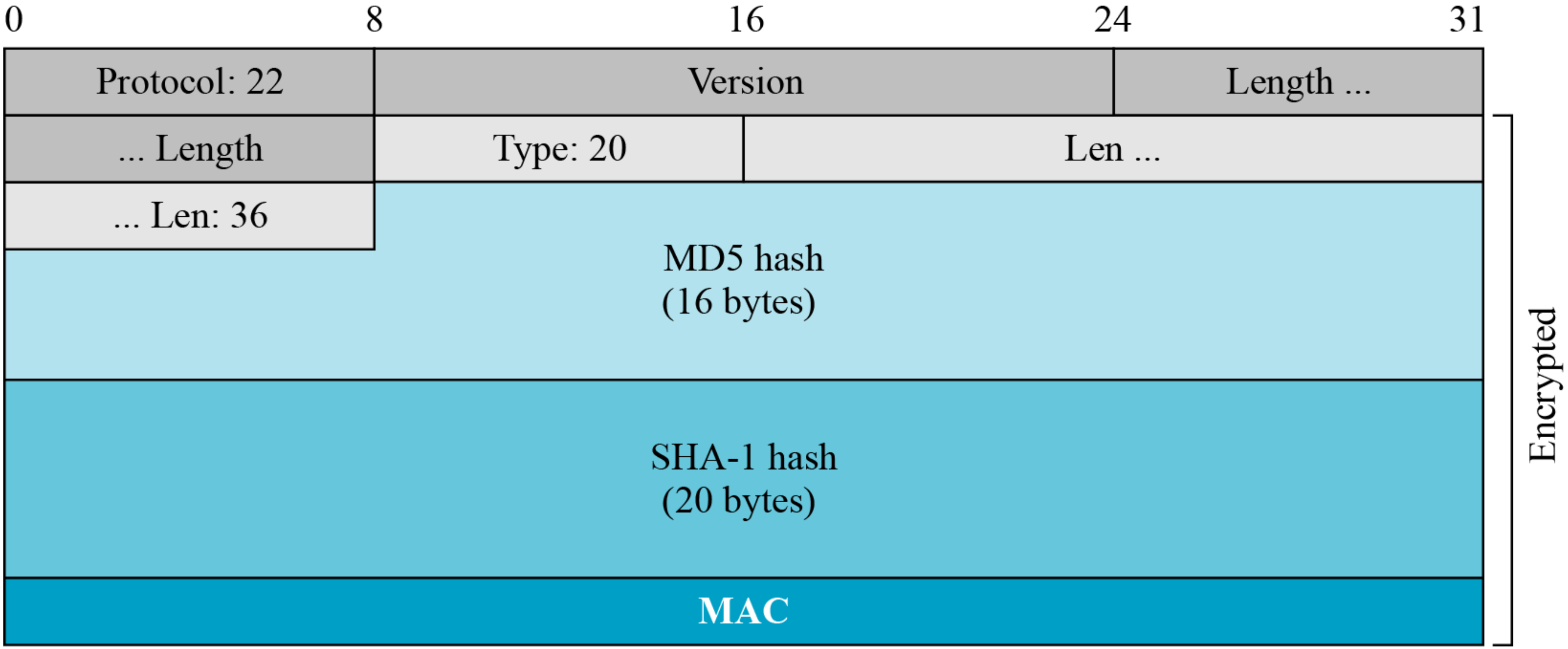
Protocol: 22
Version
Length ...

... Length
Type: 16
Len ...

... Len
Key
(variable size)

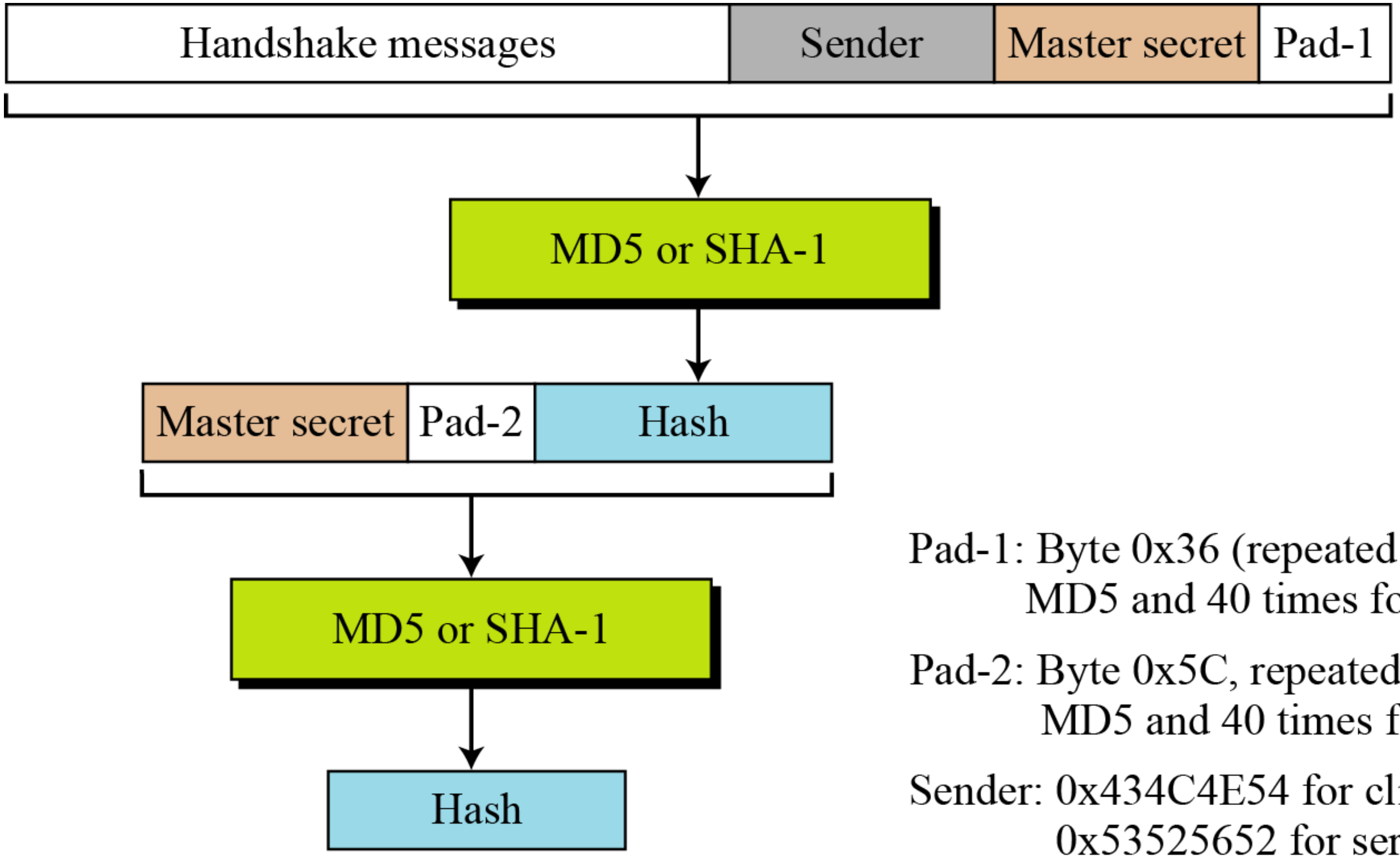
17.3.3 Continued

Figure 17.37 *Finished message*



17.3.3 Continued

Figure 17.38 *Hash calculation for Finished message*



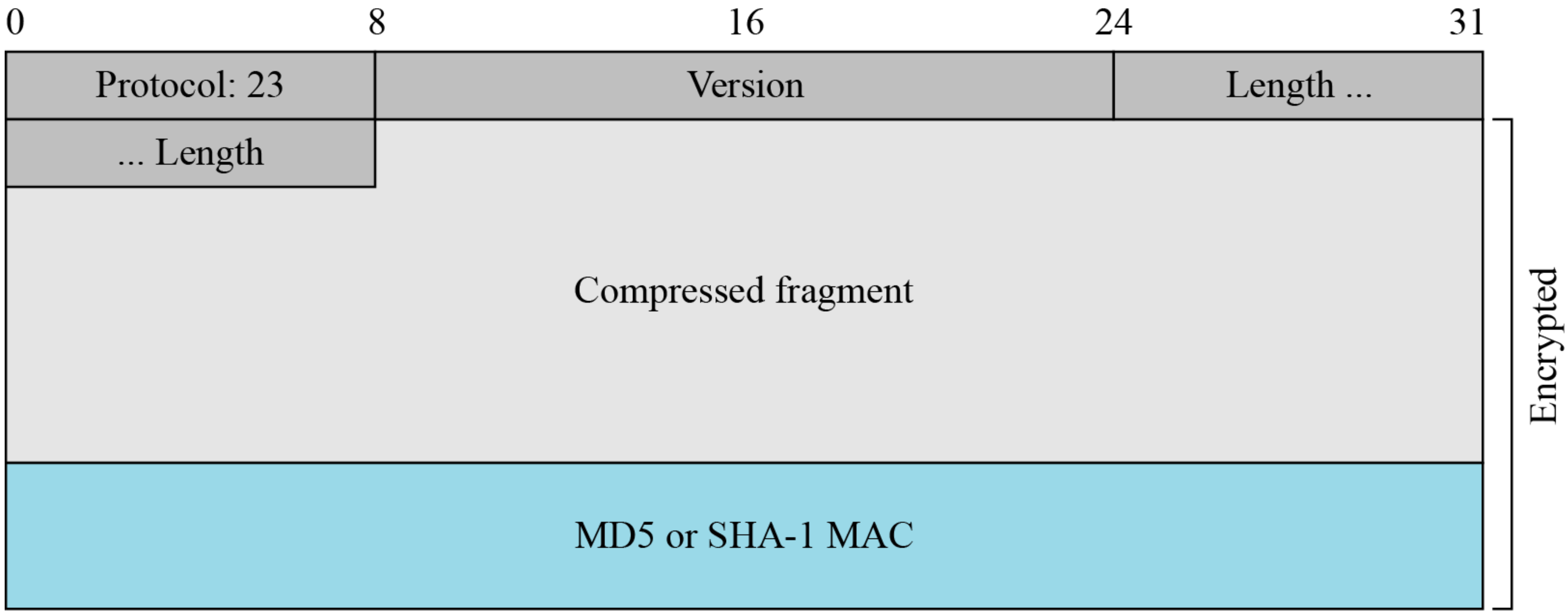
Pad-1: Byte 0x36 (repeated 48 times for MD5 and 40 times for SHA-1)

Pad-2: Byte 0x5C, repeated 48 times for MD5 and 40 times for SHA-1

Sender: 0x434C4E54 for client;
0x53525652 for server

17.3.3 Application Data

Figure 17.39 ***Record Protocol message for application data***



0 8 16 24 31

Protocol: 23

Version

Length ...

... Length

Compressed fragment

MD5 or SHA-1 MAC

Encrypted

17-4 Transport Layer Security (TLS)

The Transport Layer Security (TLS) protocol is the IETF standard version of the SSL protocol. The two are very similar, with slight differences.

Topics discussed in this section:

17.4.1 Version
17.4.2 Cipher Suite
17.4.3 Generation of Cryptographic Secrets
17.4.4 Alert Protocol
17.4.5 Handshake Protocol
17.4.6 Record Protocol

17.4.1 Version

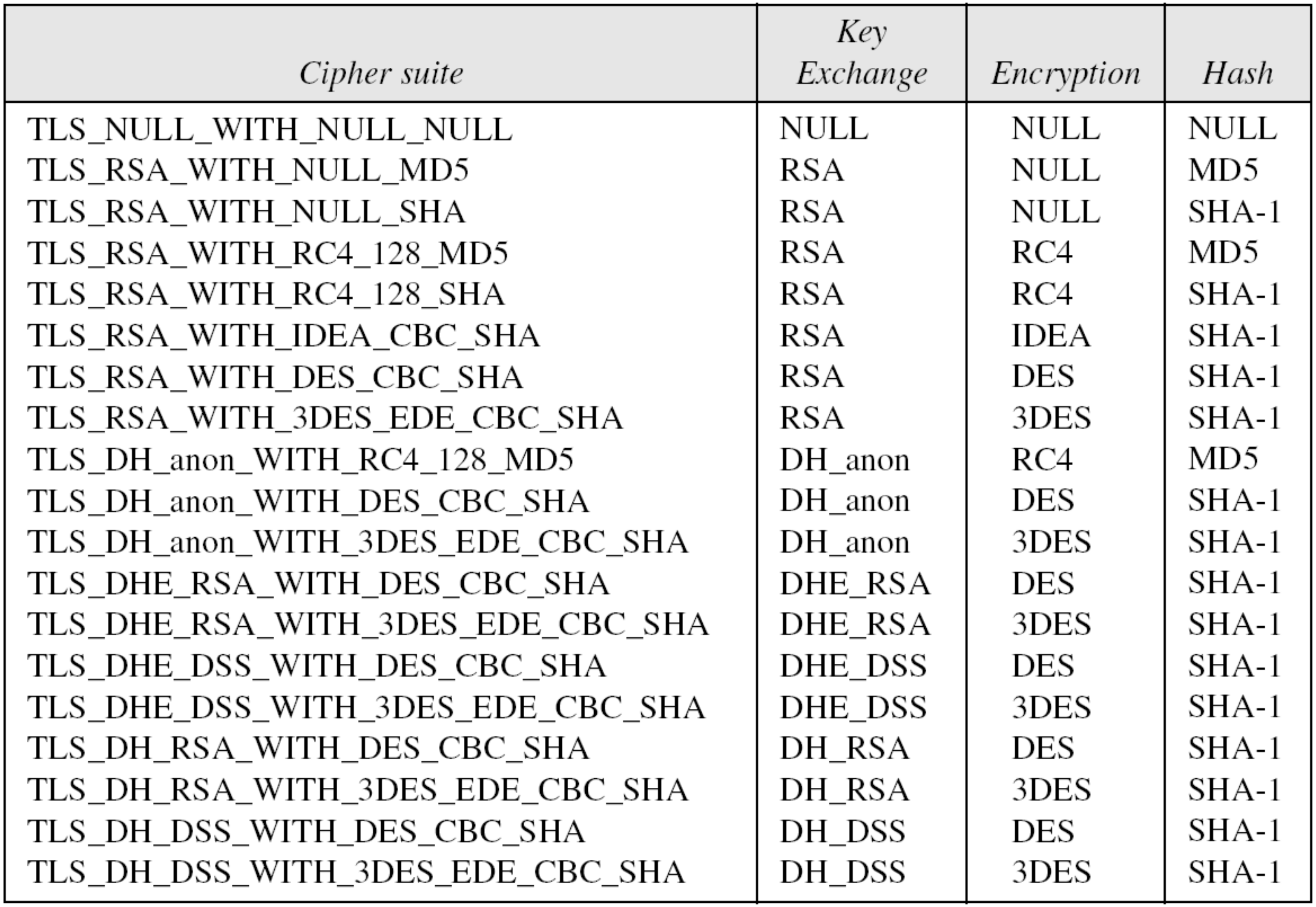
The first difference is the version number (major and minor). The current version of SSL is 3.0; the current version of TLS is 1.0. In other words, SSLv3.0 is compatible with TLSv1.0.

17.4.2 Cipher Suite

Another minor difference between SSL and TLS is the lack of support for the Fortezza method. TLS does not support Fortezza for key exchange or for encryption/decryption. Table 17.6 shows the cipher suite list for TLS (without export entries).

17.4.2 Continued

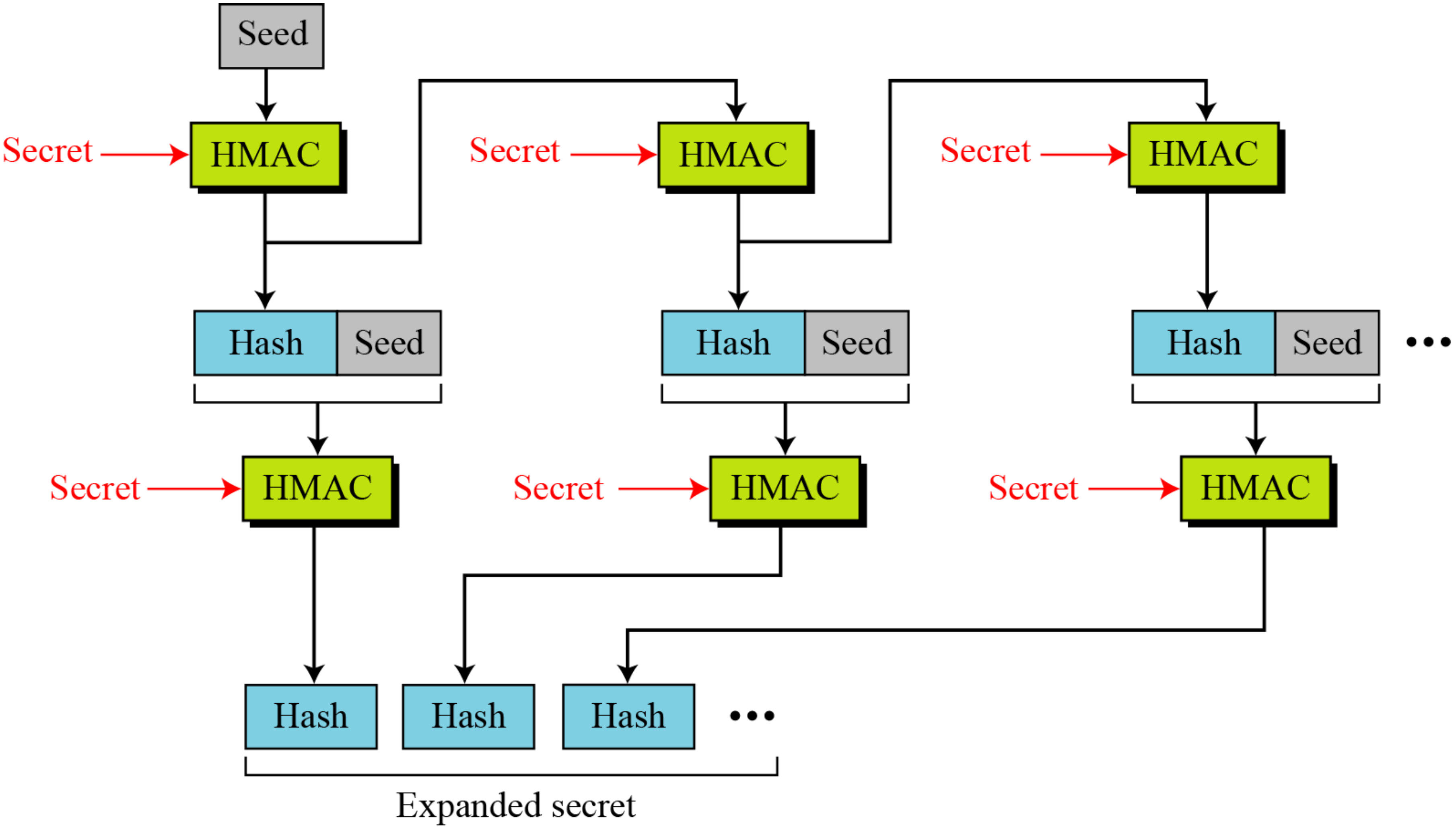
Table 17.6 ***Cipher Suite for TLS***



Cipher suite	*Key Exchange*	*Encryption*	*Hash*
TLS_NULL_WITH_NULL_NULL	NULL	NULL	NULL
TLS_RSA_WITH_NULL_MD5	RSA	NULL	MD5
TLS_RSA_WITH_NULL_SHA	RSA	NULL	SHA-1
TLS_RSA_WITH_RC4_128_MD5	RSA	RC4	MD5
TLS_RSA_WITH_RC4_128_SHA	RSA	RC4	SHA-1
TLS_RSA_WITH_IDEA_CBC_SHA	RSA	IDEA	SHA-1
TLS_RSA_WITH_DES_CBC_SHA	RSA	DES	SHA-1
TLS_RSA_WITH_3DES_EDE_CBC_SHA	RSA	3DES	SHA-1
TLS_DH_anon_WITH_RC4_128_MD5	DH_anon	RC4	MD5
TLS_DH_anon_WITH_DES_CBC_SHA	DH_anon	DES	SHA-1
TLS_DH_anon_WITH_3DES_EDE_CBC_SHA	DH_anon	3DES	SHA-1
TLS_DHE_RSA_WITH_DES_CBC_SHA	DHE_RSA	DES	SHA-1
TLS_DHE_RSA_WITH_3DES_EDE_CBC_SHA	DHE_RSA	3DES	SHA-1
TLS_DHE_DSS_WITH_DES_CBC_SHA	DHE_DSS	DES	SHA-1
TLS_DHE_DSS_WITH_3DES_EDE_CBC_SHA	DHE_DSS	3DES	SHA-1
TLS_DH_RSA_WITH_DES_CBC_SHA	DH_RSA	DES	SHA-1
TLS_DH_RSA_WITH_3DES_EDE_CBC_SHA	DH_RSA	3DES	SHA-1
TLS_DH_DSS_WITH_DES_CBC_SHA	DH_DSS	DES	SHA-1
TLS_DH_DSS_WITH_3DES_EDE_CBC_SHA	DH_DSS	3DES	SHA-1

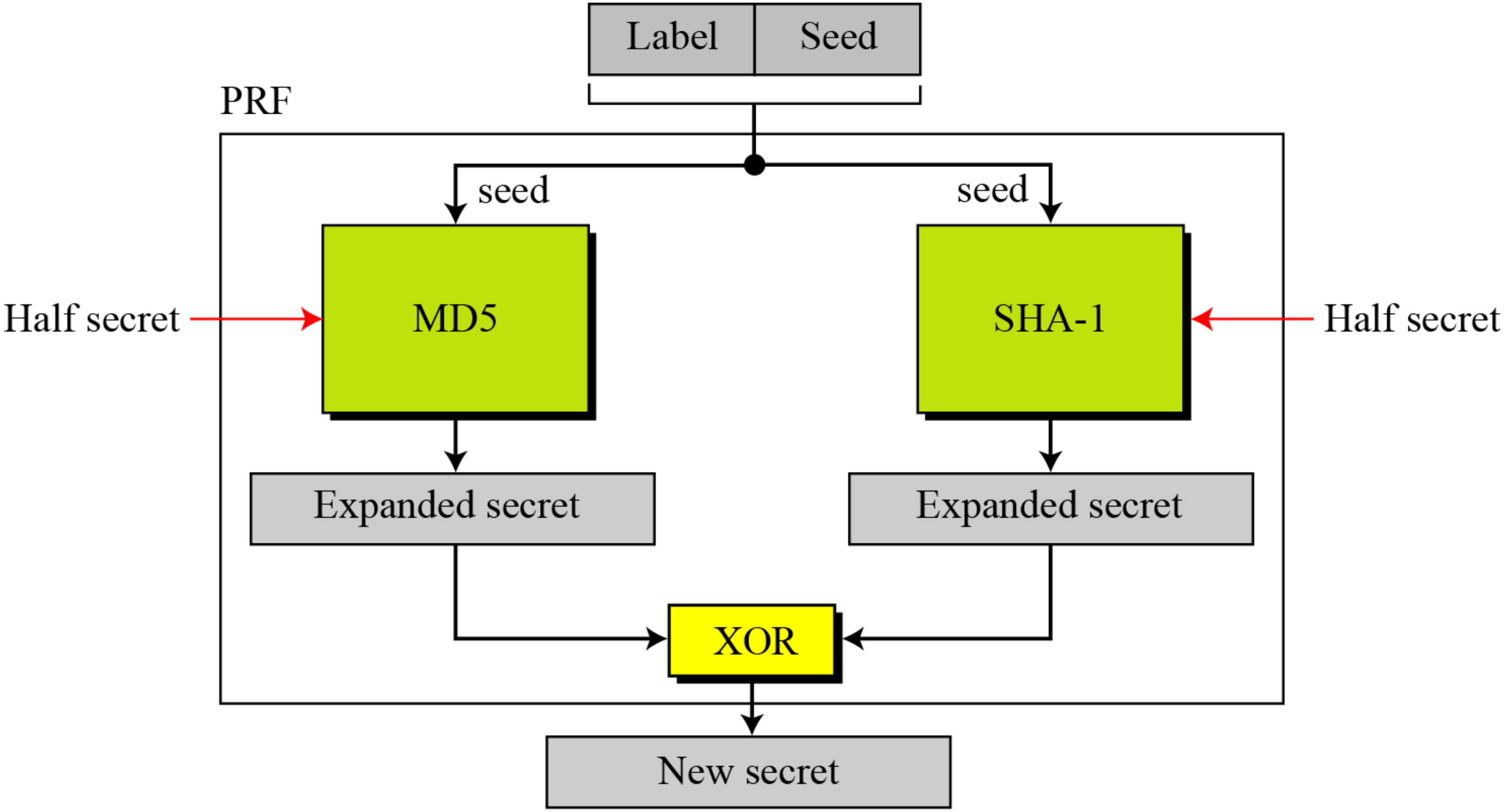
17.4.3 Generation of Cryptographic Secrets

Figure 17.40 ***Data-expansion function***



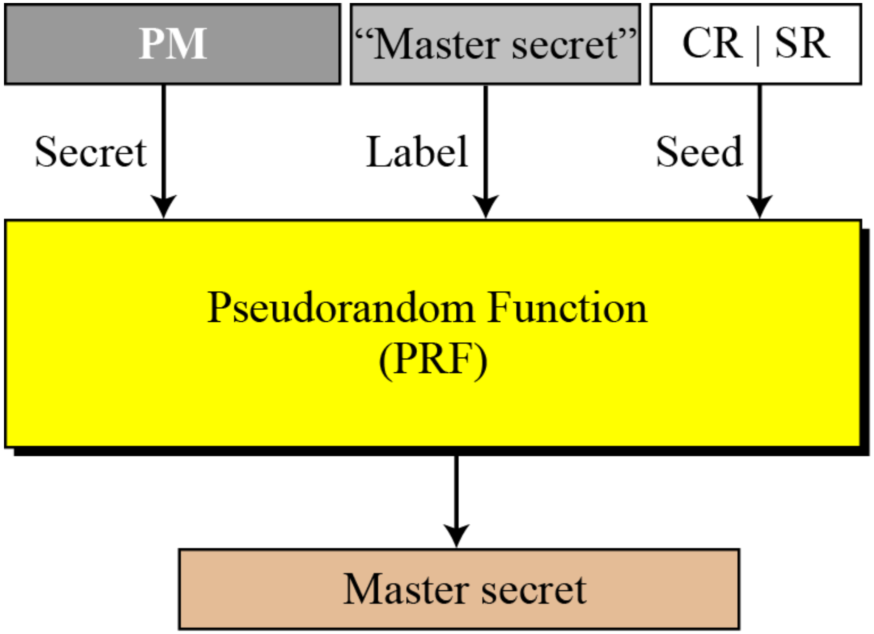
17.4.3 Continued

Figure 17.41 *PRF*



17.4.3 Continued

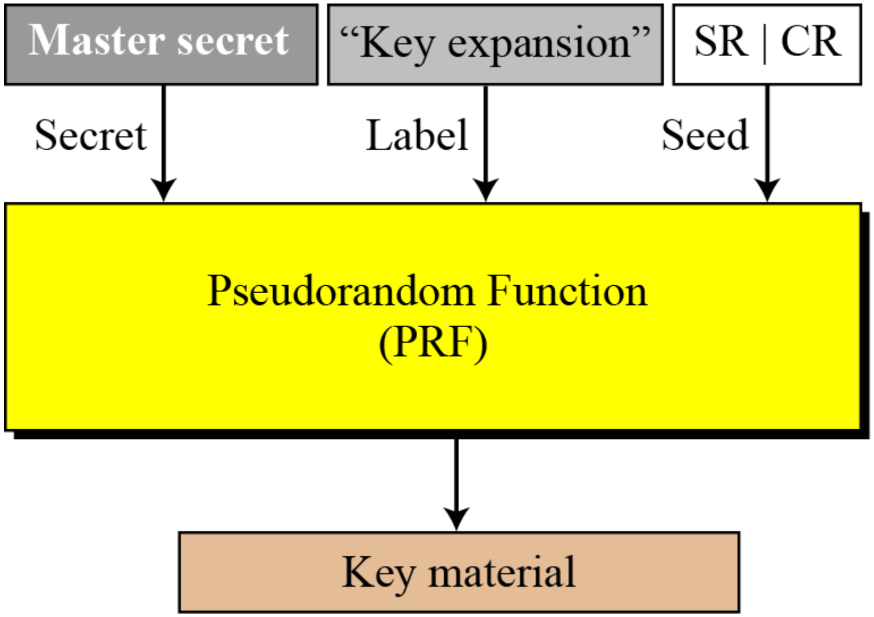
Figure 17.42 *Master secret generation*



PM: Pre-master Secret
CR: Client Random Number
SR: Server Random Number
|: Concatenation

17.4.3 Continued

Figure 17.43 *Key material generation*



CR: Client Random Number

SR: Server Random Number

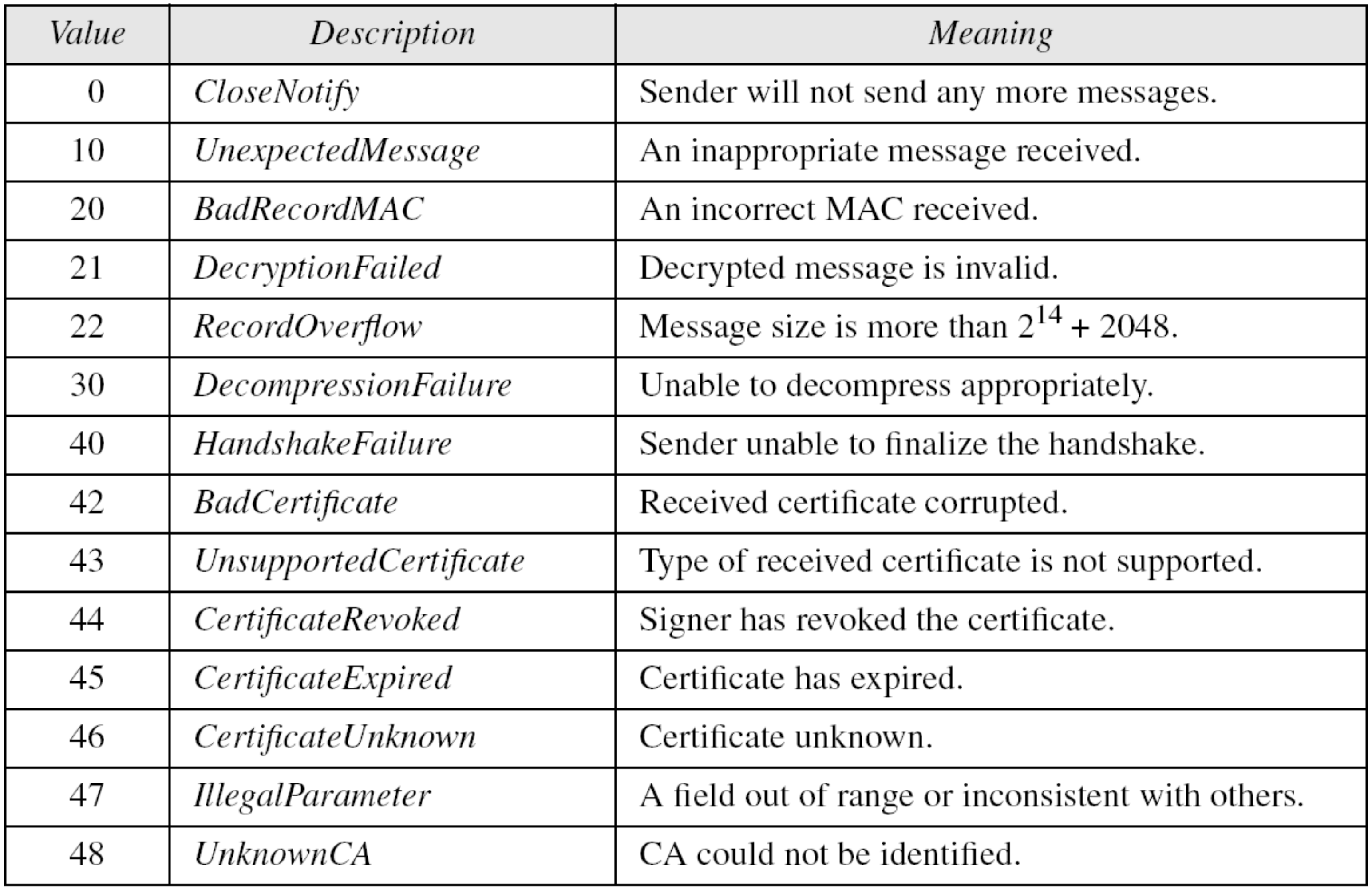
|: Concatenation

17.4.4 Alert Protocol

TLS supports all of the alerts defined in SSL except for NoCertificate. TLS also adds some new ones to the list. Table 17.7 shows the full list of alerts supported by TLS.

17.4.4 Continued

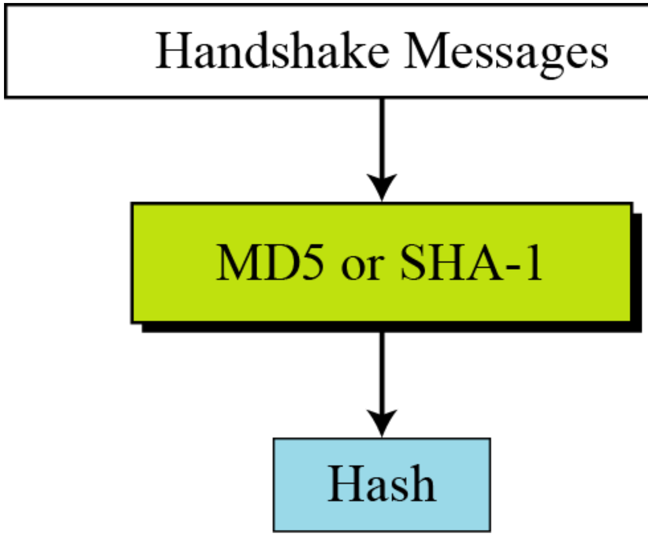
Table 17.7 ***Alerts defined for TLS***



Value	*Description*	*Meaning*
0	*CloseNotify*	Sender will not send any more messages.
10	*UnexpectedMessage*	An inappropriate message received.
20	*BadRecordMAC*	An incorrect MAC received.
21	*DecryptionFailed*	Decrypted message is invalid.
22	*RecordOverflow*	Message size is more than $2^{14} + 2048$.
30	*DecompressionFailure*	Unable to decompress appropriately.
40	*HandshakeFailure*	Sender unable to finalize the handshake.
42	*BadCertificate*	Received certificate corrupted.
43	*UnsupportedCertificate*	Type of received certificate is not supported.
44	*CertificateRevoked*	Signer has revoked the certificate.
45	*CertificateExpired*	Certificate has expired.
46	*CertificateUnknown*	Certificate unknown.
47	*IllegalParameter*	A field out of range or inconsistent with others.
48	*UnknownCA*	CA could not be identified.

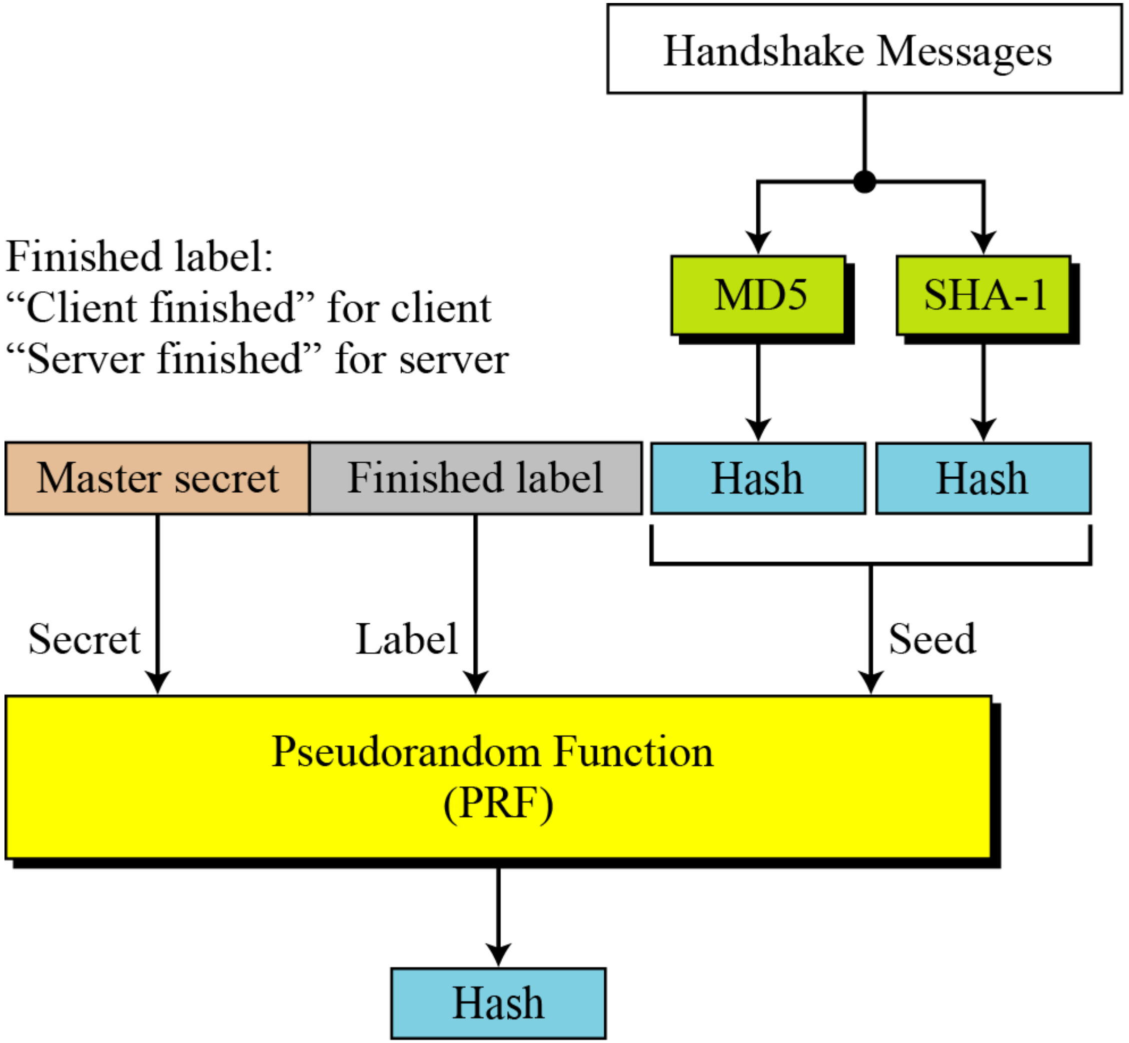
17.4.5 Handshake Protocol

Figure 17.44 ***Hash for CertificateVerify message in TLS***



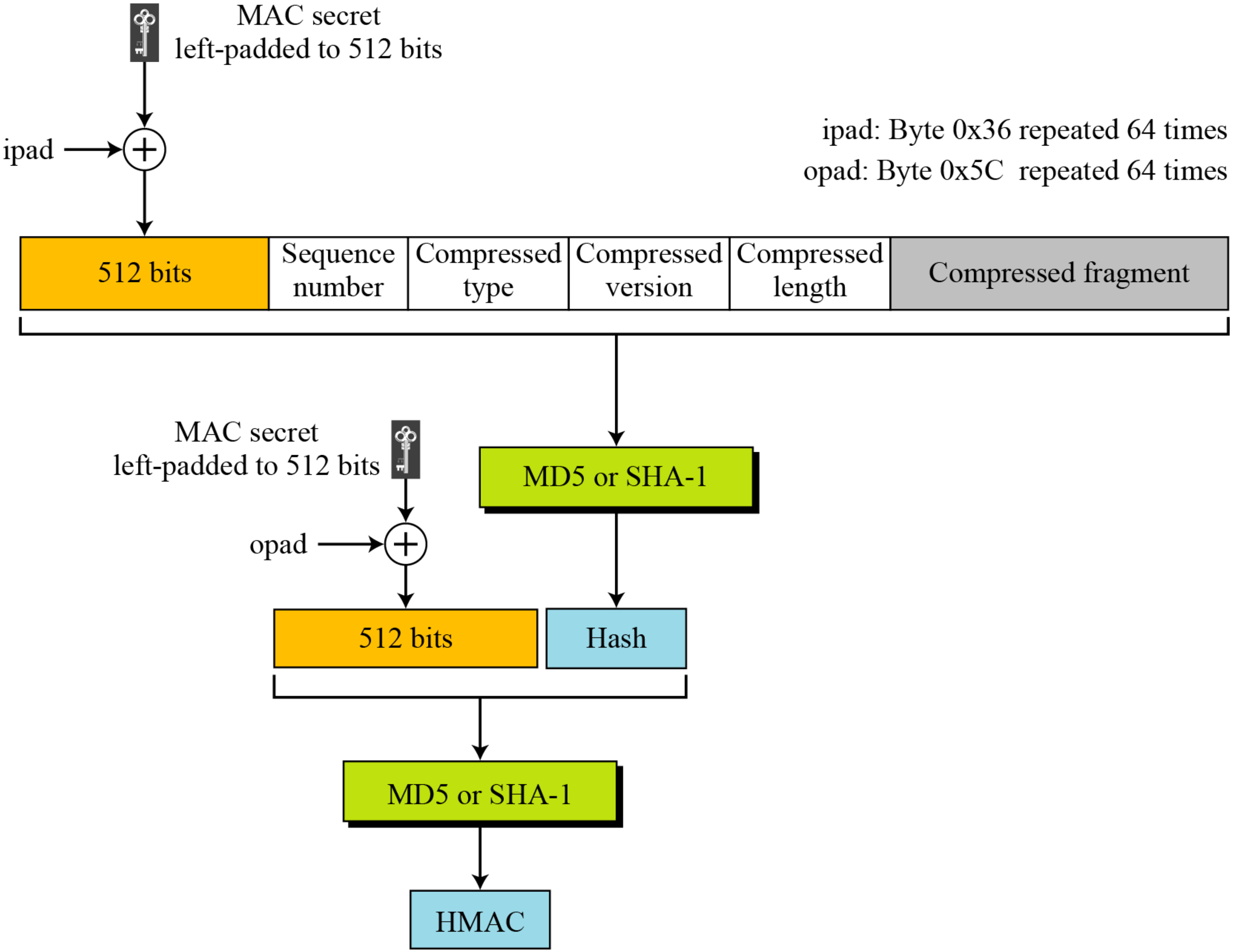
17.4.5 Continued

Figure 17.45 *Hash for Finished message in TLS*



17.4.6 Record Protocol

Figure 17.46 *HMAC for TLS*



MAC secret
left-padded to 512 bits
ipad
ipad: Byte 0x36 repeated 64 times
opad: Byte 0x5C repeated 64 times
512 bits
Sequence number
Compressed type
Compressed version
Compressed length
Compressed fragment
MAC secret
left-padded to 512 bits
MD5 or SHA-1
opad
512 bits
Hash
MD5 or SHA-1
HMAC