Network Security

Dr. Xiqun Lu
College of Computer Science
Zhejiang University

Three Important Things for Encryption

- Encryption key (Code, pseudo-random sequence generator: fast, repeated)
- Secure key exchange
- Encryption algorithm (Encode/Decode)

The Encryption Model

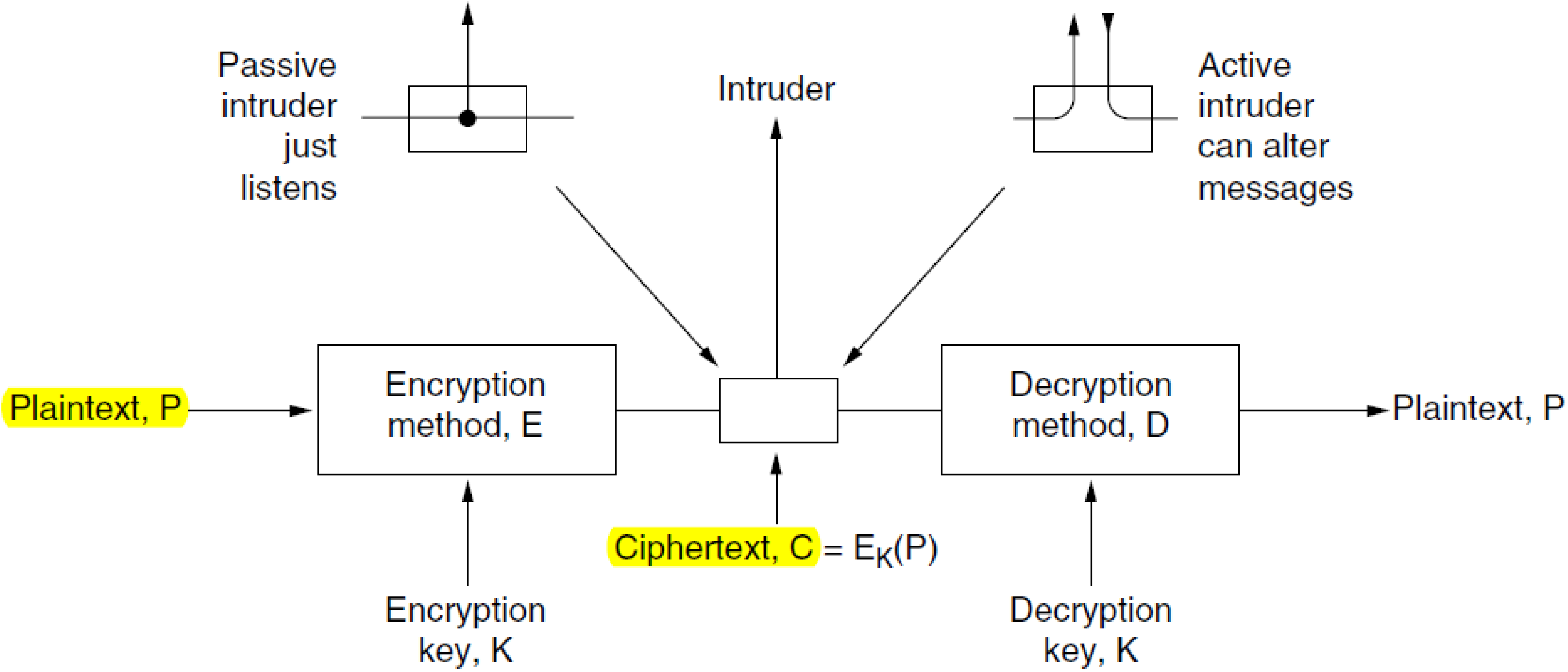


Figure 8-2. The encryption model (for a symmetric-key cipher).

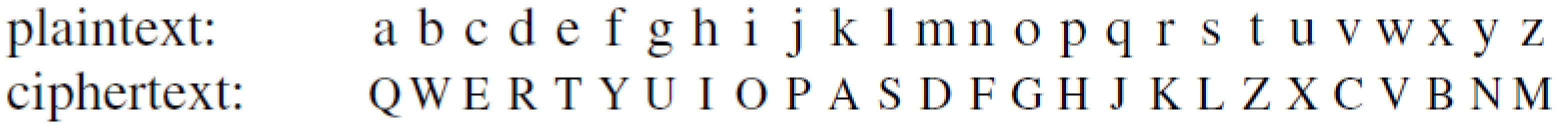
- **Passive intrude** only listen to the communication channel
- **Active intrude** not only listen to the communication channel, but can also record messages and play them back later, inject his own messages, or modified legitimate messages before they get to the receiver.

The Encryption Methods

- Kerckhoff's principle: **All algorithms must be public; only the keys are secret**.
- The longer the key, the higher the work factor the cryptanalyst has to deal with.
  - The work factor for breaking the system by exhaustive search of the key space is *exponential* in the key length.
- From the cryptanalyst's point of view, the cryptanalysis problem as three principal variations:
  - The ciphertext only problem: no plaintext but has a quantity of ciphertext
  - The known plaintext problem: has some matched ciphertext and plaintext.
  - The chosen plaintext problem: the cryptanalyst has the ability to encrypt pieces of plaintext of his own choosing.
- Encryption methods can be divided into *two categories*: **substitution ciphers** and **transposition ciphers**.

Substitution Ciphers

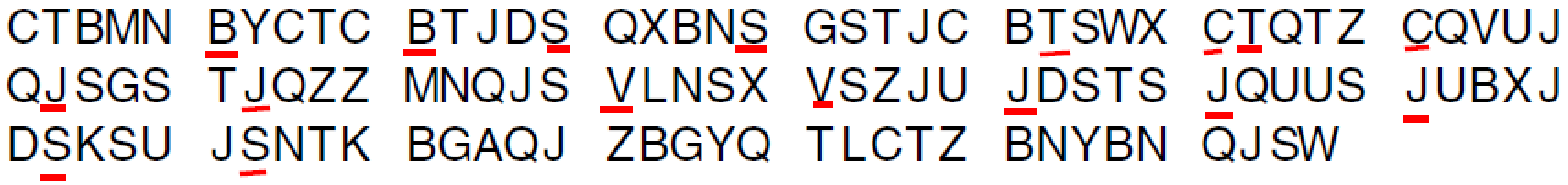
- In a substitution cipher, each letter or group of letters is replaced by another letter or group of letters to disguise it.
- **Caesar cipher** (attribute to Julius Caesar): for example, a becomes D, b becomes E, c becomes F, …, and z becomes C. so “attack” becomes DWWDFN.
  - A slight generalization of the Caesar cipher allows the ciphertext alphabet *to be shifted by k letters*, instead of always three. In this case, ***k* becomes a key** to the general method of circularly shifted alphabets.
  - The next improvement is to have each of the symbols in the plaintext



plaintext:	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z
ciphertext:	Q	W	E	R	T	Y	U	I	O	P	A	S	D	F	G	H	J	K	L	Z	X	C	V	B	N	M

Substitution Ciphers

- The basic attack takes advantage of the statistical properties of natural languages.
  - In English, for example, *e* is the most common letter, followed by *t*, *o*, *a*, *n*, *i*, etc. the most common two-letter combinations, or digrams, are *th*, *in*, *er*, *re*, and *an*. The most common three-letter combinations, or trigrams are *the*, *ing*, *and*, and *ion*.
  - For example, consider the following ciphertext from an accounting firm:



```
CTBMN BYCTC BTJDS QXBNS GSTJC BTSWX CTQTZ CQVUJ
QJSGS TJQZZ MNQJS VLNSX VSZJU JDSTS JQUUS JUBXJ
DSKSU JSNTK BGAQJ ZBGYQ TLCTZ BNYBN QJSW
```

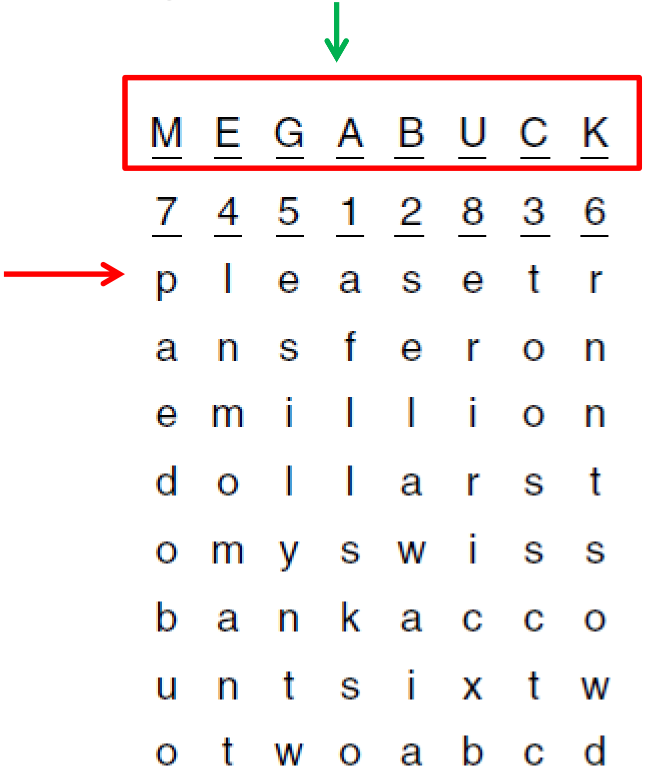
  - A likely word in a message from an accounting firm is “financial”.

CTQTZ CQVUJ: C → *i*, T → *n*, Q → *a* 这里两个重复出现字母中间有4个其它字母的组合很多，但是如果按照“financial”，只有第一行最后两块符合要求。(Z → c)

Transposition Ciphers

- Substitution ciphers preserve the order of the plaintext symbols but disguise them.
- Transposition ciphers, in contrast, reorder the letters but do not disguise them.

The cipher is keyed by a word or phrase **not** containing any repeated letters.



M	E	G	A	B	U	C	K
7	4	5	1	2	8	3	6
p	l	e	a	s	e	t	r
a	n	s	f	e	r	o	n
e	m	i	l	l	i	o	n
d	o	l	l	a	r	s	t
o	m	y	s	w	i	s	s
b	a	n	k	a	c	c	o
u	n	t	s	i	x	t	w
o	t	w	o	a	b	c	d

Plaintext

pleasetransferonemilliondollarsto
myswissbankaccountsixtwotwo

Ciphertext

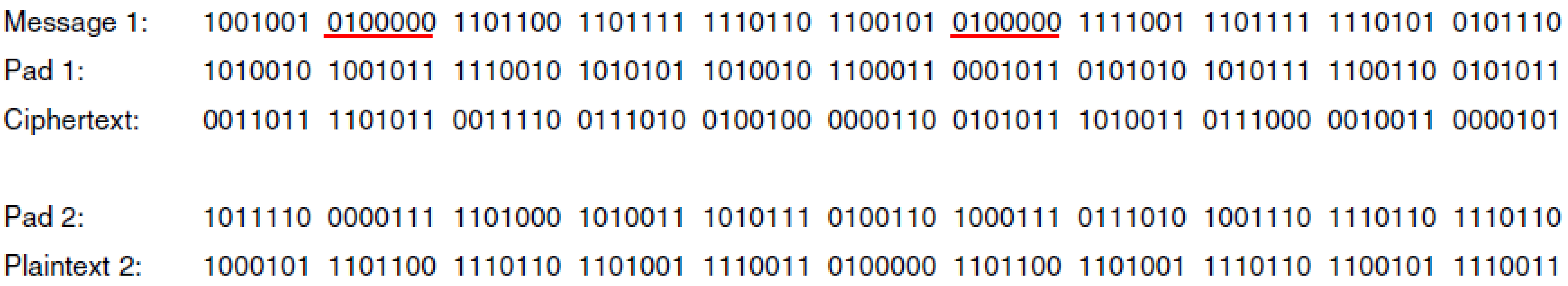
AFLLSKSOSELAWAIATOOSSCTCLNMOMANT
ESILYNTWRNNTSOWDPAEDOBUOERIRICXB

Transposition Ciphers

- 1) To break a transposition cipher, the cryptanalyst must first be aware that he is dealing with a transposition cipher.
  - By looking at the frequency of *E*, *T*, *O*, *A*, *N*, *I* etc., it is easy to see if they fit the normal pattern of plaintext.
- 2) The next step is to make the guess at the number of columns (the key length).
  - In many cases, a probable word or phrase may be guessed at from the context.
- 3) The remaining step is to order the columns.
  - When the number of columns k is small, each of the $k(k-1)$ column pairs can be examined in turn to see if its digram frequencies match those for English plaintext. The pair with the best match is assumed to be correctly positioned. Now each of the remaining columns is tentatively tried as the successor to this pair.

One-Time Pads*

- First choose a random bit string as the key. Then convert the plaintext into a bit string, for example, by using its ASCII representation. Finally, compute the XOR of these two strings, bit by bit.
- The resulting ciphertext cannot be broken because in a sufficiently large sample of ciphertext, each letter will occur equally often, as will every digram, every trigram, and so on.
  - The reason derives from information theory: there is simply no information in the message because all possible plaintexts of the given length are equally likely.



Message 1:	1001001	0100000	1101100	1101111	1110110	1100101	0100000	1111001	1101111	1110101	0101110
Pad 1:	1010010	1001011	1110010	1010101	1010010	1100011	0001011	0101010	1010111	1100110	0101011
Ciphertext:	0011011	1101011	0011110	0111010	0100100	0000110	0101011	1010011	0111000	0010011	0000101
Pad 2:	1011110	0000111	1101000	1010011	1010111	0100110	1000111	0111010	1001110	1110110	1110110
Plaintext 2:	1000101	1101100	1110110	1101001	1110011	0100000	1101100	1101001	1110110	1100101	1110011

Figure 8-4. The use of a one-time pad for encryption and the possibility of getting any possible plaintext from the ciphertext by the use of some other pad.

One-Time Pads*

- One-time pads are great in theory but have a number of **disadvantages** in practice.
  - The key cannot be memorized, so both sender and receiver must carry a written copy with them.
  - The total amount of data that can be transmitted is limited by the amount of key available.
  - Another problem is the sensitivity of the method to lost or inserted characters.

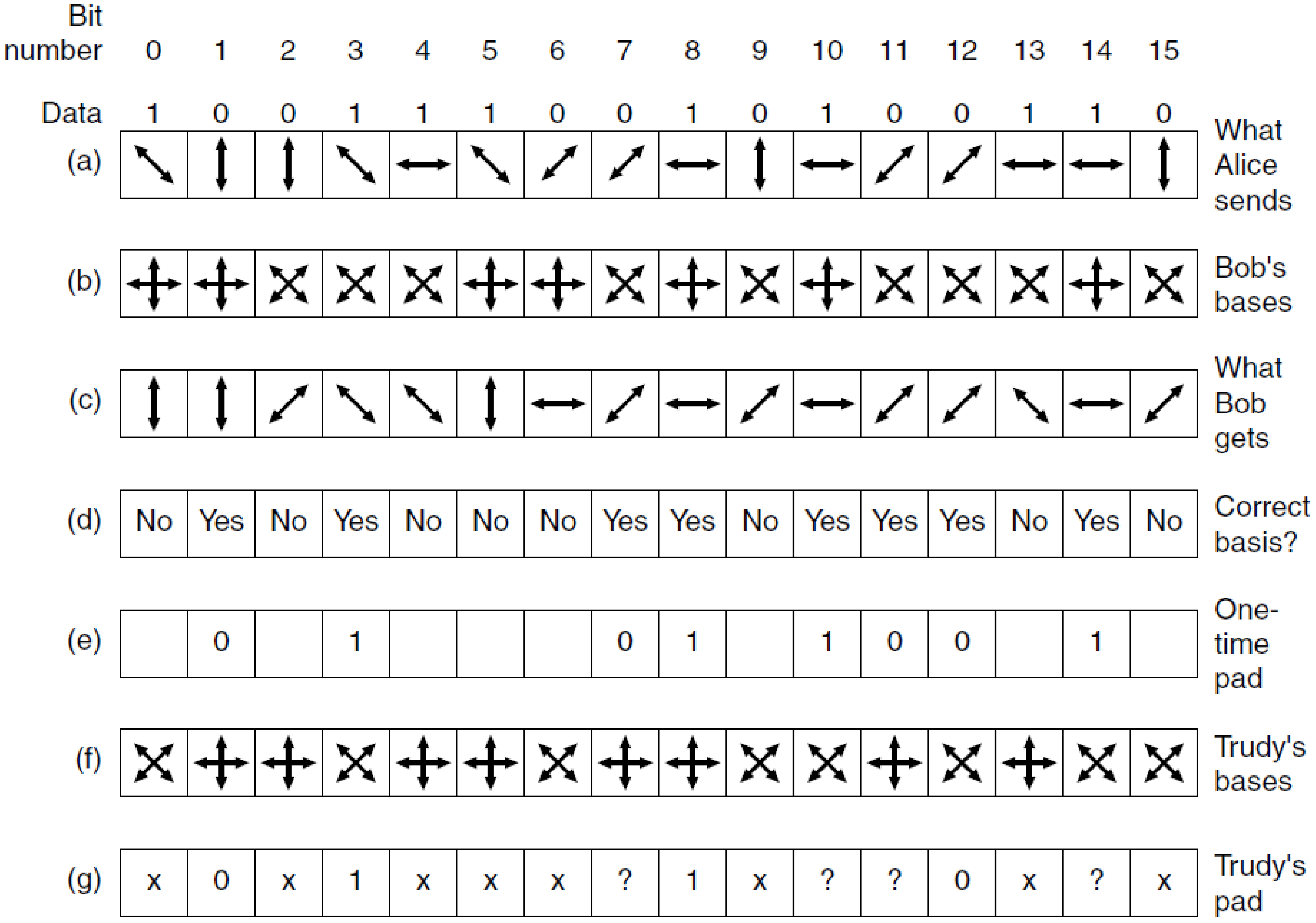
Quantum Cryptography*

- BB84 (Bennet and Brassard 1984)
- Quantum cryptograph is based on the fact that light comes in little packets called **photons**, which have some peculiar properties.
- Light can be polarized by being pass through a polarizing filter.
  - If a beam of light is passed through a polarizing filter, all the photons emerging from it will be polarized in the direction of the filter's axis. If the beam is now passed through a second polarizing filter, the intensity of the light emerging from the second filter is proportional to the square of the cosine of the angle between the axes. If the two axes are **perpendicular**, no photons get through.
- Bits sent one photon at a time are called **qubits**.

Quantum Cryptography*

- To generate a one-time pad, Alice needs two sets of polarizing filters: one is a rectilinear basis (one vertical filter and one horizontal filter), and the other is a diagonal basis.
  - In reality, Alice does not have four separate filters, but a crystal whose polarization can be switched electrically to any of the four allowed directions at great speed.
  - For each basis, Alice assigns one direction as 0 and the other as 1.
  - Now Alice picks a one-time pad, for example based on a random number generator (a complex subject all by itself). She transfer it bit by bit to Bob, choosing one of her two bases at random for each bit.
  - To send a bit, her photon gun emits one photon polarized appropriately for the basis she is using for that bit.
  - Given the one-time pad and the sequence of the bases, the polarization to use for each bit is uniquely determined. Bits sent one photon at a time are called **qubits**.
- Bob has the same equipment as Alice.
- The fact that Alice and Bob each have two bases available is essential to quantum cryptography.

Quantum Cryptography*



Bit number	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Data	1	0	0	1	1	1	0	0	1	0	1	0	0	1	1	0	
(a)	⤡	↕	↕	⤡	↔	⤡	⤢	⤢	↔	↕	↔	⤢	⤢	↔	↔	↕	What Alice sends
(b)	✛	✛	✕	✕	✕	✛	✛	✕	✛	✕	✛	✕	✕	✕	✛	✕	Bob's bases
(c)	↕	↕	⤢	⤡	⤡	↕	↔	⤢	↔	⤢	↔	⤢	⤢	⤡	↔	⤢	What Bob gets
(d)	No	Yes	No	Yes	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No	Correct basis?
(e)		0		1				0	1		1	0	0		1		One-time pad
(f)	✕	✛	✛	✕	✛	✛	✕	✛	✛	✕	✕	✛	✕	✛	✕	✕	Trudy's bases
(g)	x	0	x	1	x	x	x	?	1	x	?	?	0	x	?	x	Trudy's pad

Figure 8-5. An example of quantum cryptography.

Bob does not know which bases to use, so he picks one **at random** for each arriving photon and just uses it. If he picks the incorrect basis, he gets a random bit because if a photon hits a filter polarized at 45 degrees to its own polarization, it randomly jumps to the polarization of the filter or a polarization perpendicular to the filter, with equal probability.

Quantum Cryptography*

- How does Bob find out which bases he got right and which he got wrong?
- He simply tells Alice which basis he used for each bit in plaintext and she tells him which are right and which are wrong in plaintext. From this information, both of them can build a bit string from the correct guesses.
- On the average, this bit string will be half the length of the original bit string, but since both parties know it, they can use it as a one-time pad. All Alice has to do is transmit a bit string slightly more than twice the desired length, and she and Bob will have a one-time pad of the desired length.

Two Fundamental Cryptographic Principles

- 1) All the encrypted messages must contain some *redundancy*.
- 2) Measures must be taken to ensure that each message received can be verified as being fresh.

Symmetric-Key Algorithms

- In **symmetric-key** algorithms, they use **the same key** for encryption and decryption.
- Block ciphers take an *n*-bit block of plaintext as input and transform it using the key into an *n*-bit block of ciphertext.

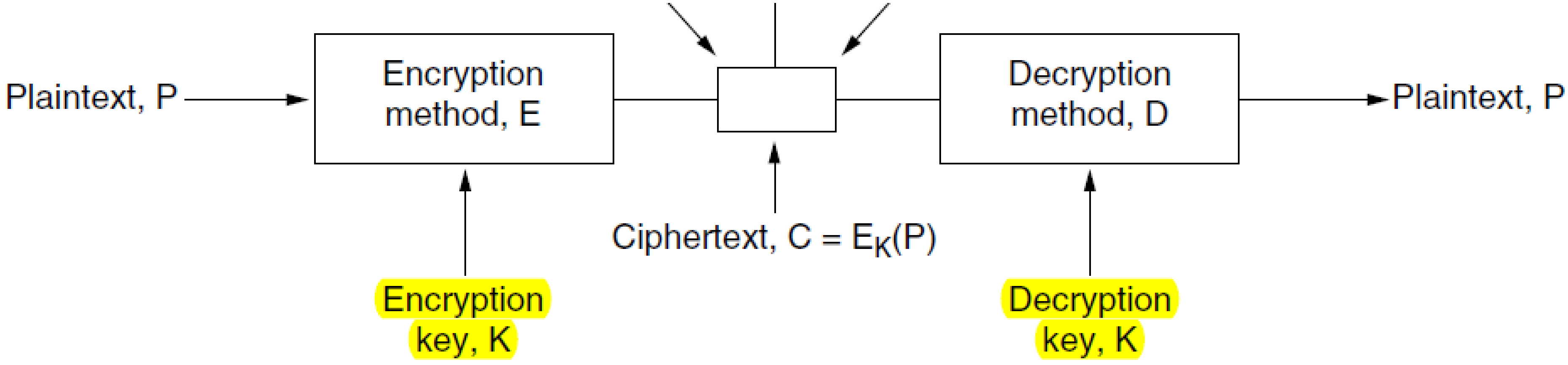


Figure 8-2. The encryption model (for a symmetric-key cipher).

Symmetric-Key Algorithms

- P-box: permutation
- S-box:
  - The 3-bit input selects one of the eight lines exiting from the first stage and sets it to 1; all the other lines are 0.
  - The 2nd stage is a P-box
  - The 3rd stage encodes the selected input line in binary again.

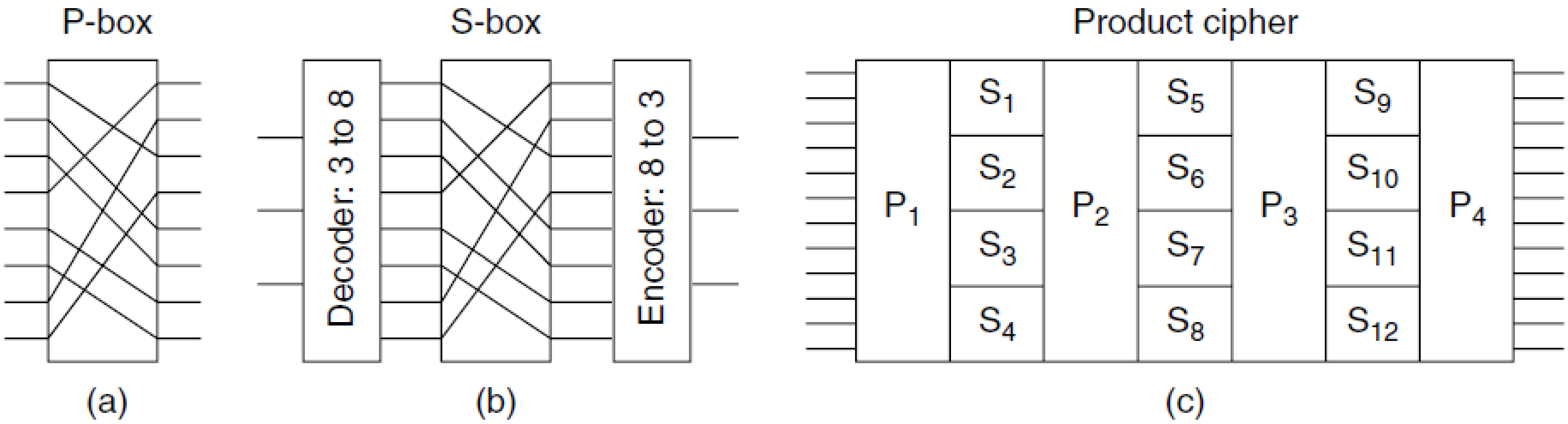
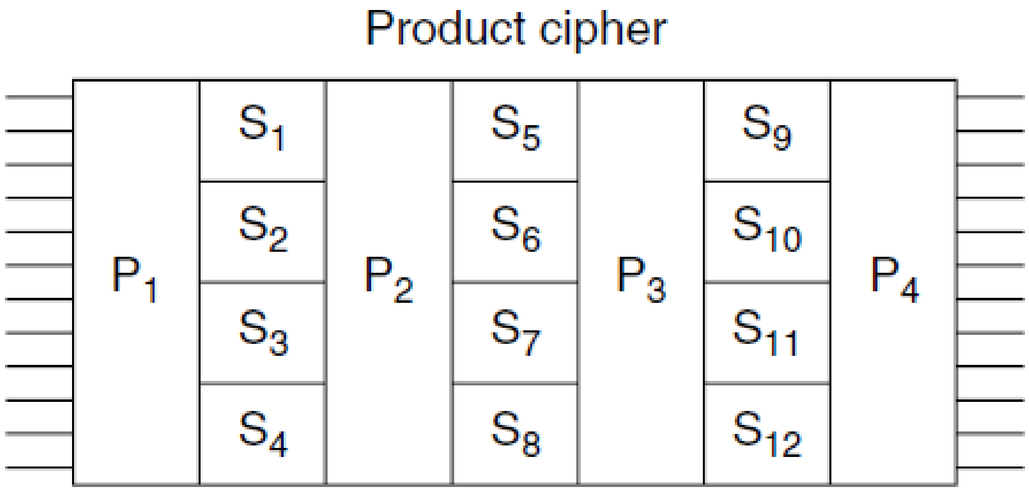


Figure 8-6. Basic elements of product ciphers. (a) P-box. (b) S-box. (c) Product.

Symmetric-Key Algorithms

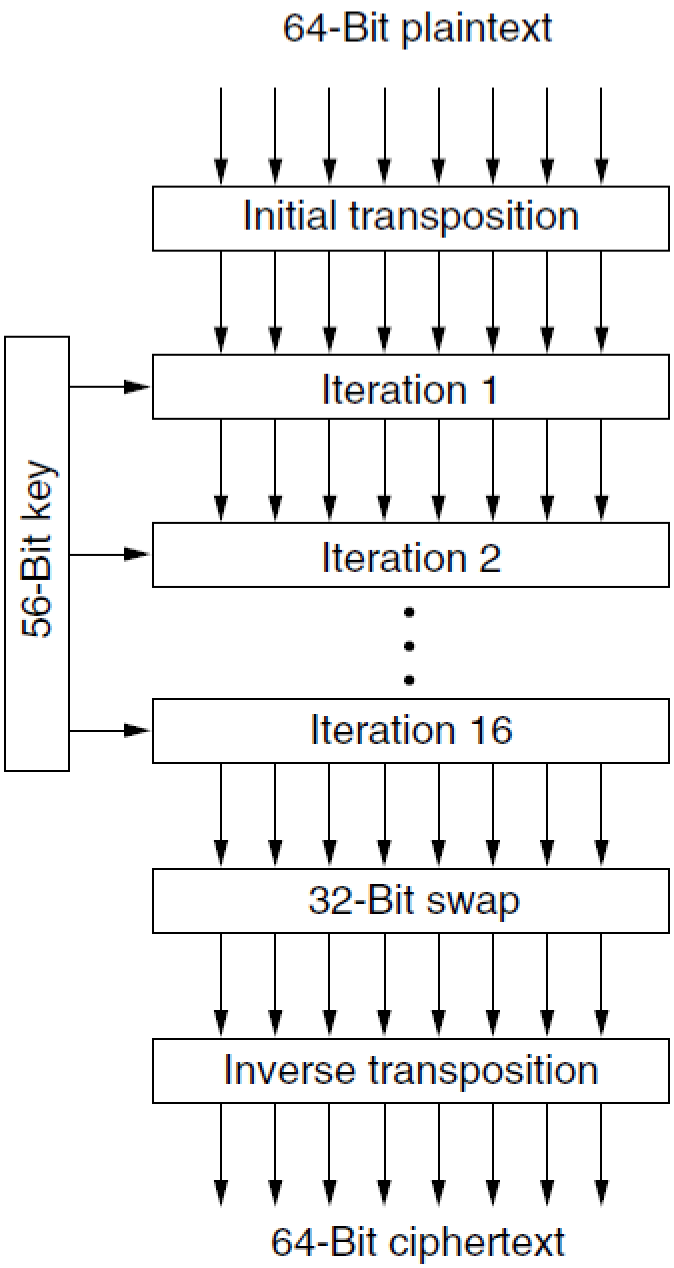
- The real power of these basic elements only becomes apparent when we cascade a whole series of boxes to form a product cipher.
  - Typically, *k* is 64 to 256. A hardware implementation usually has at least 10 physical stages, instead of just 7 as in Fig.8-6 (c).



Note here each S is a S-box contains a Decoder, a P-box and an Encoder.

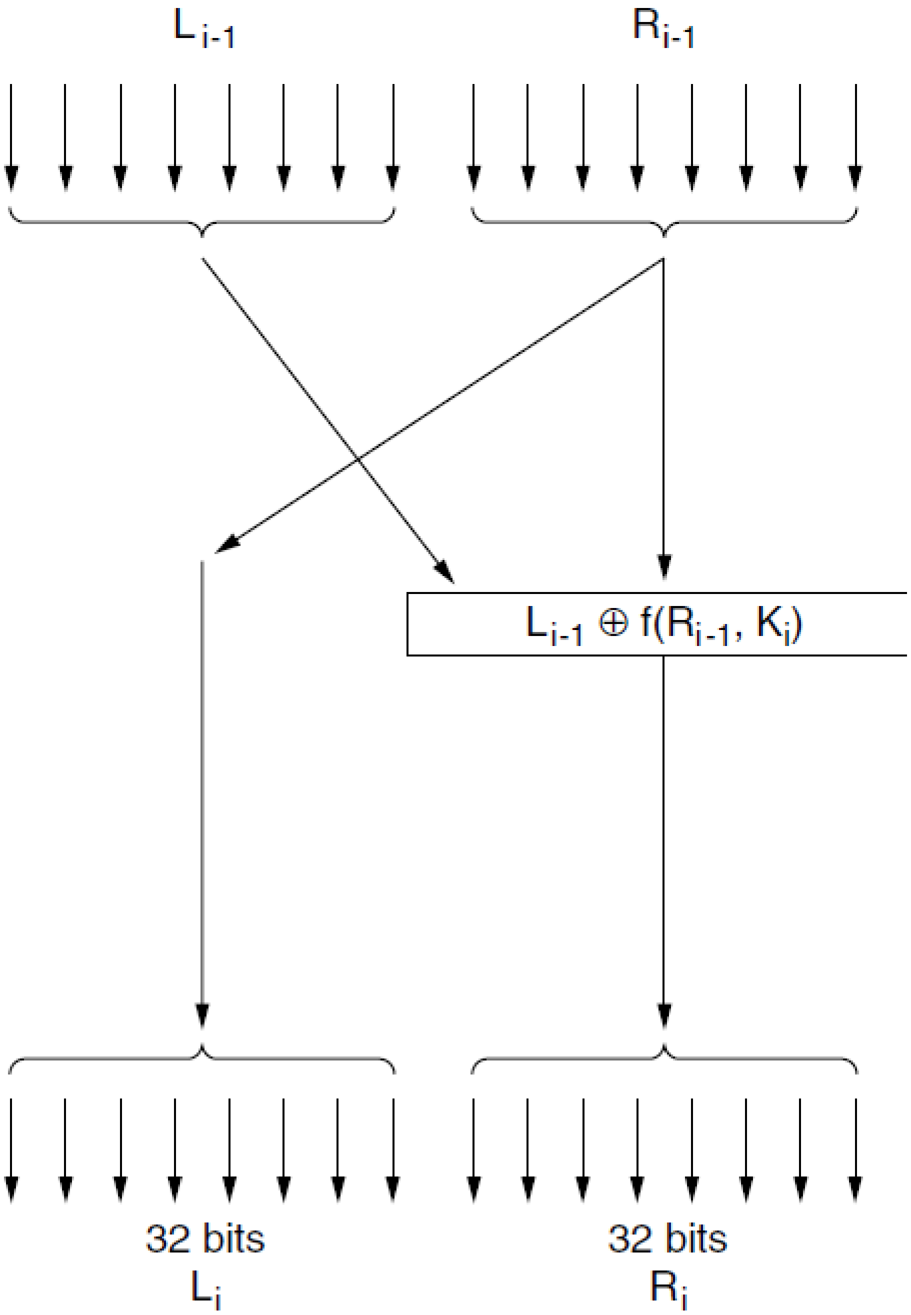
DES

- **DES** (Data Encryption Standard, Jan. 1977 for unclassified information)
  - Plaintext is encrypted in blocks of 64 bits, yielding 64 bits of ciphertext.
  - The algorithm, which is parameterized by **a 56-bit key**, has **19 distinct stages**.
  - The first stage is a key-independent transposition on the 64-bit plaintext.
  - The last stage is the exact inverse of this transposition.
  - The stage prior to the last one exchanges the leftmost 32 bits with the right-most 32 bits.
  - The remaining 16 stages are functionally identical but are parameterized by different functions of the key.
  - The algorithm has been designed to allow decryption to be done with the same key as encryption. The steps are just run in the reverse order.



DES

- The left output is simply a copy of the right input.
- The right output is the bitwise XOR of the left input and *a function* of the right input and the key for this stage K_i.
- The function consists of 4 steps:
  - 1) A 48-bit number, E, is constructed by expanding the 32-bit R_{i-1} according to a fixed transposition and duplication rule.
  - 2) <u>E and K_i are XORed together.</u>
  - 3) This output is then partitioned into 8 groups of 6 bits each, each of which is fed into a different S-box. <u>Each of the 64 possible inputs to an S-box is mapped onto a 4-bit output</u>
  - 4) these 8 × 4 bits are passed through a P-box.
- <u>In each of the 16 iterations, a different key is used</u>.



Detail of One Iteration

EDE

- A technique that is sometimes used to make DES stronger is called **whitening**.
  - It consists of XORing a random 64-bit key with each plaintext block before feeding it into DES and then XORing a second 64-bit key with the resulting ciphertext before transmitting it.
  - Whitening can easily be removed by running the reverse operations (if the receiver has the two whitening keys).
- **Triple DES** (IBM, 1979) — EDE (Encrypt Decrypt Encrypt)
  - The reason for encrypting, decrypting, and then encrypting again is backward compatibility with existing single-key DES systems.

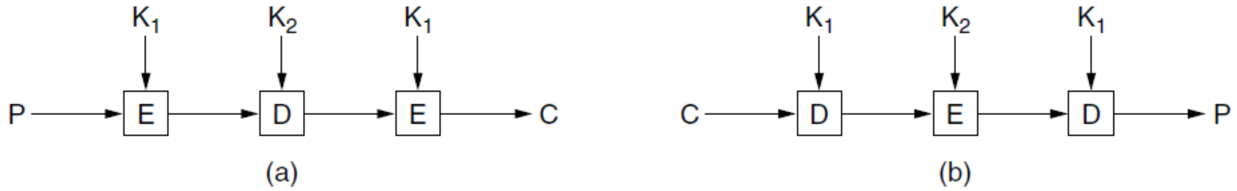
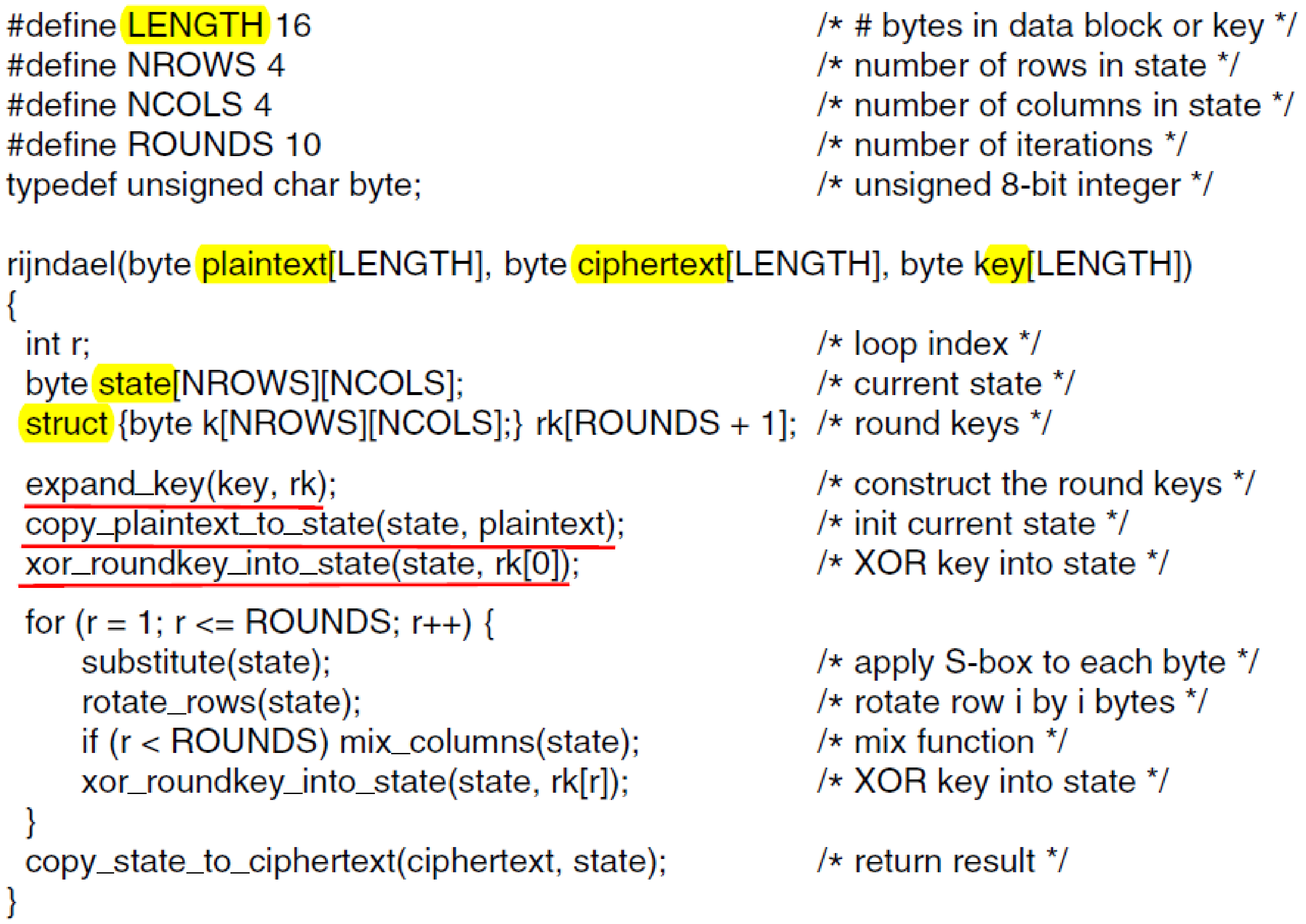


Figure 8-8. (a) Triple encryption using DES. (b) Decryption.

AES (The Advanced Encryption Standard)

- Rijndael (Oct. 2000, by Joan Daemen and Vincent Rijmen, two young Belgian cryptographers)
  - Based on Galois field theory
  - Like DES, Rijndael uses substitution and permutations, and it also use multiple rounds.
  - Unlike DES, all operations involve entire bytes, to allow for efficient implementation in both hardware and so software.
  - **AES encryption and decryption is now part of the instruction set for some microprocessors**.

AES (The Advanced Encryption Standard)



```
#define LENGTH 16                                   /* # bytes in data block or key */
#define NROWS 4                                     /* number of rows in state */
#define NCOLS 4                                     /* number of columns in state */
#define ROUNDS 10                                   /* number of iterations */
typedef unsigned char byte;                         /* unsigned 8-bit integer */

rijndael(byte plaintext[LENGTH], byte ciphertext[LENGTH], byte key[LENGTH])
{
 int r;                                             /* loop index */
 byte state[NROWS][NCOLS];                          /* current state */
 struct {byte k[NROWS][NCOLS];} rk[ROUNDS + 1];     /* round keys */

 expand_key(key, rk);                               /* construct the round keys */
 copy_plaintext_to_state(state, plaintext);         /* init current state */
 xor_roundkey_into_state(state, rk[0]);             /* XOR key into state */

 for (r = 1; r <= ROUNDS; r++) {
      substitute(state);                            /* apply S-box to each byte */
      rotate_rows(state);                           /* rotate row i by i bytes */
      if (r < ROUNDS) mix_columns(state);           /* mix function */
      xor_roundkey_into_state(state, rk[r]);        /* XOR key into state */
 }
 copy_state_to_ciphertext(ciphertext, state);       /* return result */
}
```

Figure 8-9. An outline of Rijndael in C.

AES (The Advanced Encryption Standard)

- During the calculation, the current state of the data is maintained in a byte array, **state**, whose size is *NROWS* × *NCOLS*.
- *The state array is initialized to the plaintext and modified by every step in the computation*. In some steps, byte-for-byte substitution is performed. In others, the bytes are permuted within the array. Other transformations are also used. At the end, the contents of the state are returned as the ciphertext.
- 1) expand_key(key, *rk*): The code starts out by expanding the key into 11 arrays of the same size as the *state*. They are stored in *rk*, which is *an array of structs*, each containing a state array. One of these will be used at the start of the calculation and the other 10 will be used during the 10 rounds, one per round.

```
struct {byte k[NROWS][NCOLS];} rk[ROUNDS + 1];
```

AES (The Advanced Encryption Standard)

- 2) copy_plaintext_to_state(state, plaintext): copy in column order.
- 3) xor_roundkey_into_state(state, rk[0]): *rk*[0] is XORed into state, byte for byte.

The calculation of the round keys from the encryption key is too complicated for us to get into here.

4 × 4 × 8 = 128 bit

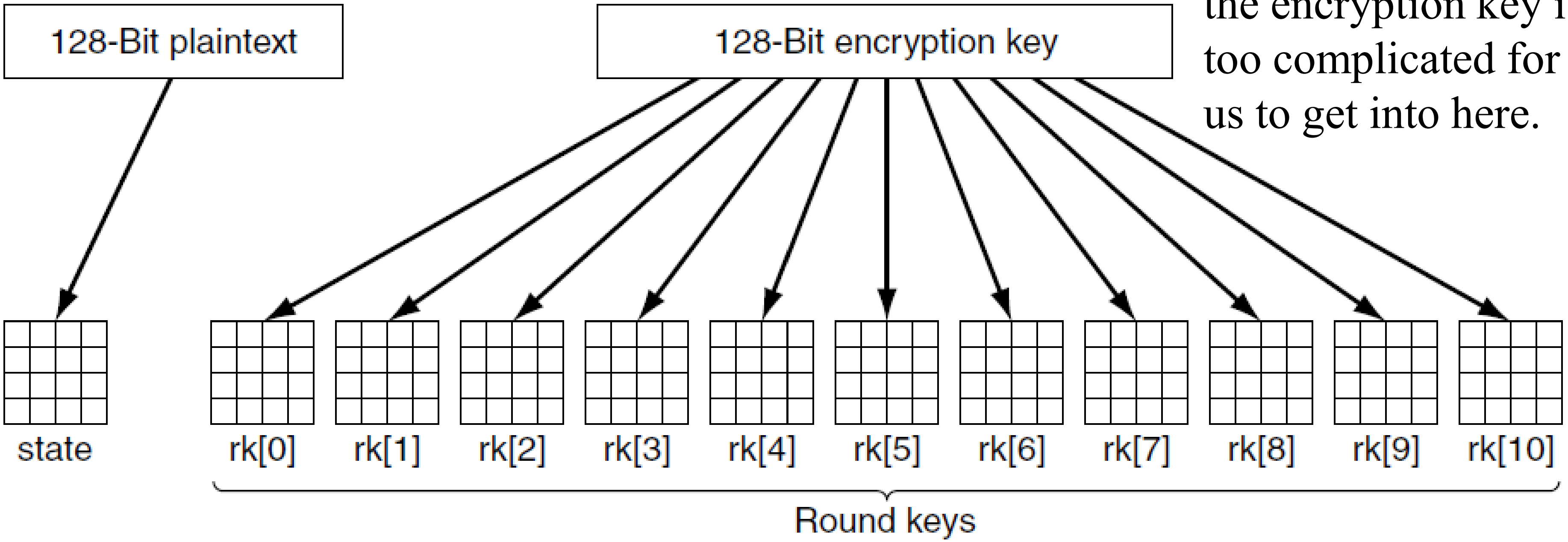


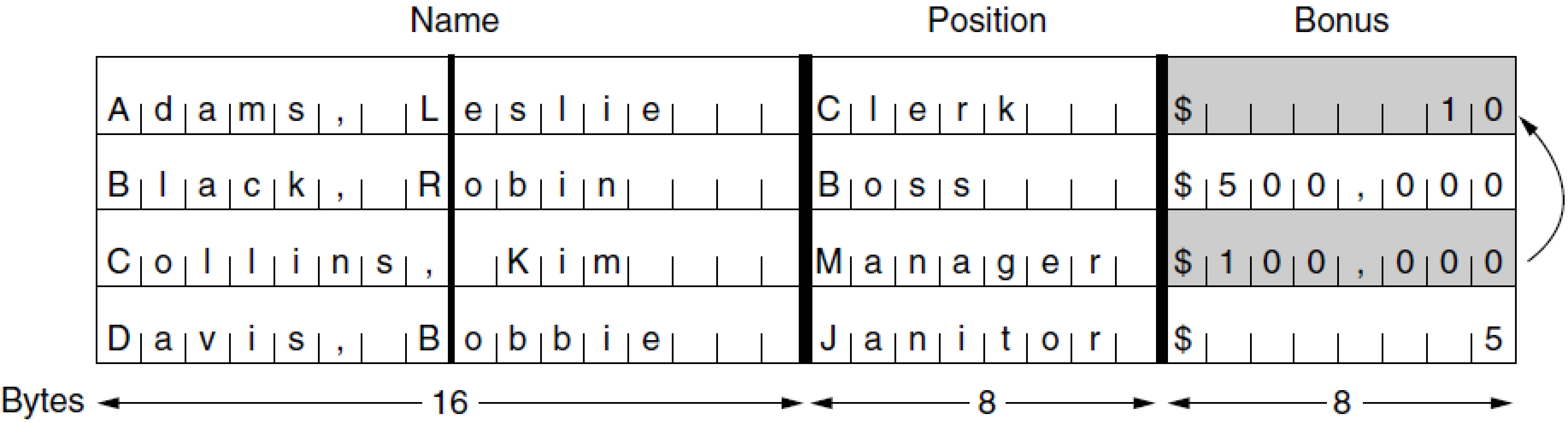
Figure 8-10. Creating the *state* and *rk* arrays.

AES (The Advanced Encryption Standard)

- The loop executes 10 iterations: one per round, transforming state on each iteration. The contents of each round is produced in 4 steps:
  - Step 1 does a byte-for-byte substitution on state. Each byte in turn is used as an index into an S-box to replace its value by the contents of that S-box entry. ~ subsitute (state)
  - Step 2 rotates each of the four rows to the left. Row 0 is rotated by 0 bytes (i.e., not changed), row 1 is rotated 1 byte, row 2 is rotated by 2 bytes, and row 3 is rotated by 3 bytes. ~ rotate_rows (state)
  - Step 3 mixes up each column independently of the other ones. The mixing is done using matrix multiplication in which the new column is the product of the old column and a constant matrix, with the multiplication done using the finite Galois field, $GF(2^8)$. ~ mix_columns (state)
  - Step 4 XORs the key for this round into the state array for use in the next round.~ xor_roundkey_into_state (state, *rk*[r])

Cipher Modes*

- For either AES or DES, whenever the same plaintext block goes in the front end, the same ciphertext block comes out the back end. An intruder can exploit this property to help subvert the cipher.
- **ECB Mode (Electronic Code Book mode)** — in analogy with old-fashioned code books where each plaintext word was listed, followed by its ciphertest.
  - Each block is ciphered individually (memoryless encryption).



	Name	Position	Bonus
	Adams, Leslie	Clerk	$ 10
	Black, Robin	Boss	$500,000
	Collins, Kim	Manager	$100,000
	Davis, Bobbie	Janitor	$ 5
Bytes	16	8	8

Figure 8-11. The plaintext of a file encrypted as 16 DES blocks.

Cipher Modes: Cipher Block Chaining Mode*

- Each plaintext block is XORed with the previous ciphertext block before being encrypted.
- The first block is XORed with a randomly chosen IV (Initialization Vector), which is transmitted (in plaintext) along with the ciphertext.
  - Consequently, the same plaintext block no longer maps onto the same ciphertext block.
- Cipher block chaining has the disadvantage of requiring an entire 64-bit block to arrive before decryption can begin.

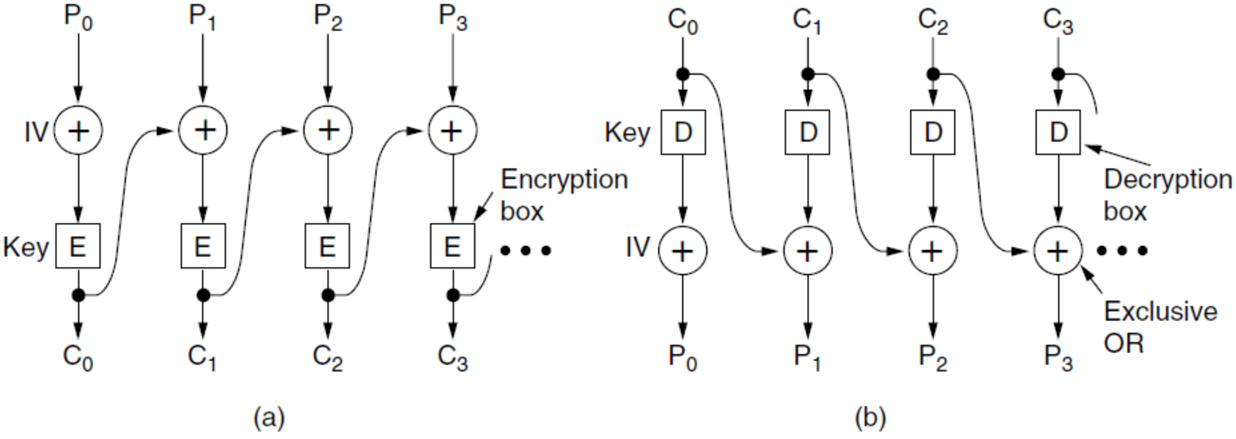


Figure 8-12. Cipher block chaining. (a) Encryption. (b) Decryption.

Cipher Modes: Cipher Feedback Mode*

- Cipher Feedback Mode
  - The contents of the shift register depend on the entire previous history of the plaintext, so a pattern that repeats multiple times in the plaintext will be encrypted differently each time in the ciphertext.
  - A problem with cipher feedback mode is that if one bit of the ciphertext is accidentally inverted during transmission, the 8 bytes that are decrypted while the bad byte is in the shift register will be corrupted.
    - The effects of a single inverted bit are relatively localized and do not ruin the rest of the message, but they do ruin as many bits as the shift register is wide.

Cipher Modes: Cipher Feedback Mode*

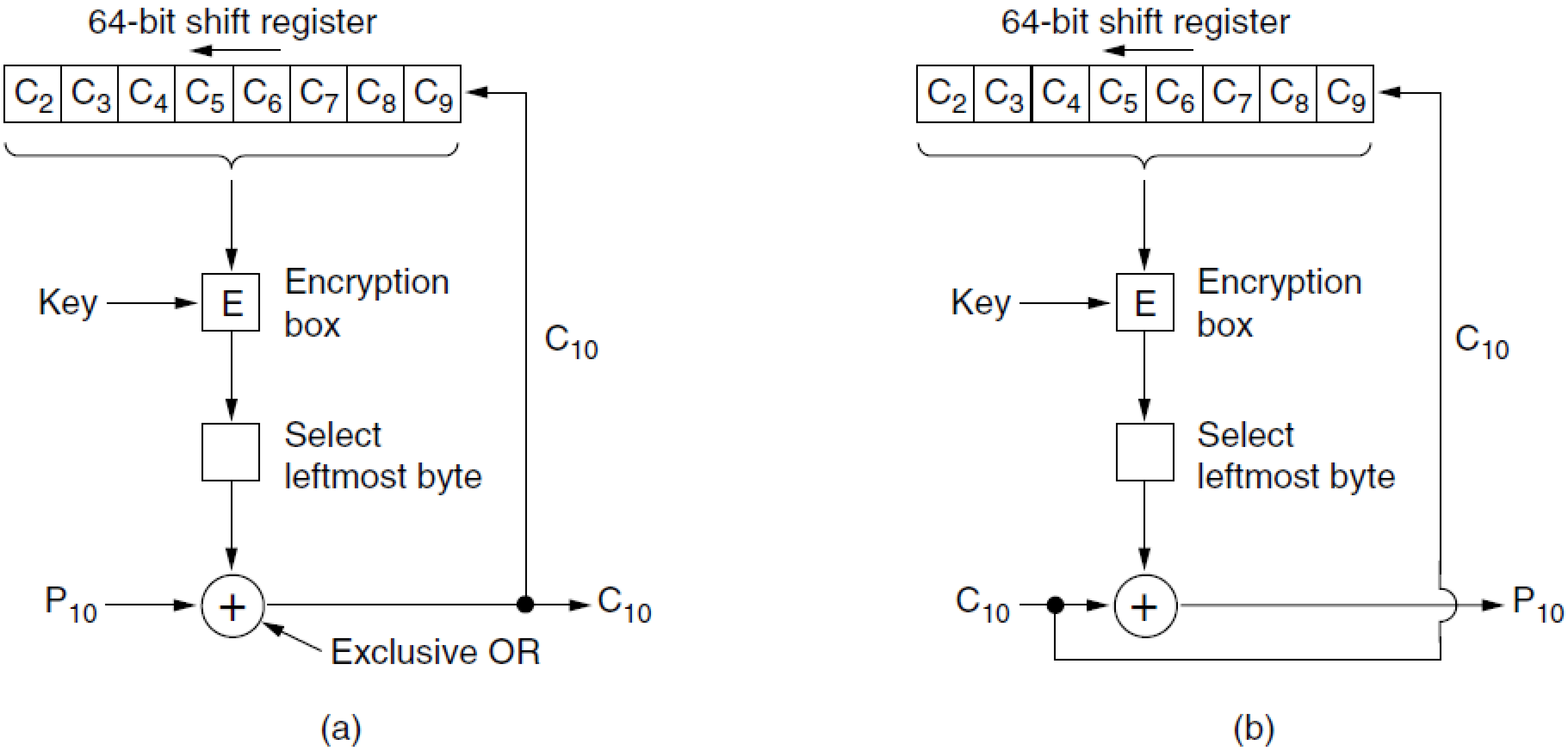


Figure 8-13. Cipher feedback mode. (a) Encryption. (b) Decryption.

Cipher Modes: Stream Cipher Mode*

- Nevertheless, applications exist in which having a 1-bit transmission error mess up 64 bits of plaintext is too large an effect.
- Stream Cipher Mode — It works by encrypting an initialization vector, using a key to get an output block. The output block is then encrypted, using the key to get a second output block. This block is then encrypted to get a third block, and so on.

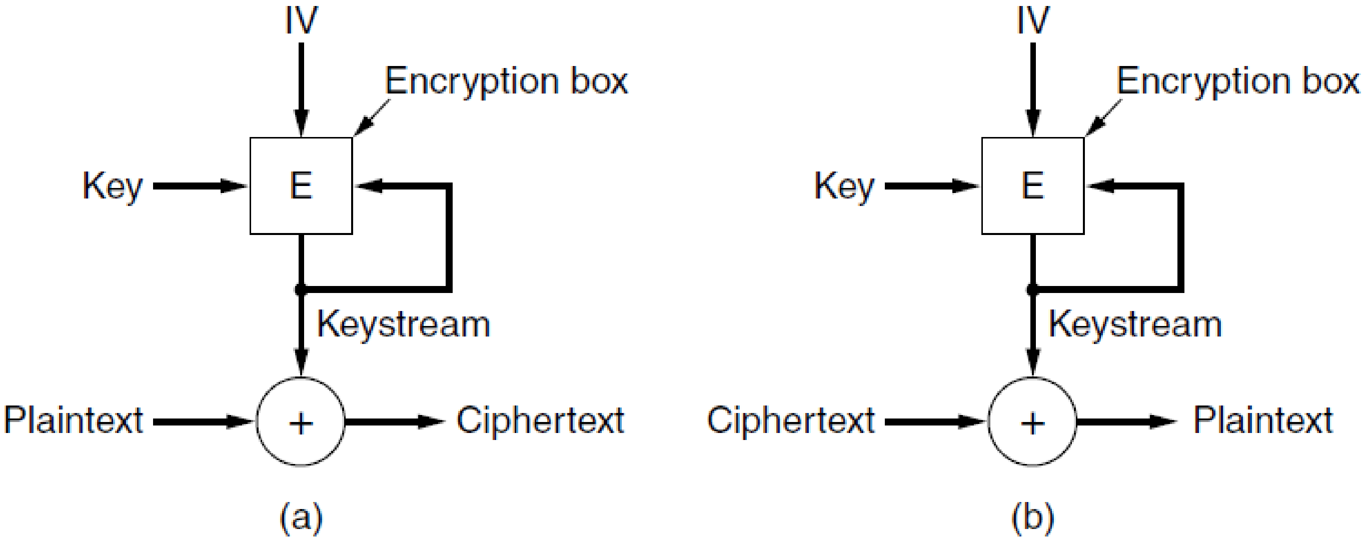


Figure 8-14. A stream cipher. (a) Encryption. (b) Decryption.

Cipher Modes: Stream Cipher Mode*

- The keystream is independent of the data, so it can be computed in advance, if need be, and is completely insensitive to transmission error.
- Since the keystream depends only on the IV and the key, it is not affected by transmission error in the ciphertext.
  - Thus, a 1-bit error in the transmitted ciphertext generates only a 1-bit error in the decrypted plaintext.
- It is essential never to use the same (key, IV) pair twice with a stream cipher because doing so will generate the same keystream each time.
  - A keystream reuse attack

Cipher Modes: Counter Mode*

- One problem that all the modes except electronic code book mode have is that random access to encrypted data is possible.
  - However, disk files are often accessed in nonsequential order, especially files in database.
  - By stepping the initialization vector by 1 for each new block, it is easy to decrypt a block anywhere in the file without first having to decrypt all of its predecessors.

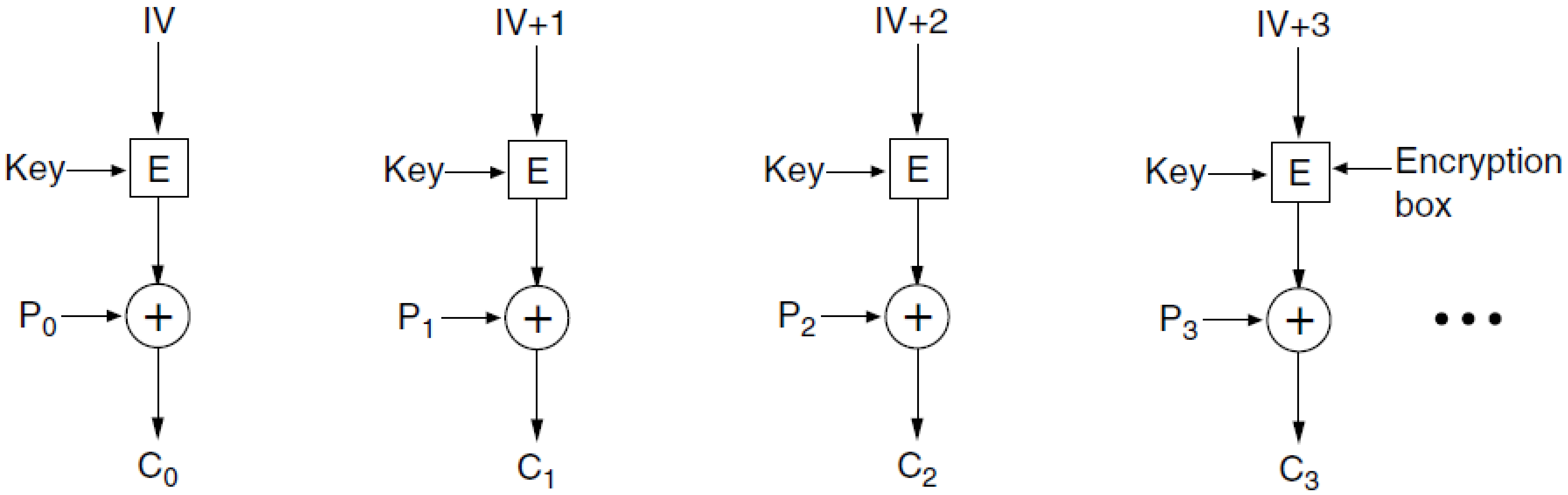
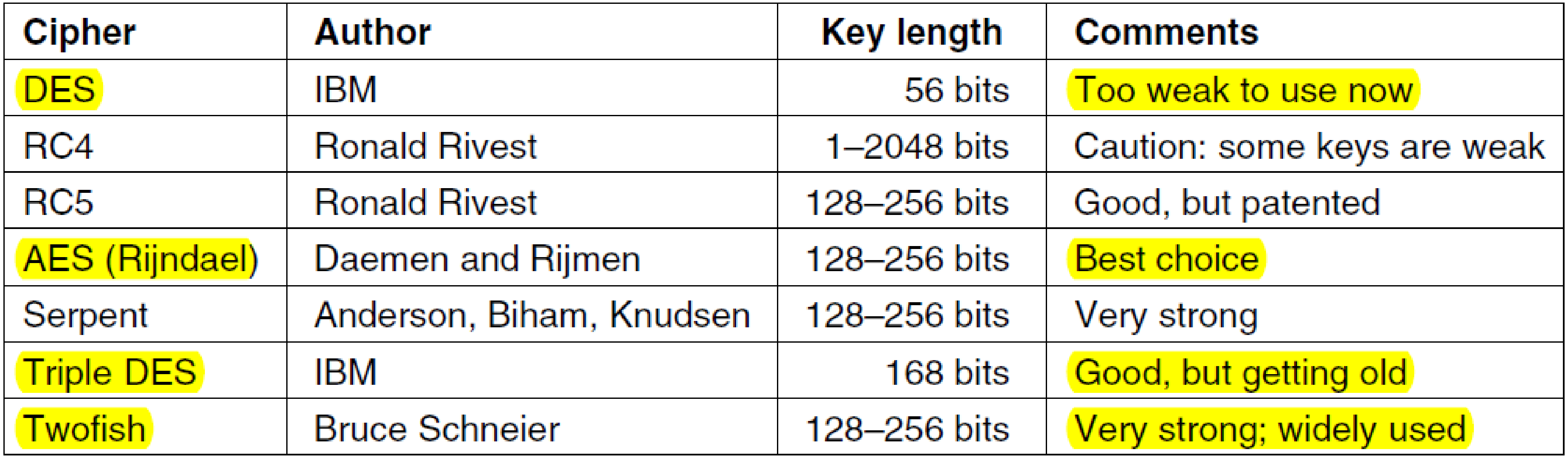


Figure 8-15. Encryption using counter mode.

Other Ciphers



Cipher	Author	Key length	Comments
DES	IBM	56 bits	Too weak to use now
RC4	Ronald Rivest	1–2048 bits	Caution: some keys are weak
RC5	Ronald Rivest	128–256 bits	Good, but patented
AES (Rijndael)	Daemen and Rijmen	128–256 bits	Best choice
Serpent	Anderson, Biham, Knudsen	128–256 bits	Very strong
Triple DES	IBM	168 bits	Good, but getting old
Twofish	Bruce Schneier	128–256 bits	Very strong; widely used

Figure 8-16. Some common symmetric-key cryptographic algorithms.

Public-Key Algorithms

- Historically, *distributing the keys has always been the weakest link in most cryptosystems*. No matter how strong a cryptosystem was, if an intruder could steal the key, the system as worthless.
- In 1976, two researchers at Stanford University, Diffie and Hellman proposed a radically new kind of cryptosystem, one in which *the encryption and decryption keys were so different that the decryption key could not feasibly be derived from the encryption key*.
- **These requirements** can be stated simply as follows:
  - 1. D(E(*P*)) = *P*.
  - 2. It is exceedingly difficult to deduce D from E.
  - 3. E cannot be broken by a chosen plaintext attack.
- Public-key cryptography requires each user to have two keys: **a public key**, used by the entire world for encrypting message to be sent to that user, and **a private key**, which the user needs for decrypting messages.

RSA

- In 1970, **James H. Ellis**, a British Engineering mathematician was working on an idea for **non secret encryption**. It is based on a simple yet clever concept: Alice can send the open lock to Bob, but keep the key secretly. — No keys are exchanged.
  - To split a key into an encryption key and a decryption key, and the decryption key performs the inverse or undo operation which was applied by the encryption key.
- The solution was found by another British mathematician encryptographer: **Clifford Christopher Cocks**. Cocks needed to construct a special kind of **one-way function**, called *the Trapdoor one-way function*. This is a function that is easy to compute in one direction yet difficult to reverse unless you have special information called Trapdoor.

RSA (I)

- Modular exponentiation (one-way function)

$$\underset{\substack{\uparrow \\ \text{Base}}}{3}^{\overset{\substack{\text{Exponent} \\ \downarrow}}{4}} \,\text{mod}\, \underset{\substack{\uparrow \\ \text{Modulus}}}{17} = \overset{\substack{\text{Remainder} \\ \downarrow}}{13}$$

- Message → a number "m"

$$m^e \,\text{mod}\, N = c \xrightarrow{\quad\text{easy}\quad}$$

$$\xleftarrow{\quad\textit{hard}\quad} ?^e \,\text{mod}\, N = c$$

Here N is a random number

RSA (II)

- To reverse the encryption

$$m^e \bmod N = c$$

$$c^d \bmod N = m$$

$$\downarrow$$

$$\left(m^e\right)^d \bmod N = m$$

$$m^{ed} \bmod N = m$$

- Here e is the encryption key and d is the decryption key.

RSA (III)

- Therefore, we need a way to construct *e* and *d*, which makes it difficult for anyone else to find *d*.
- Now the question is how to find *d*? — **Euclidean's Prime Factorization**: Euclidean showed that every number has exactly one prime factorization.
  - For example: 30 = 5 × 3 × 2
- As we all known, the multiplication of two primes is easy, but to find the prime factorization of a very large number is hard.
  - For example: to find the prime factorization for 437231?
  - If we try to get a computer to factor larger and larger numbers, there is **a runway effect**. This is a hard problem.

RSA (IV)

- 1) So factorization is what Cocks used to build the Trapdoor solution.
  - Alice generate two random **prime** numbers **with roughly the same size**: P_1 and P_2 (~ 150 digits) and multiply them together to get a composite number $N = P_1 \times P_2$ (~ 300 digits long).
  - She can give the number N to anyone else, but hide the factorization as a secret. They would have to have a computer running for years to find the solution.
- 2) Cocks needed to find a function which depends on knowing the factorization of N. Now he turned to **the Distribution of Prime Numbers** found by Leonardo Euler (Swiss mathematician) in 1760.

RSA (V)

- One important function Euler defined is called Φ (**Phi function**) — it measures the breakability of a number. Φ(*N*) outputs how many integers that are less than N that do **not** share any common factor with *N*.
  - For example Φ(8) = 4. (∵ 1, 2, 3, 4, 5, 6, 7), so calculating the Phi function is hard, except in one case: **The Phi of any prime number P is simply P – 1**. Φ(7) = 6. Φ(21377) = 21376. Therefore, Phi of any prime is easy to computer.
  - The Phi function is also multiplicative: Φ(A×B) = Φ(A) × Φ(B).
- If we know a number *N* is the product of two primes P_1 and P_2, then : $\Phi(N) = \Phi(P_1) \times \Phi(P_2) = (P_1 - 1) \times (P_2 - 1)$.
- We now have a trapdoor for solving Φ (Phi). If you know the factorization of *N*, then finding the Φ(*N*) is easy.

RSA (VI)

- 3) How to connect the Φ (Phi) function to modular exponentiation? **Euler's Theorem**: the relationship between the Phi function and modular exponentiation:

$$\boxed{m^{\Phi(n)} = 1 \bmod n = 1}$$

  - This means that you can pick any two numbers such that they do not share a common factor. For example: $m = 5$, $n = 8$, $5^{\Phi(8)} = 5^4 = 625 = 1 \bmod 8 = 1$ ($625 \bmod 8 = 1$).

$$1^k = 1$$

$$m^{k\Phi(n)} = 1 \bmod n$$

RSA (VII)

$$1 \times m = m \qquad m^{k\Phi(n)} = 1 \bmod n = 1$$

$$m \times m^{k\Phi(n)} = m \bmod n$$

Note: *m* and *n* share no common factor

$$m^{k\Phi(n)+1} = m \bmod n$$

$$m^{e \times d} = m \bmod n$$

$$e \times d = k\Phi(n) + 1 \rightarrow d = \frac{k\Phi(n)+1}{e}$$

- We now have an equation for finding *e* times *d* which depends on Φ(*n*). It is easily to calculate *d* only if the factorization of *n* is known. Now *d* should be **the private key** of Alice.

RSA (VIII)

- An simple example: $P_1 = 53$, $P_2 = 59$, $n = P_1 \times P_2 = 3127$. $\Phi(n) = 52 \times 58 = 3016$. If Alice choose $e = 3$ (<u>e should be an odd number and does not share a factor with $\Phi(n)$</u>).
  - Alice's private key $d = (2\times\Phi(n)+1)/e = 2011$. Now Alice hided everything except e and n.
- Now Alice sends Bob her **public key**: <u>e and n</u>. And Bob uses the Alice public key to encrypt his message "hi" → m = 89 as following:
  - $m^e \bmod n = 89^3 \bmod 3127 = 1394 = c$
- Now Bob sends back his encrypted message "c" to Alice. Finally, Alice decrypts his message using her private key
  - $c^d \bmod n = m = 89$.

RSA (IX)

- This trick was *rediscovered* a group at MIT (Rivest, Shamir, Adleman, 1978)
  - It has survived all attempts to break it for more than 30 years and is considered very strong.
  - Rivest, Shamir and Adleman were given **the 2002 ACM Turing Award**.
- The RSA method is based on some principles from **number theory**.
  - 1. Choose two large primes, p and q (typically 1024 bits)
  - 2. Compute $n = p \times q$ and $z = (p - 1) \times (q - 1)$.
  - 3. Choose a number relatively prime to z and call it d.
  - 4. Find e such that $e \times d = 1 \bmod z$.
- <u>Its major disadvantage is that it requires keys of at least 1024 bits for good security</u>.

RSA

- A trivial pedagogical example of how the RSA algorithm works: $p = 3$ and $q = 11$, giving $n = 33$ and $z = 20$. A suitable value for d is $d = 7$, since 7 and 20 have no common factors. With these choices, e can be found by solving the equation $7e = 1 \pmod{z}$, which yields $e = 3$.
- The ciphertext, C, corresponding to a plaintext message, P, is given by $C = P^3 \pmod{33}$.
- The ciphertext is decrypted by the receiver by making use of the rule $P = C^7 \pmod{33}$.
- Most RSA-based systems use public-key cryptography primarily for distributing one-time session keys for use with some symmetric-key algorithm such as AES and triple DES.

RSA

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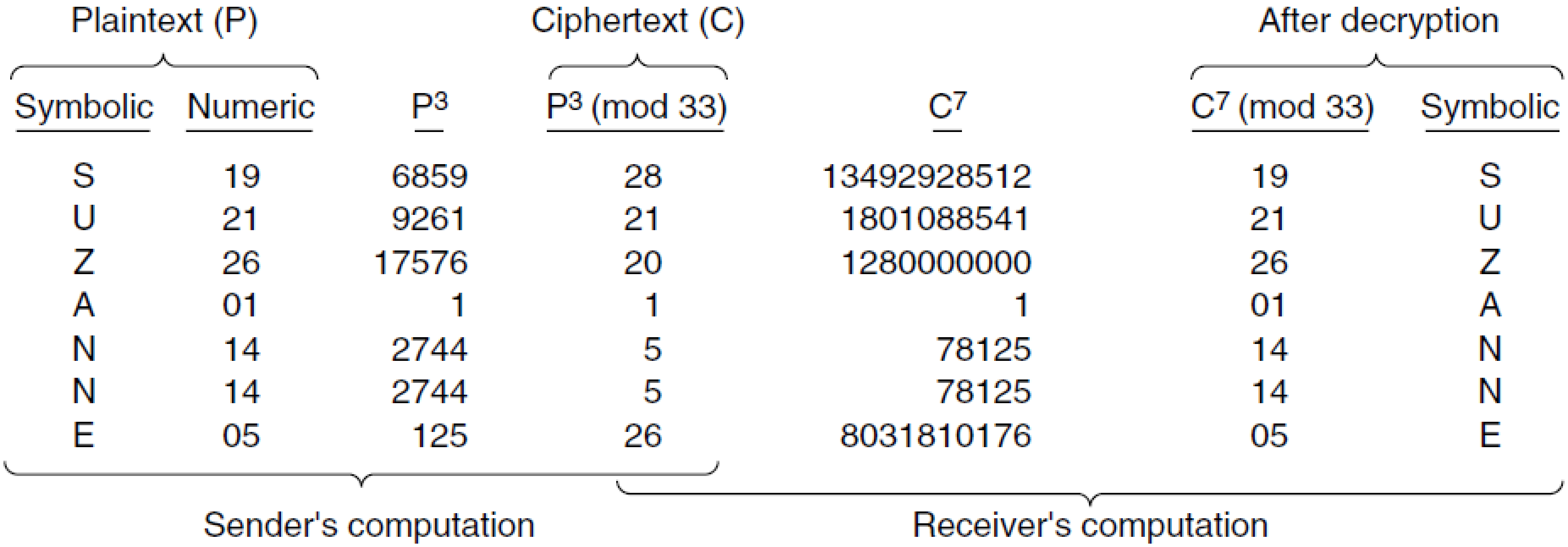


Plaintext (P)			Ciphertext (C)		After decryption	
Symbolic	Numeric	P^3	$P^3 \pmod{33}$	C^7	$C^7 \pmod{33}$	Symbolic
S	19	6859	28	13492928512	19	S
U	21	9261	21	1801088541	21	U
Z	26	17576	20	1280000000	26	Z
A	01	1	1	1	01	A
N	14	2744	5	78125	14	N
N	14	2744	5	78125	14	N
E	05	125	26	8031810176	05	E

Sender's computation

Receiver's computation

Figure 8-17. An example of the RSA algorithm.

Other Public-Key Algorithms*

- The knapsack algorithm (Merkle and Hellman 1978)
- The idea is that someone owns a large number of objects, each with a different weight. The owner encodes the message by secretly selecting a subset of the objects and placing them in the knapsack. The total weight of the objects in the knapsack is made public, as is the list of all possible objects and their corresponding weights. The list of objects in the knapsack s kept secret.
- ~ Factoring large numbers and computing discrete logarithms modulo a large prime.

Digital Signatures

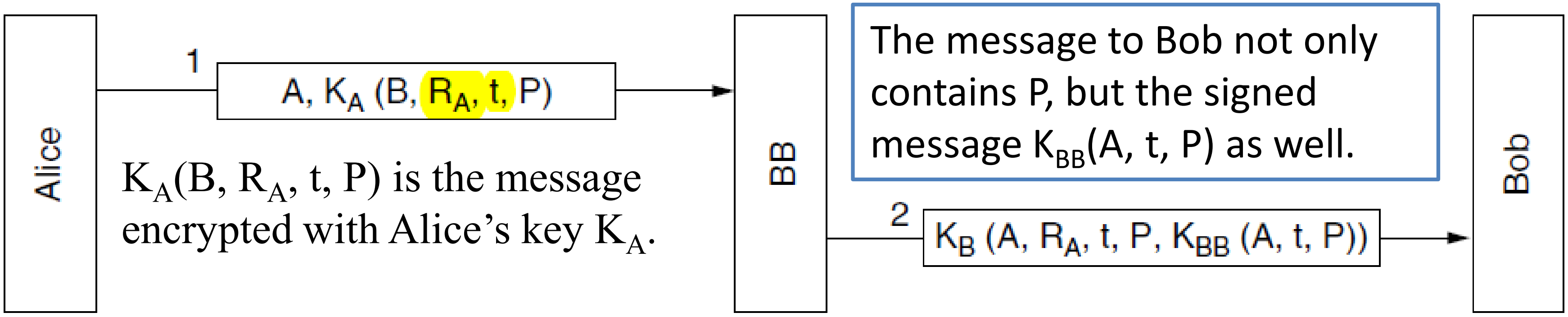
- The authenticity of many legal, financial, and other documents is determined by the presence or absence of an authorized handwritten signature.
- Digital signatures allow digital documents to be signed in an unforgeable way.
- The basic requirements of digital signatures:
  - 1. The receiver can verify the claimed identity of the sender.
  - 2. The sender cannot later repudiate the contents of the message.
  - 3. The receiver cannot possibly have concocted the message himself.

- Contents of digital signatures
  - Symmetric-key signatures and public-key signatures
  - Message digests
  - The birthday attack

Symmetric-Key Signatures

- To have a **central authority** (such as Big Brother)
- A and B are Alice and Bob's identities, respectively
- P is a signed plaintext sent by Alice to Bob.
- R_A (a random number chosen by Alice) and the timestamp *t* is used for freshness.
- K_A, K_B and K_{BB} are the secrete keys of Alice, Bob and BB, respectively.

- One potential problem with the signature protocol of Fig.8-18 is **the replay attack**.
  - To minimize this problem, timestamps are used throughout
  - To check all recent message to see if R_A is used in any of them



$K_A(B, R_A, t, P)$ is the message encrypted with Alice's key K_A.

The message to Bob not only contains P, but the signed message $K_{BB}(A, t, P)$ as well.

Figure 8-18. Digital signatures with Big Brother.

Replay Attack [2]

- A **replay attack** (also known as **playback attack**) is a form of network attack in which a valid data transmission is maliciously or fraudulently repeated or delayed.
- This is carried out either by the originator or by an adversary who intercepts the data and re-transmits it, possibly as part of a *spoofing attack* by **IP packet substitution**. This is one of the lower-tier versions of a man-in-the-middle attack.

Public-Key Signatures (I)

- A structural problem with using symmetric-key cryptography for digital signatures is that everyone has to agree to *trust Big Brother*.
- Signing documents did not require a trusted authority.
- Assume that the public-key encryption and decryption algorithms have the property that $E(D(P)) = P$, in addition, to the usual property $D(E(P)) = P$.
  - **RSA** has this property. The de facto industry standard is the RSA algorithm. Many security products use it.
  - In principle, any public-key algorithm can be used for digital signatures.

Public-Key Signatures (II)

- Alice can send a signed plaintext message, P, to Bob by transmitting $E_B(D_A(P))$. (D_A is Alice’s private key, and E_B is Bob’s public key.)
- When Bob receives the message, he transforms it using his private key, D_B, as usual, yielding $D_A(P)$. He stores this text is a safe place and then applies E_A (Alice’s public key) to get the original plaintext.
  - Because Bob don’t now what Alice’s private key is ($D_A(P)$), the only way Bob could have acquired a message encrypted by it is if Alice did indeed send it.

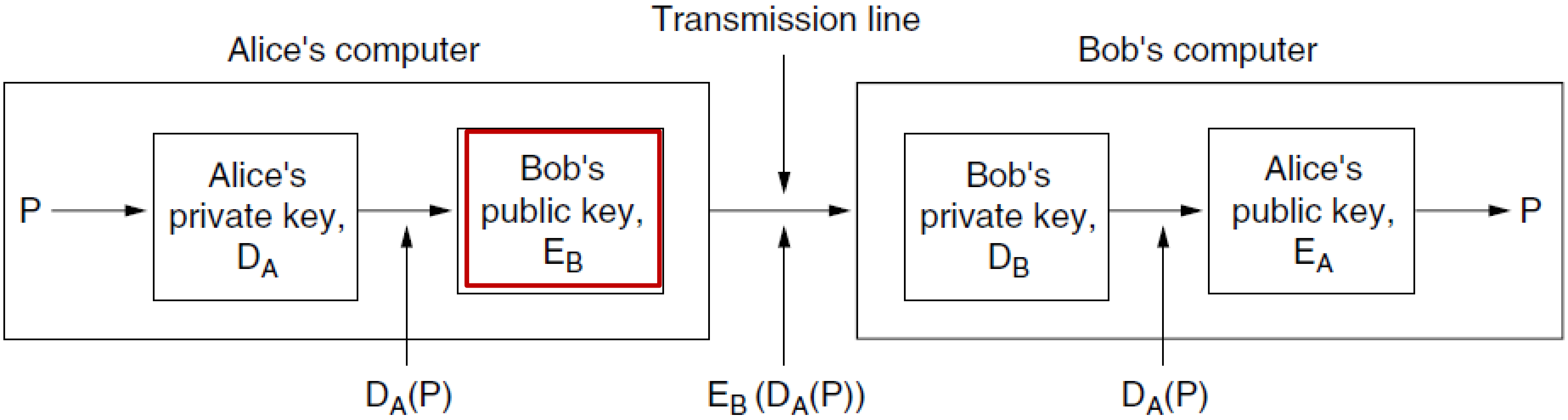


Figure 8-19. Digital signatures using public-key cryptography.

Message Digests (I)

- One criticism of signature methods is that they often couple two distinct functions: *authentication* and *secrecy*. Often authentication is needed but secrecy is not always needed.
- The following authentication scheme is based on the idea of **a one-way hash function** that takes an arbitrarily long piece of plaintext and from it computes a fixed-length bit string.
  - This scheme does not require encrypting the entire message.
- This hash function, MD, often called a **message digest**, has four important properties:
  - 1. Given P, it is easy to compute $MD(P)$. — **efficiency**
  - 2. Given $MD(P)$, it is effectively impossible to find P. — **confidential**
  - 3. Given P, no one can find P' such that $MD(P') = MD(P)$. — **uniqueness**
    - The hash should be at least 128 bits long, preferably more.
  - 4. A change to the input of even 1 bit produces a very different output. — **trustworthiness**
    - The hash must mangle the bits very thoroughly.

Message Digests (II)

- Computing a message digest from a piece of plaintext is much faster than encrypting that plaintext with a public-key algorithm, so message digests can be used to speed up digital signature algorithms.
- Message digests work in public-key cyptosystems, as shown in Fig.8-20.
  - Alice first computes the message digest of her plaintext. She then signs the message digest and sends both the signed digest and the plaintext to Bob.
  - If Trudy replaces *P* along the way, Bob will see this when he computes MD(*P*)

Alice’s private key is (D_A(P))

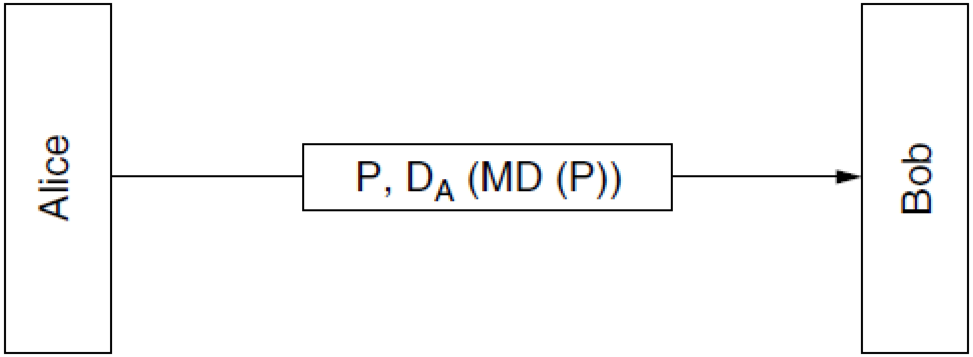


Figure 8-20. Digital signatures using message digests.

SHA-1 and SHA-2

- SHA-1 (Secure Hash Algorithm, **NIST**, 1993)
  - It operates by mangling bits in a sufficiently complicated way that every output bit is affected by every input bit.
  - It processes input data in 512-bit blocks, and it generates a 160-bit message digest.
- After receiving the message, Bob computes the SHA-1 hash himself and also applies Alice's public key to the signed hash to get the original hash, H. If the two agree, the message is considered valid.

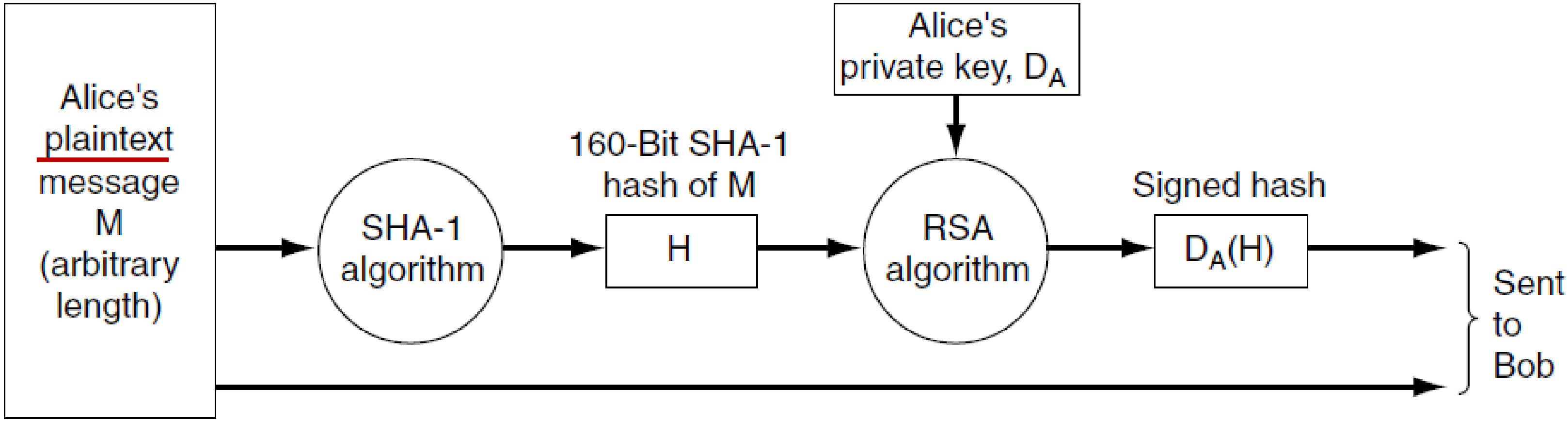


Figure 8-21. Use of SHA-1 and RSA for signing nonsecret messages.

SHA-1 (I)

- How SHA-1 works:
  - It starts out by padding the message by adding a 1 bit to the end, followed by as many 0 bits as are necessary, but at least 64, to make the length a multiple of 512 bits. SHA-1 always pads the end of the message, no matter which endian machine is used (Big-endian or small-endian).

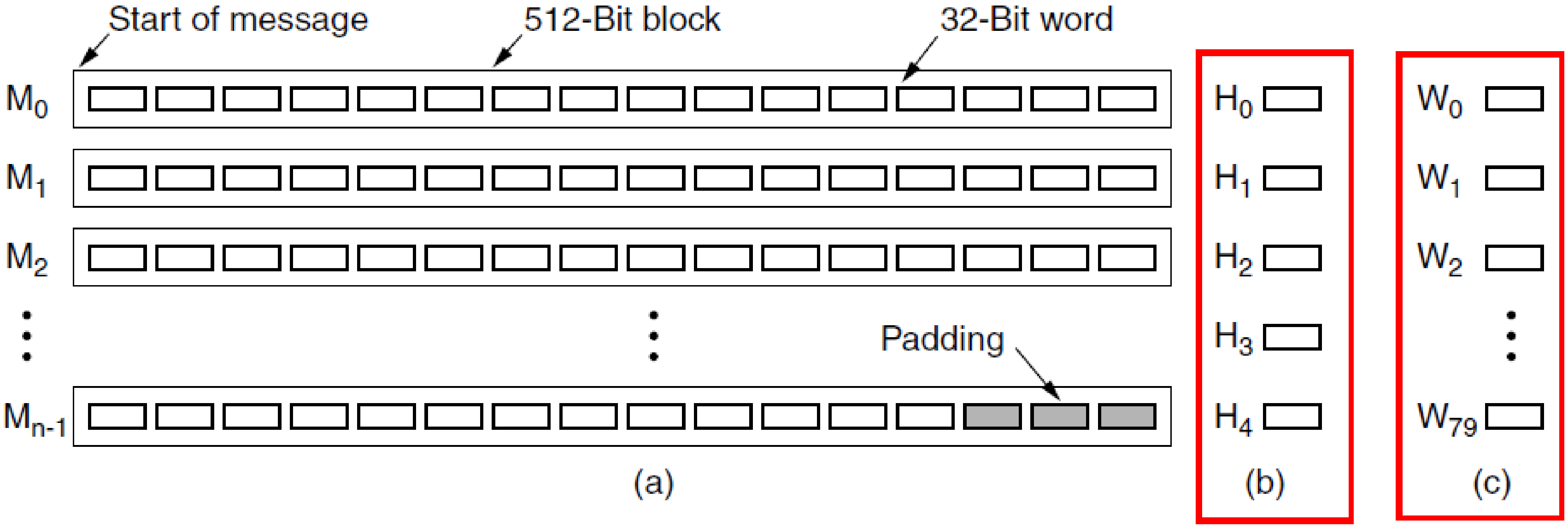


Figure 8-22. (a) A message padded out to a multiple of 512 bits. (b) The output variables. (c) The word array.

每个块block有16个words，每个word有32-bit。

SHA-1 (II)

- Then a 64 bit number containing the message length before padding is ORed into the low-order 64 bits.
- SHA-1 maintains five 32-bit variables H_0 through H_4, where the hash accumulates. They are *initialized to constants* specified in the standard.

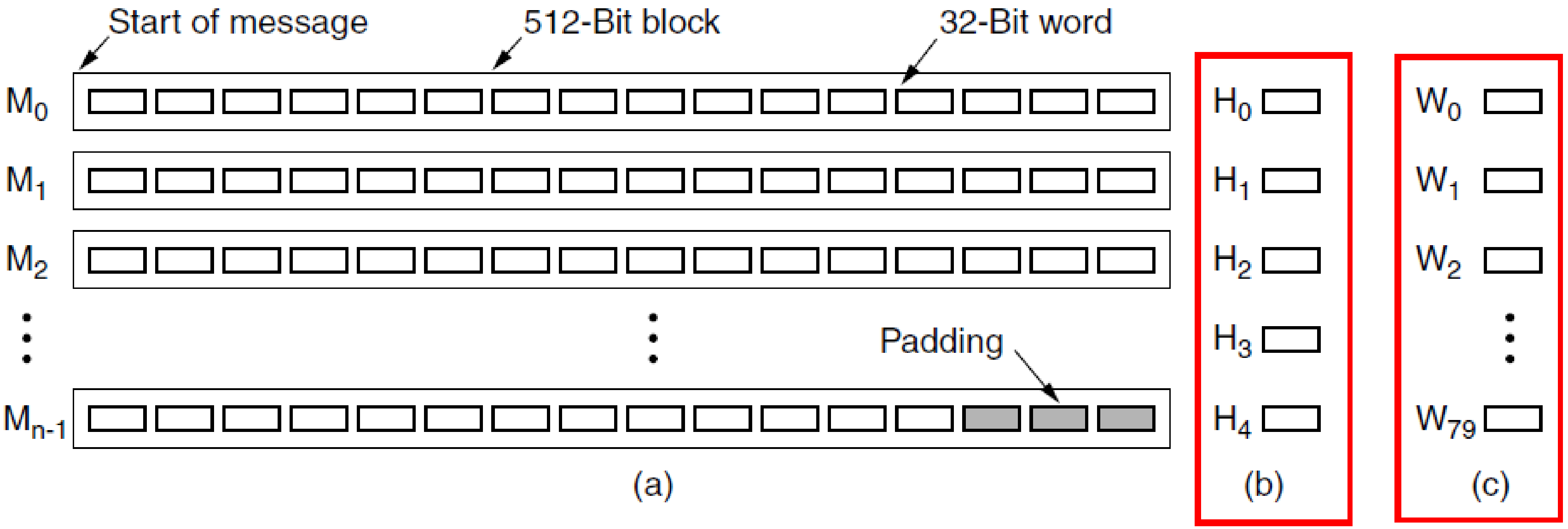


Figure 8-22. (a) A message padded out to a multiple of 512 bits. (b) The output variables. (c) The word array.

SHA-1 (III)

- Each of the blocks M_0 through M_{n-1} is processed in turn.
  - For the current block, the 16 words (each word is with 32-bit) are first copied into the start of an auxiliary 80-word array W (W_0, W_1, …, W_{15}). Then the other 64 words in W are filled in using the formula

$$W_i = S^1(W_{i-3}\ \text{XOR}\ W_{i-8}\ \text{XOR}\ W_{i-14}\ \text{XOR}\ W_{i-16}) \quad (16 \le i \le 79)$$

where $S^b(W)$ represents the left circular rotation of the 32-bit word, W, by b bits.

  - Now 5 scratch variables, A through E, are initialized from H_0 through H_4, respectively ($A = H_0$, $B = H_1$, $C = H_2$, $D = H_3$, $E = H_4$).

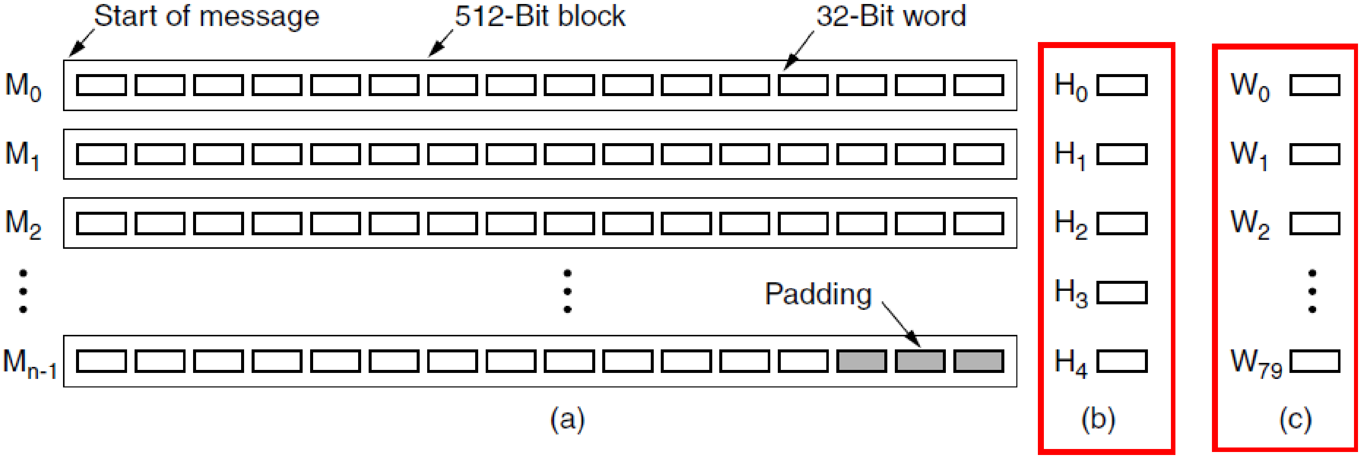
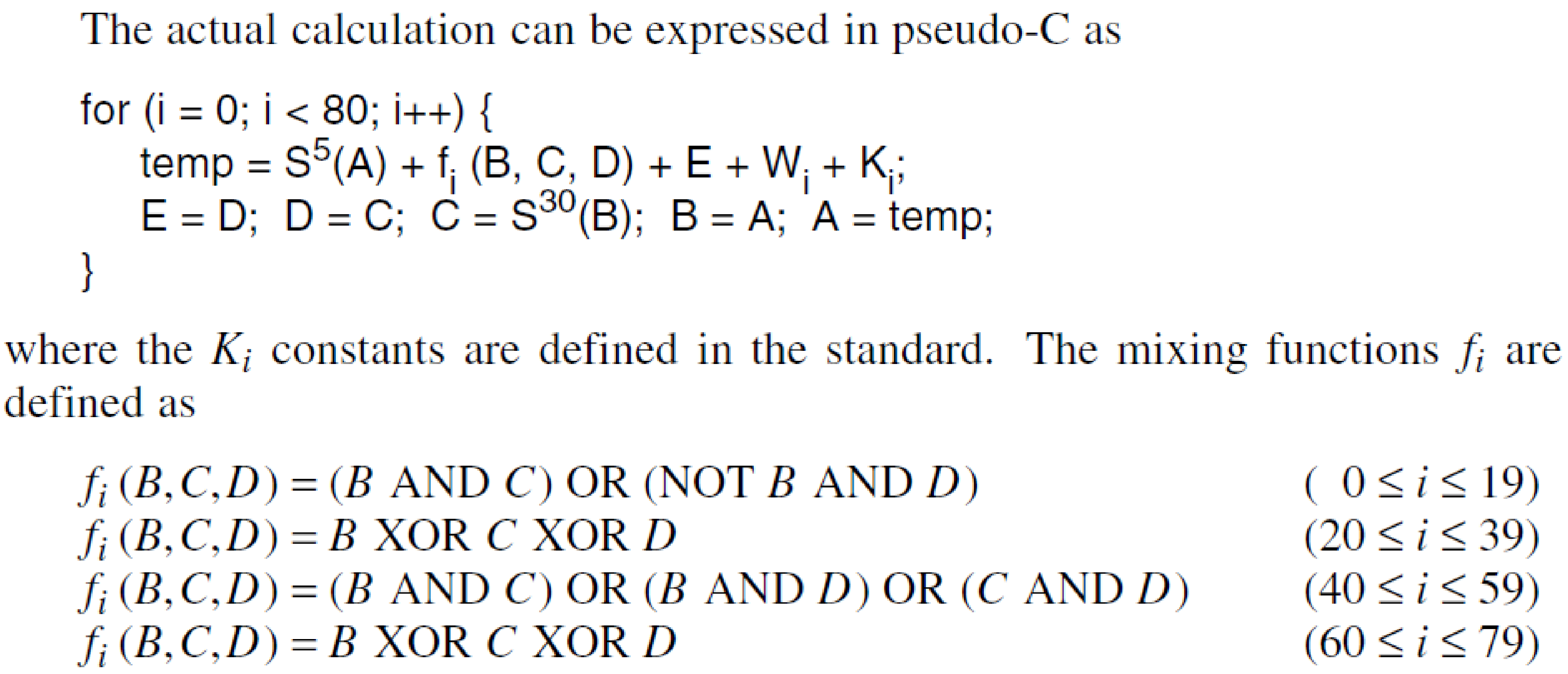


Figure 8-22. (a) A message padded out to a multiple of 512 bits. (b) The output variables. (c) The word array.

SHA-1 (IV)



The actual calculation can be expressed in pseudo-C as

```
for (i = 0; i < 80; i++) {
    temp = $S^5(A) + f_i (B, C, D) + E + W_i + K_i$;
    E = D;  D = C;  C = $S^{30}(B)$;  B = A;  A = temp;
}
```

where the K_i constants are defined in the standard. The mixing functions f_i are defined as

$$f_i(B,C,D) = (B \text{ AND } C) \text{ OR } (\text{NOT } B \text{ AND } D) \qquad (\ 0 \le i \le 19)$$
$$f_i(B,C,D) = B \text{ XOR } C \text{ XOR } D \qquad (20 \le i \le 39)$$
$$f_i(B,C,D) = (B \text{ AND } C) \text{ OR } (B \text{ AND } D) \text{ OR } (C \text{ AND } D) \qquad (40 \le i \le 59)$$
$$f_i(B,C,D) = B \text{ XOR } C \text{ XOR } D \qquad (60 \le i \le 79)$$

- – When all 80 iterations of the loop are completed, A through E are added to H_0 through H_4, respectively.

- Now that the first 512-bit block has been processed, the next one is started. The W array is reinitialized from the new block, but H is left as it was.
- When the last block has been finished, the 5 32-bit words in the H array are output as the 160-bit cryptographic hash.

SHA-2

- New version of SHA-1 have been developed that produce hashes of 224, 256, 384, and 512 bits. Collectively, these versions are called SHA-2.

- MD5 (Rivest, 1992)
  - The death knell is that different messages with the same hash.

The Birthday Attack*

- The idea for this attack comes from a traditional probability question: how many students do you need in a class before the probability of having two people with the same birthday exceeds ½?
- Probability theory says it is just 23. With 23 students, we can form (23 × 22)/2 = 253 different pairs, each of which as a probability of 1/365 of being a hit.
- Generally, there are $n(n-1)/2$ input pairs. If $n(n-1)/2 > k$ the chance of having a least one match is pretty good. Thus approximately, a match is likely for $n > (k)^{1/2}$.
- The birthday attack is that with two different plaintexts, but have the same message digests.

Management of Public Keys (I)

- If Alice and Bob do not know each other, how do they get each other's public keys to start a communication process?
  - The obvious solution is to put your public key on your web page, but the following example says it does not work.

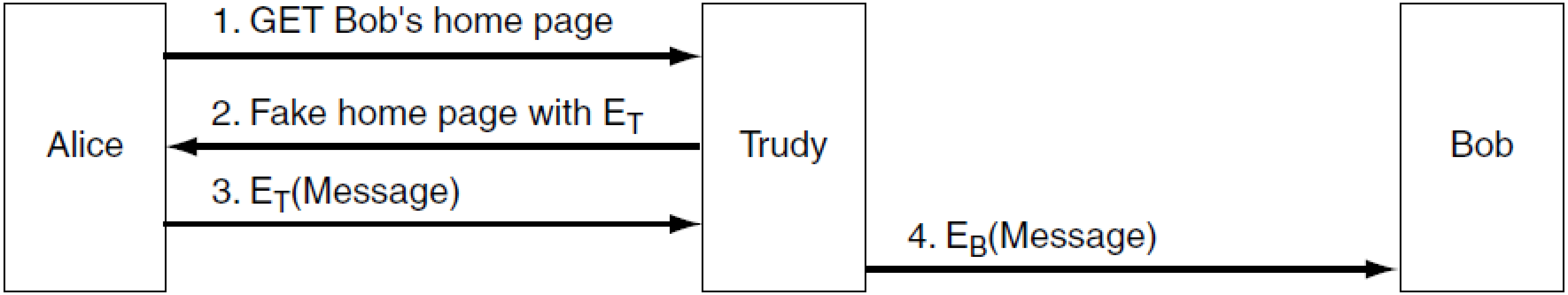


Figure 8-23. A way for Trudy to subvert public-key encryption.

Management of Public Keys (II)

- Some mechanism is needed to make sure that public keys can be exchanged securely.
  - CA (Certification Authority)
  - Standard X.509 (RFC5280)
  - Public key infrastructure

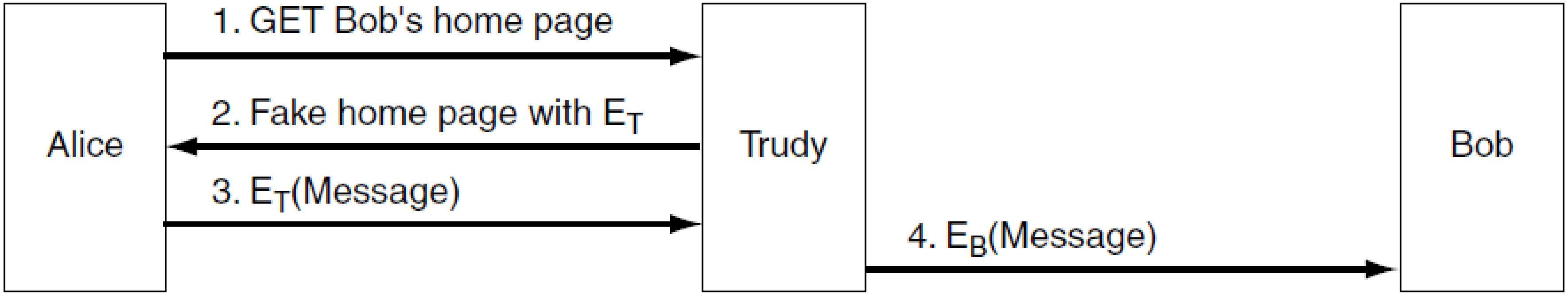
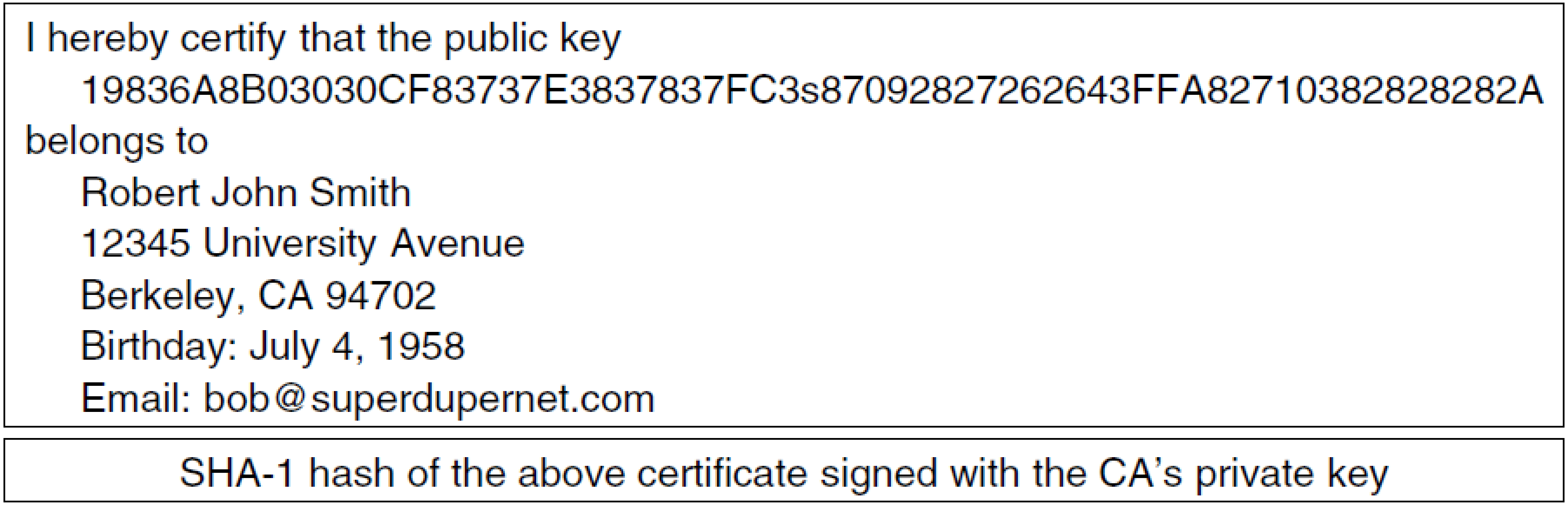


Figure 8-23. A way for Trudy to subvert public-key encryption.

Certificates

- An organization that certifies public keys is now called a **CA** (Certification Authority)
  - The fundamental job of a certificate is to build a public key to the name of a principal (individual, company, etc.)



I hereby certify that the public key
    19836A8B03030CF83737E3837837FC3s87092827262643FFA82710382828282A
belongs to
    Robert John Smith
    12345 University Avenue
    Berkeley, CA 94702
    Birthday: July 4, 1958
    Email: bob@superdupernet.com

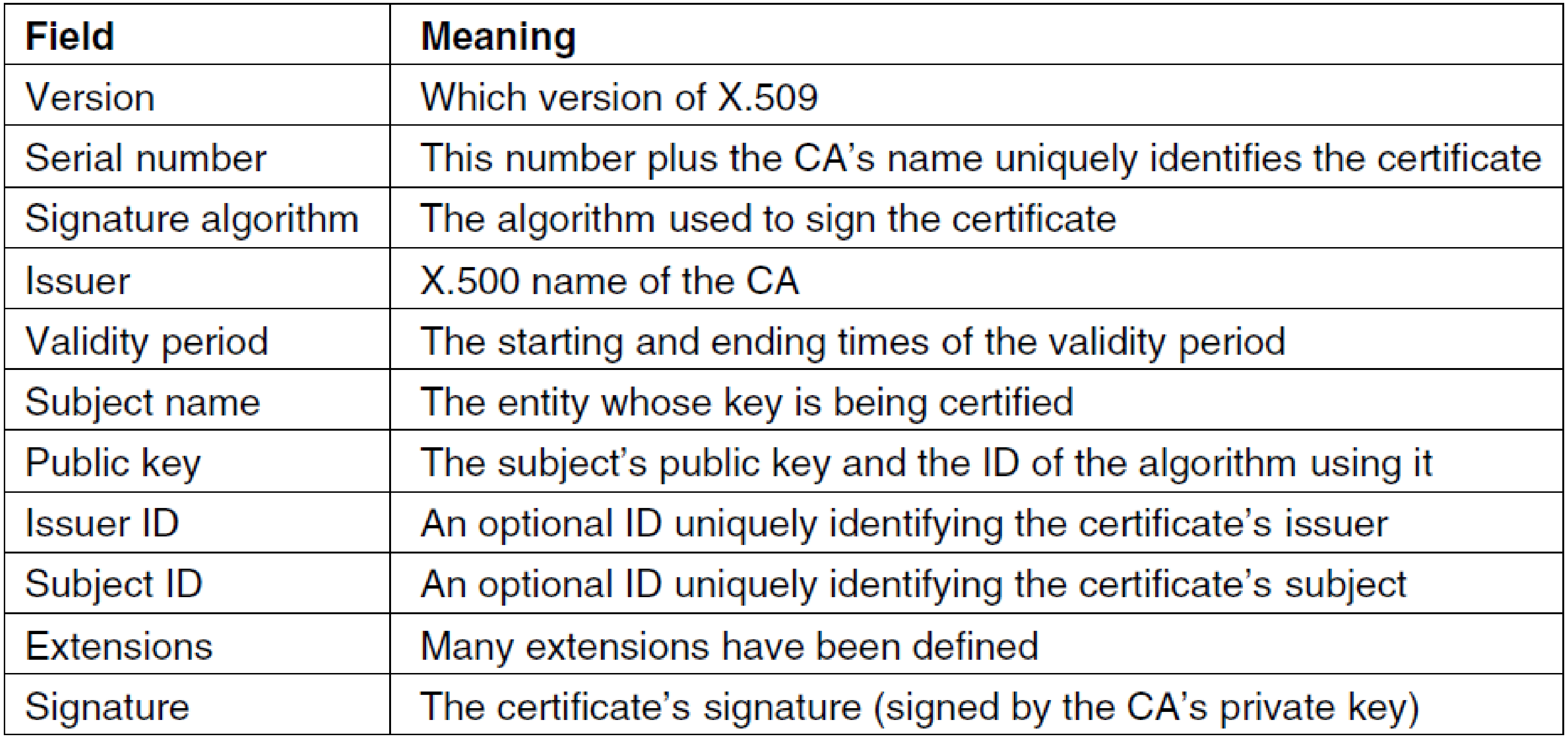
SHA-1 hash of the above certificate signed with the CA's private key

Figure 8-24. A possible certificate and its signed hash.

- The certificate and the signature block (the signed SHA-1 hash of the certificate)

X.509: a standard for certificates*

- The primary fields in a certificate



Field	Meaning
Version	Which version of X.509
Serial number	This number plus the CA's name uniquely identifies the certificate
Signature algorithm	The algorithm used to sign the certificate
Issuer	X.500 name of the CA
Validity period	The starting and ending times of the validity period
Subject name	The entity whose key is being certified
Public key	The subject's public key and the ID of the algorithm using it
Issuer ID	An optional ID uniquely identifying the certificate's issuer
Subject ID	An optional ID uniquely identifying the certificate's subject
Extensions	Many extensions have been defined
Signature	The certificate's signature (signed by the CA's private key)

Figure 8-25. The basic fields of an X.509 certificate.

Public Key Infrastructures (I)

- Having a single CA to issue all the world's certificates obviously would not work.
  - It would collapse under the load and be a central point of failure as well.
- PKI (Public Key Infrastructure) has multiple components, including users, CAs, certificates, and directories.
  - What the PKI does is provide a way of structuring these components and define standards for the various documents and protocols.
  - A particularly simple form of PKI is a hierarchy of CAs.

Public Key Infrastructures (II)

- The top level CA, the root, certifies second-level CAs, which we call RAs (Regional Authorities)
- When the root authorizes a new RA, it generates an X.509 certificate stating that it has approved the RA, includes the new RA's public key in it, signs it, and hands it to the RA. Similarly, when an RA approves a new CA, it produces and signs a certificate stating its ppproval and containing the CA's public key.

It is assumed that everyone knows the root's public key.

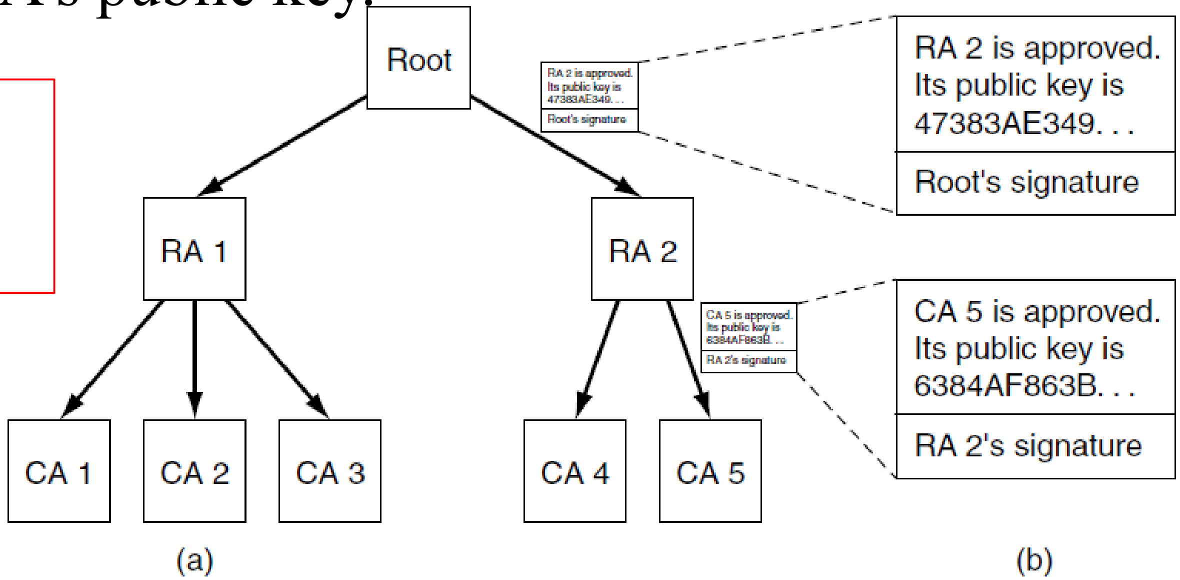

Root
RA 1
RA 2
CA 1
CA 2
CA 3
CA 4
CA 5
RA 2 is approved. Its public key is 47383AE349. . .
Root's signature
RA 2 is approved. Its public key is 47383AE349. . .
Root's signature
CA 5 is approved. Its public key is 6384AF863B. . .
RA 2's signature
CA 5 is approved. Its public key is 6384AF863B. . .
RA 2's signature
(a)
(b)

Figure 8-26. (a) A hierarchical PKI. (b) A chain of certificates.

Public Key Infrastructures (III)

- It is assumed that everyone knows the root's public key.
- A chain of certificates going back to the root is called **a chain of trust** or **a certification path**.
- Modern browsers come preloaded with the public keys for over 100 roots.
- Most browser allow users to inspect the root keys (usually in the form of certificates signed by the root) and delete any that seem shady.

Communication Security

- Although IETF has known for years that security was lacking in the Internet, there are many different views about in which layer should encryption be put.
  - 1) Application layer (encryption and integrity checks have to be end to end)
    - The trouble with this approach is that it requires changing all the applications to make them security aware.
  - 2) Transport layer (or a new layer between the application layer and the transport layer)
    - It is still end to end but not requiring applications to be changed.
    - The opposite view is that users do no understand security and will not be capable of using it correctly and nobody wants to modify existing programs in any way.
  - 3) network layer
    - The network layer should authenticate and/or encrypt packets without users being involved.
    - After years of pitched battles, this view won enough support that a network layer security standard was defined.

IPsec (I)

- **IPsec** (**IP security**) described in RFCs 2401, 2402, 2406, and 2410, among others.
- The complete IPsec design is a framework for multiple services, algorithms, and granularities.
  - The reason for multiple services is that not everyone wants to pay the price for having all the services all the time, so the services are available a la carte (套餐).
    - The major services are secrecy, data integrity, and protection from replay attacks.
    - All of these are based on symmetric-key cryptography because high-performance is crucial.
  - The reason for multiple algorithms is that an algorithm that is now thought to be secure may be broken in the future. By making IPsec algorithm-in-dependent, the framework can survive even if some particular algorithm is later broken.
  - The reason for multiple granularities is to make it possible to protect a single TCP connection, all traffic between pair of hosts, or all traffic between a pair of secure routers, among other possibilities.

IPsec (II)

- IPsec is in the IP layer (the network layer), and it is connection oriented.
- A "connection" in the context of IPsec is called an SA (Security Association).
    - An SA is a simplex connection between two endpoints and has a security identifier associated with it.
    - If secure traffic is needed in both directions, two security associations are required.
    - Security identifiers are carried in packets traveling on these secure connections and are used to look up keys and other relevant information when a secure packet arrives.

IPsec (III)

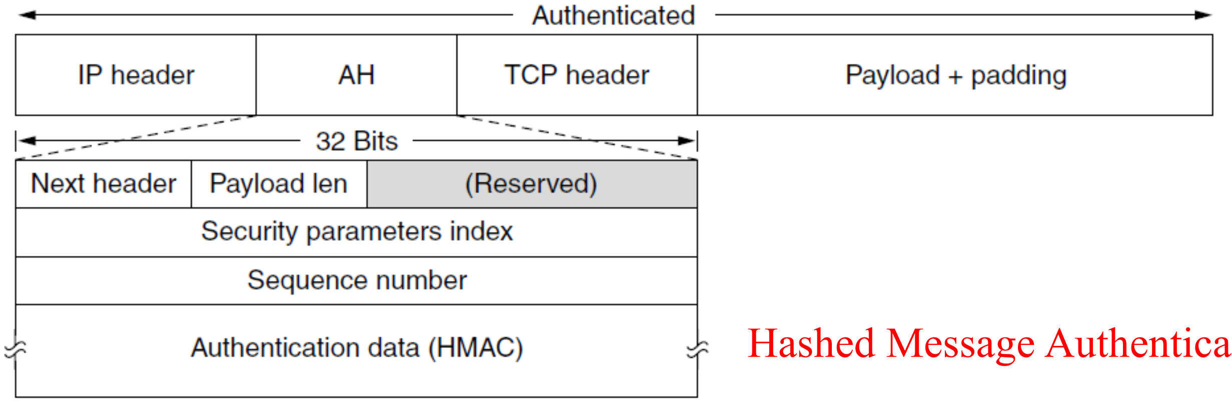
- IPsec has two principal parts:
  - The 1st part describes two new headers that can be added to packets to carry the security identifier, integrity control data, and other information.
  - The other part, **ISAKMP** (Internet Security Association and Key Management Protocol), deals with establishing keys.
    - ISAKMP is a framework.
    - The main protocol for carrying out the work is IKE (Internet Key Exchange), RFC4306.

IPsec (IV)

- **IPsec** can be used in either of *two modes*:
  - In **transport mode**, the IPsec header is inserted just after the IP header. The protocol field in the IP header is changed to indicate that an IPsec header follows the normal IP header (before the TCP header).
    - The IPsec header contains security information, primarily the **SA identifier**, a new sequence number and possibly an integrity check of the payload.
  - In **tunnel mo**de, the entire IP packet, header and all, is encapsulated in the body of a new IP packet with a completely new IP header.
    - Tunnel modes is useful when the tunnel ends at a location other than the final destination. In some cases, the end of the tunnel is *a security gateway machine*.
      - This is commonly the case for a VPN (Virtual Private Network).
    - Studying the flow patterns of packets, even if they are encrypted, is called **traffic analysis**. Tunnel mode provides a way to foil it to some extent.
    - The disadvantage of tunnel mode is that it adds an extra IP header, thus increasing packet size substantially. In contrast, transport mode does not affect packet size as much.

IPsec (V)

- AH (Authentication Header) It provides **integrity checking** and **anitreplay security**, but no secrecy (i.e., no data encryption).
  - In IPv4, it is interposed between the IP header (including any options) and the TCP header.
  - In IPv6, it is just another extension header and is treated as such.
  - The payload may have to be padded out to some particular length for the authentication algorithm.
  - The next header field is used to store the value that the IP Protocol field had before it was replaced with **51** to indicate that an AH header follows. In most cases, the code for **TCP** (**6**) will go here.

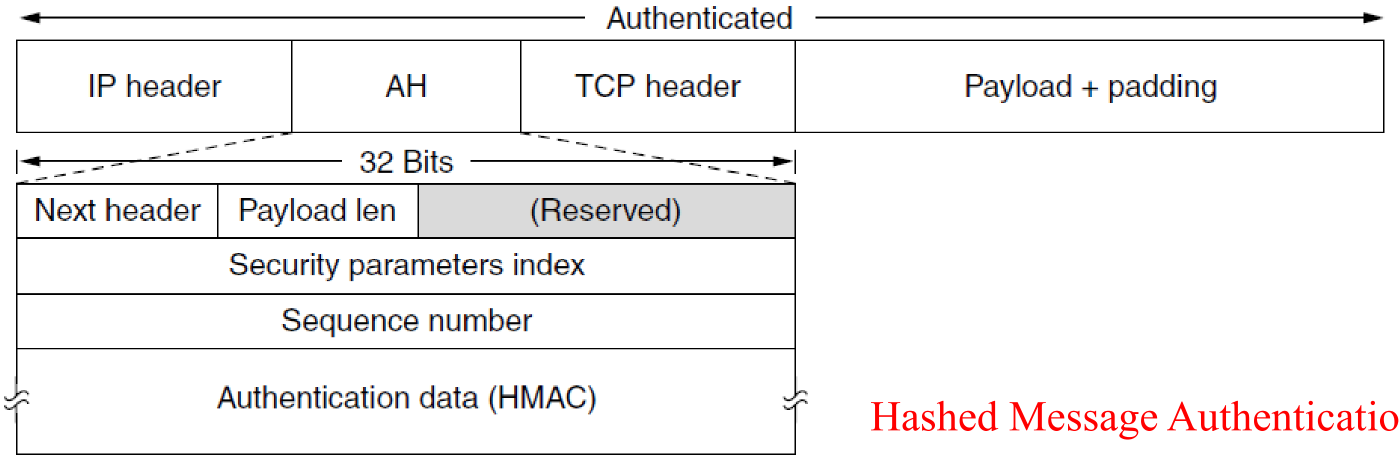


Hashed Message Authentication Code (HMAC)

Figure 8-27. The IPsec authentication header in transport mode for IPv4.

IPsec (VI)

- The **payload length** is the number of 32-bit words in the AH header minus 2.
- The **security parameters index** is the connection identifier. It is inserted by the sender to indicate a particular record in the receiver's database. This record contains the shared key used on this connection and other information about the connection.
- The **sequence number field** is used to number all the packets sent on an SA. Every packet gets a unique number, even retransmissions. The purpose of this field is to detect replay attacks. These sequence numbers may not wrap around. If all 2^{32} are exhausted, a new SA must be established to continue communication.



Hashed Message Authentication Code (HMAC)

Figure 8-27. The IPsec authentication header in transport mode for IPv4.

IPsec (VII)

- **Authentication data**, which is a variable-length field that contains the payload's digital signature.
  - When the SA is established, the two sides negotiate which signature algorithm they are going to use.
  - Since IPsec is base on symmetric-key cryptography and the sender and the receiver negotiate a shared key before setting up an SA, the shared key is used in the signature computation.
  - One simple way is to compute the hash over the packet plus the shared key. The shared key is not transmitted.
    - HMAC (Hashed Message Authentication Code)
  - AH handled only integrity checking, no data encryption.
    - It is much faster to compute than first running SHA-1 and then running RSA on the result.

IPsec (VIII)

- **ESP** (Encapsulation Security Payload) Its use for both transport mode and tunnel mode. ESP handled only secrecy.
- The ESP header consists of two 32-bit words. They are **Security parameters index** and **Sequence number** fields that we saw in AH.
- Putting the HMAC at the end has an advantage in a hardware implementation: the HMAC can be calculated as the bits are going out over the network interface and appended to the end.
  – This is why Ethernet and other LANs have their CRCs in a trailer.

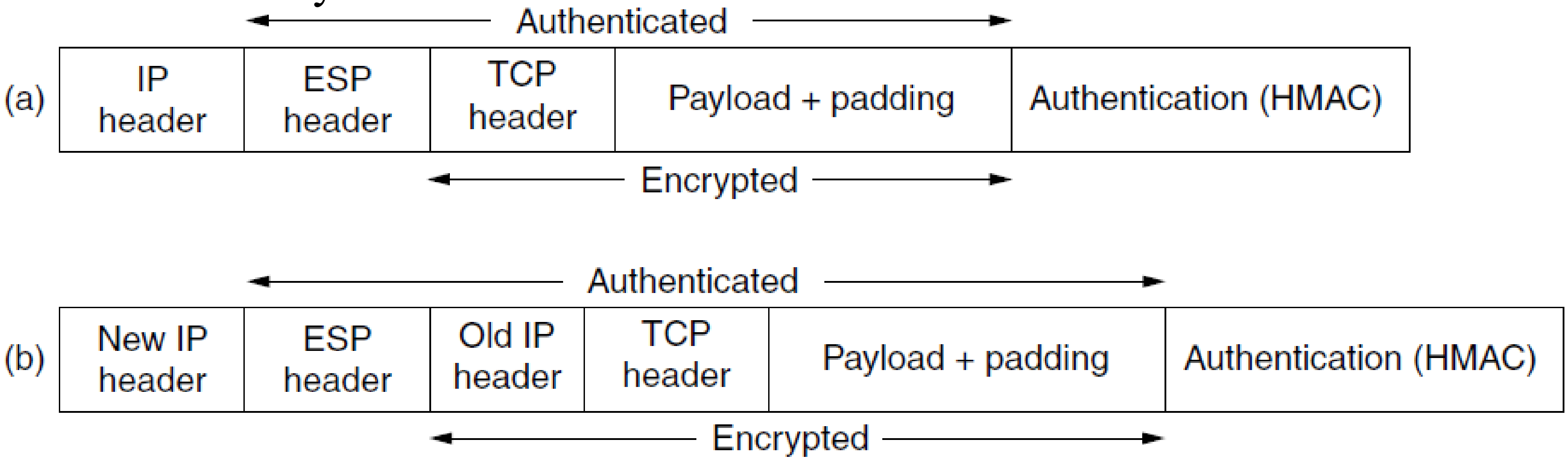
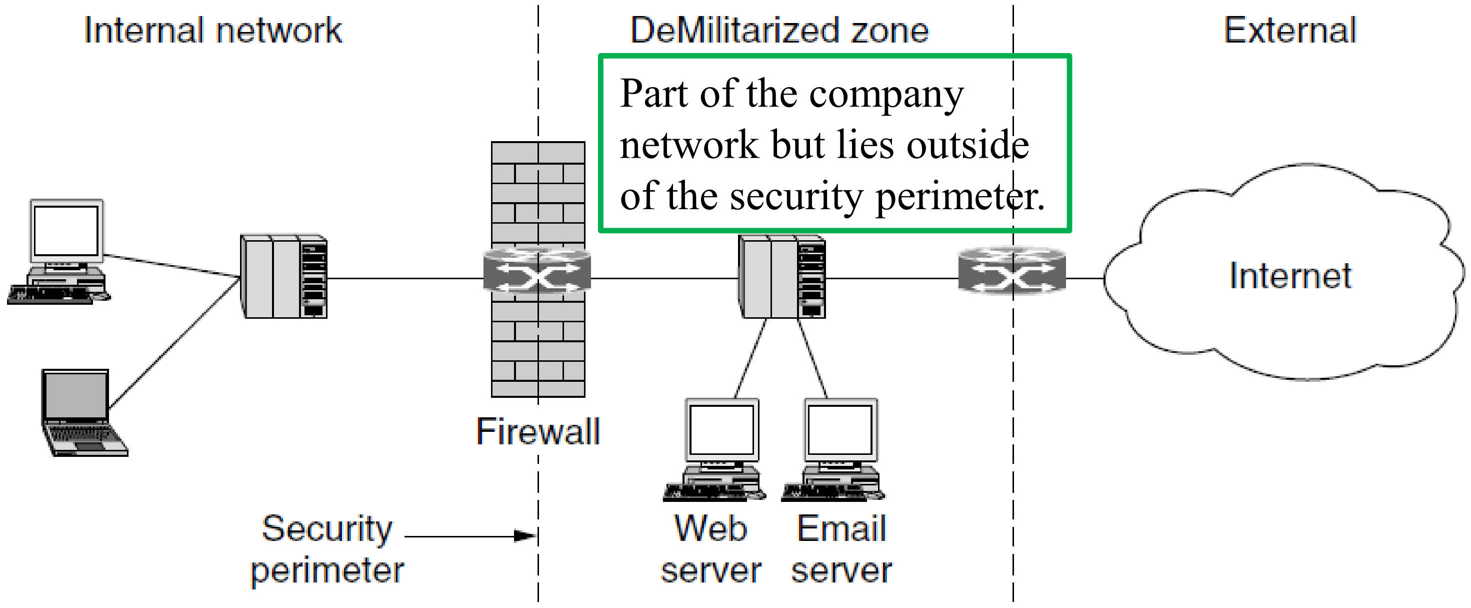


Figure 8-28. (a) ESP in transport mode. (b) ESP in tunnel mode.

Firewalls (I)

- IPsec protects data in transit between secure sites. But IPsec does nothing to keep digital pests (virus, worms) and intruders from getting into the company LAN.
- The firewall acts as **a packet filter**.
    - It inspects each and every incoming and outgoing packet. Packets meeting some criterion described in rules formulated by the network administrator are forward normally. Those that failed the test are unceremoniously dropped.

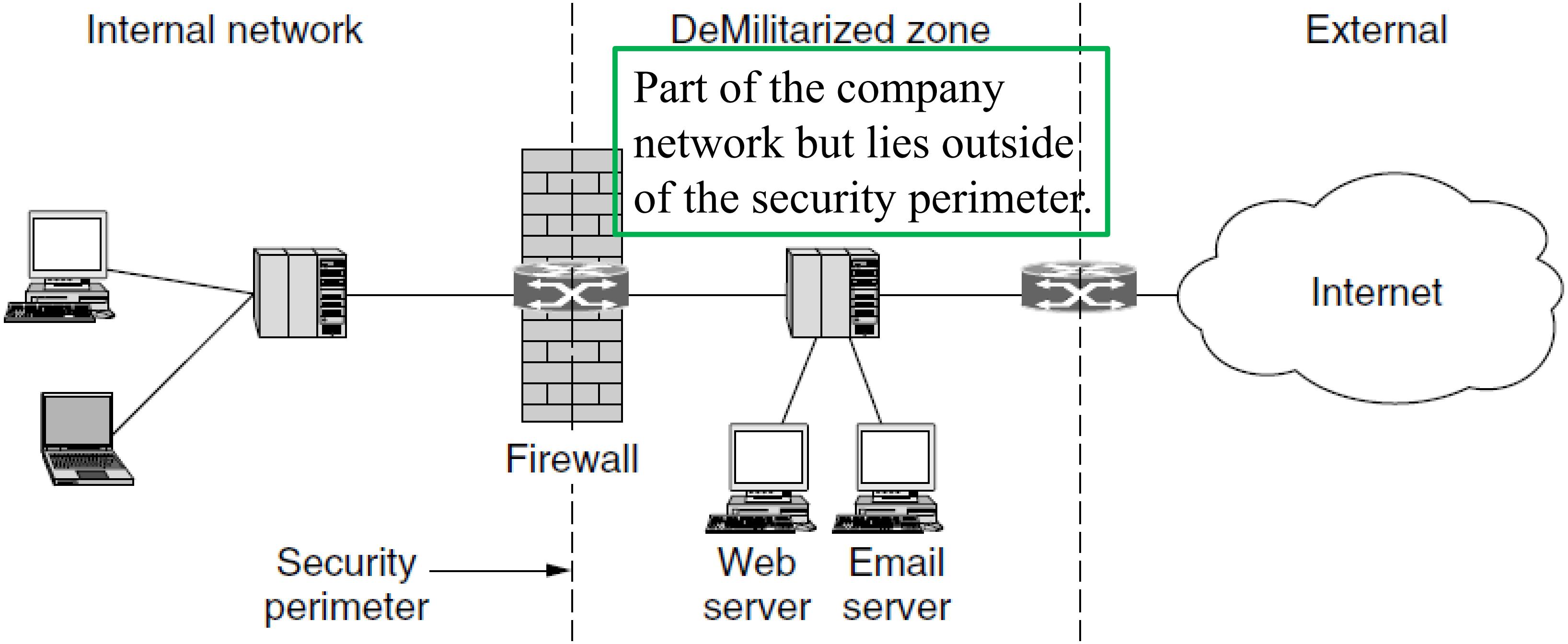


Part of the company network but lies outside of the security perimeter.

Figure 8-29. A firewall protecting an internal network.

Firewalls (II)

- The firewall acts as **a packet filter**, but violate the standard layering of protocols.
  - They are network layer devices, but they peek at the transport and application layers to do their filtering.



Part of the company network but lies outside of the security perimeter.

Figure 8-29. A firewall protecting an internal network.

Firewalls (III)

- Firewalls tend to *rely on standard port numbering conventions* to determine what kind of traffic is carried in a packet.
  - Some peer-to-peer applications select ports dynamically to avoid being easily spotted (and blocked).
  - Encryption with IPsec or other schemes hides higher-layer information from the firewall.
- Firewalls are often used in *a layered defense*.
  - For example, a firewall may guard the entrance to the internal network and each computer may also run its own firewall.
- The basic idea of a firewall is to prevent intruders from getting in and secret data from getting out. But
  - **DoS** (Denial of Service): Attacks in which the intruder's goal is to shut down the target rather than steal data. — *DNS DoS*
  - **DDoS** (Distributed Denial of Service) attack

Virtual Private Networks (VPN)

- A network build up from company computers and leased telephone lines is called a **private network**.
  - Expensive
- VPNs are overlay networks on top of public networks (i.e. the Internet) but with most of the properties of private networks.
  - To equip each office with a firewall and create tunnels through the Internet between all pairs of offices
    - flexible

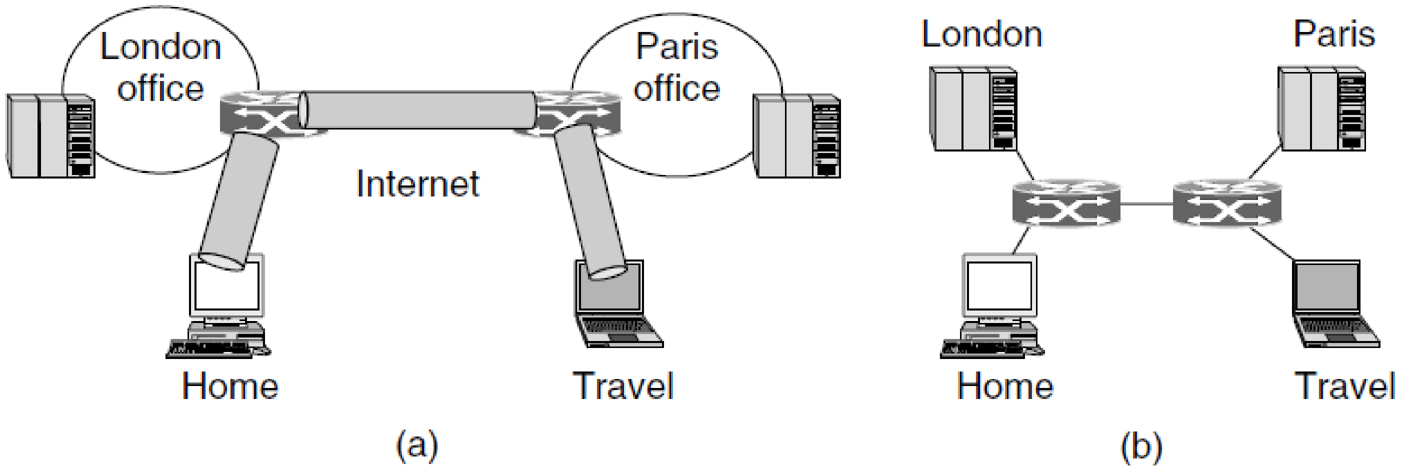


Figure 8-30. (a) A virtual private network. (b) Topology as seen from the inside.

Virtual Private Networks (VPN)

- When the system is brought up, each pair of firewalls has to negotiate the parameters of its SA, including the services, modes, algorithms, and keys.
- If IPsec is used for tunneling, it is possible to aggregate all traffic between any two pairs of officers onto a single authenticated, encrypted SA, thus providing integrity control, secrecy, and even considerable immunity to traffic analysis.

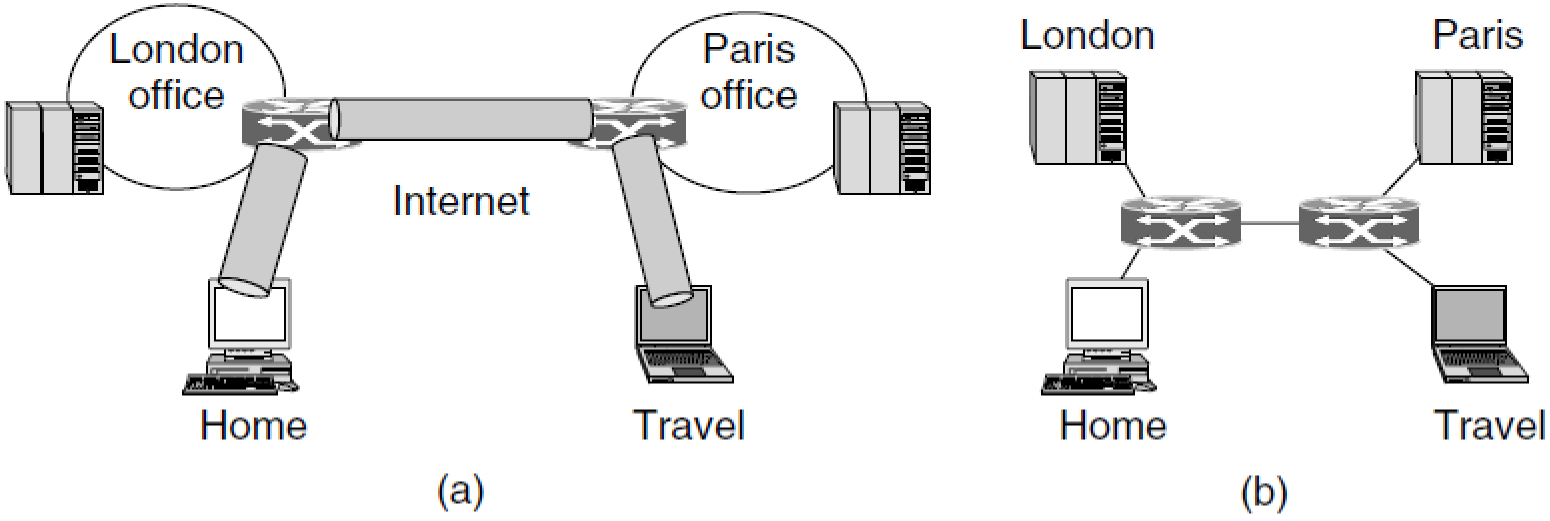


Figure 8-30. (a) A virtual private network. (b) Topology as seen from the inside.

Virtual Private Networks (VPN)

- Firewalls, VPNs, and IPsec with ESP in tunnel mode are a natural combination and widely used in practice.
- Another approach is to have the ISP set up the VPN.
  - MPLS (MultiProtocol Label Switching, Chapter 5), paths for the VPN traffic can be set up across the ISP network between the company offices.

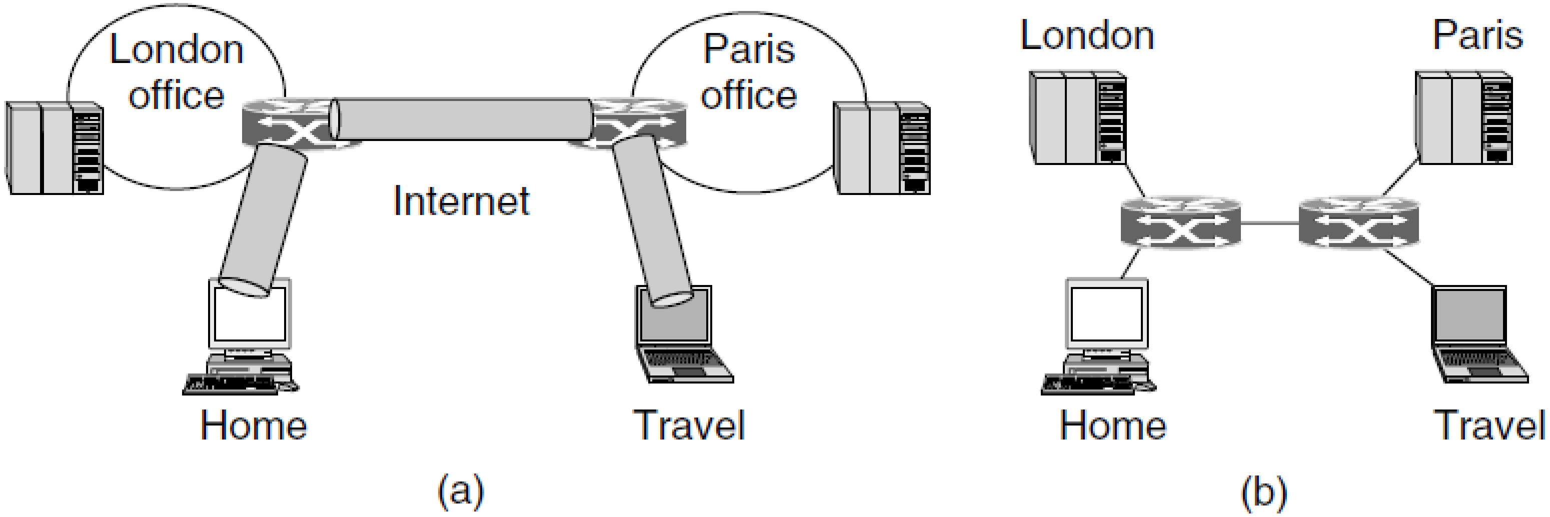


Figure 8-30. (a) A virtual private network. (b) Topology as seen from the inside.

Wireless Security (I)

- Security is more important for wireless systems than for wired systems.
- WEP (Wired Equivalent Privacy), the first generation of 802.11 security protocols.
  - WEP encrypted data for confidentiality by XORing it with the output of a stream cipher.
  - Weak keying arrangements meant that the output was often reused.
  - WEP was broken came when Adam Stubblefield was an intern at AT&T.
  - The use of WEP is very strongly discouraged.

Wireless Security (II)

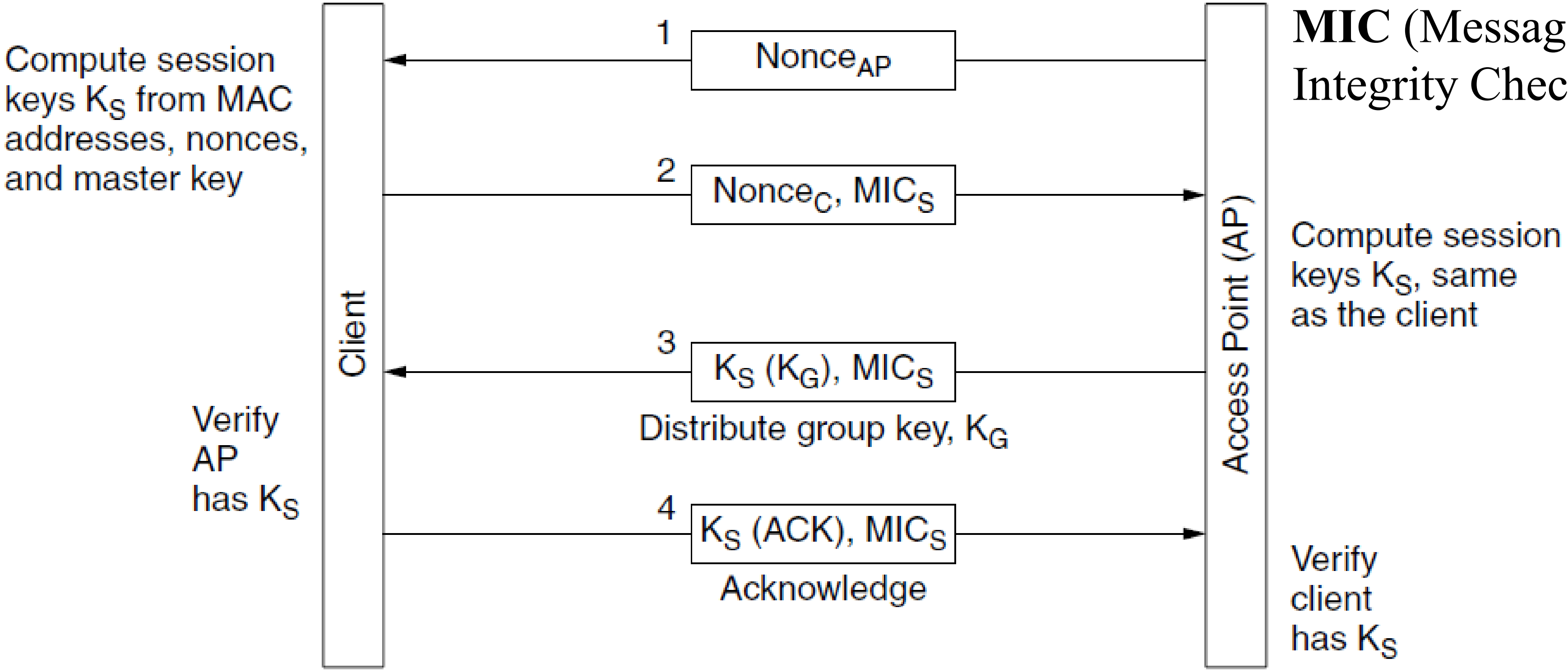
- 802.11i prescribes **a data link-level security protocol** for preventing a wireless node from reading or interfering with messages sent between another pair of wireless nodes.
  - WPA2 (WiFi Protected Access 2)
- There are two common scenarios in which WPA2 is used.
  - 1)A separate authentication server that has a username and password database that can be used to determine if a wireless client is allowed to access the network. In this setting, clients use standard protocols to authenticate themselves to the network.
  - 2) A single shared password that is used by clients to access the wireless network (Home WiFi environment).
  - The main difference is that with an authentication server each client gets a key for encrypting traffic that is not known by the other clients. With a single shared password, different keys are derived for each client, but all clients have the same password and can derive each other’s keys if they want to.

Wireless Security (III)

- The keys that are used to encrypt traffic are computed as part of *an authentication handshake*.
  - The handshake happens right after the client associates with a wireless network and authenticates with an authentication server, if there is one.
  - At the start of the handshake, the client has either *the shared network password* or its password for the authentication server. This password is used to derive **a master key**.
  - However, the master key is not used directly to encrypt packets. It is standard cryptographic practice to derive **a session key** for each period of usage, to change the key for different sessions, and to expose the master key to observation as little as possible.

Wireless Security (IV)

- The session key is computed with the four-packet handshake.
  - 1) The AP (access point) sends a random number of identification (**nonces**) The client also picks its own nonce. It uses the nonces, its MAC address and that of the AP, and the master key to compute a session key, Ks.

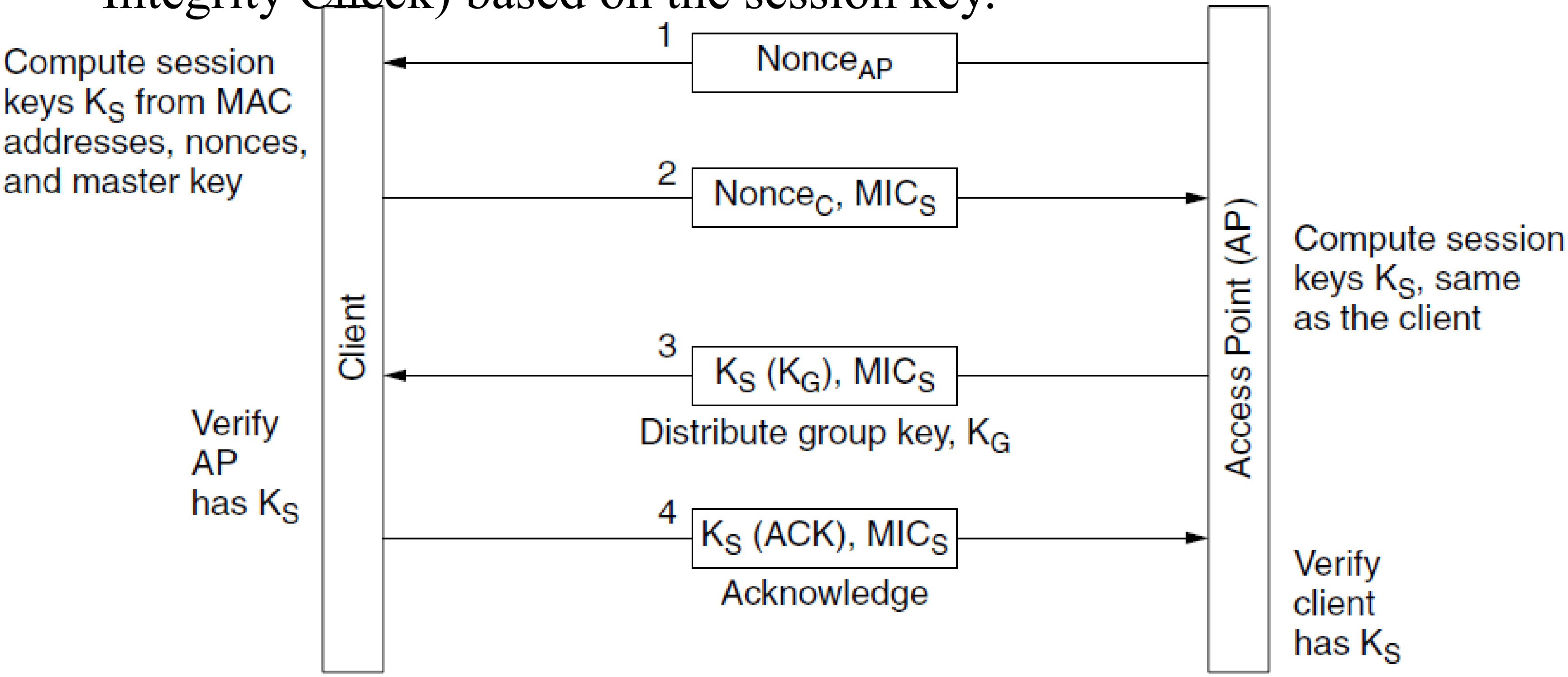


MIC (Message Integrity Check)

Figure 8-31. The 802.11i key setup handshake.

Wireless Security (V)

- The session key is computed with the four-packet handshake.
  - 2) The client sends its nonce to the AP, and the AP performs the same computation to derive the same session keys. The message from the client is protected with an integrity check called MIC (Message Integrity Check) based on the session key.



Compute session keys K_S from MAC addresses, nonces, and master key
Client
1
Nonce_{AP}
2
Nonce_C, MIC_S
Access Point (AP)
Compute session keys K_S, same as the client
3
K_S (K_G), MIC_S
Distribute group key, K_G
Verify AP has K_S
4
K_S (ACK), MIC_S
Acknowledge
Verify client has K_S

Figure 8-31. The 802.11i key setup handshake.

Wireless Security (VI)

- The session key is computed with the four-packet handshake.
  - 3) The AP distributes a group key, K_G, to the client.
  - 4) The client acknowledges the message.
    - The group key is used for broadcast and multicast traffic on 802.11 LAN.

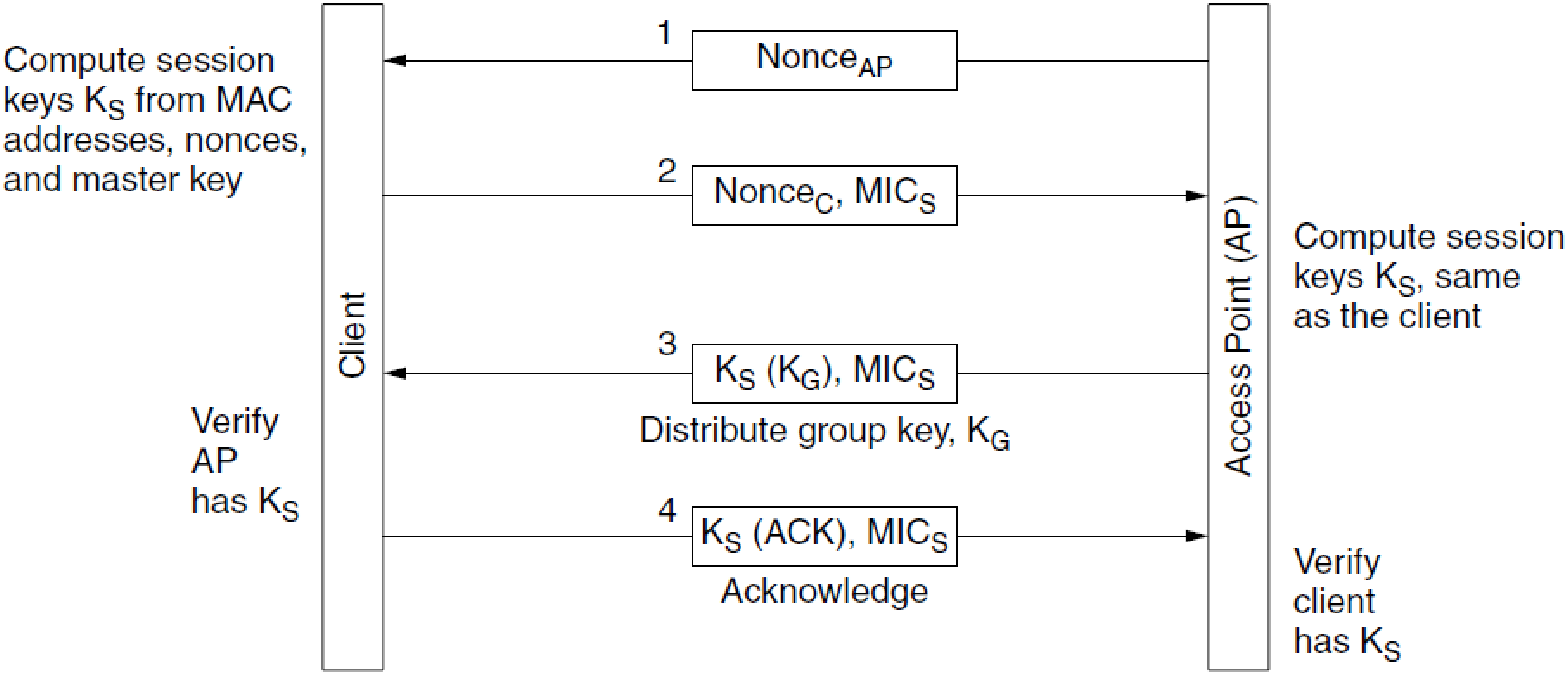


Figure 8-31. The 802.11i key setup handshake.

Wireless Security (VII)

- The session key is split into portions, each of which is used for different purposes.
- Because every client has its own encryption keys, none of these keys can be used by the AP to broadcast packets to all of the wireless clients.
- A shared key is distributed so that broadcast traffic can be sent only once and received by all the clients. It must be updated as clients leave and join the network.
- Two protocols can be used in 802.11i to provide message confidentiality, integrity and authentication.
  - TKIP
  - CCMP

Authentication Protocols

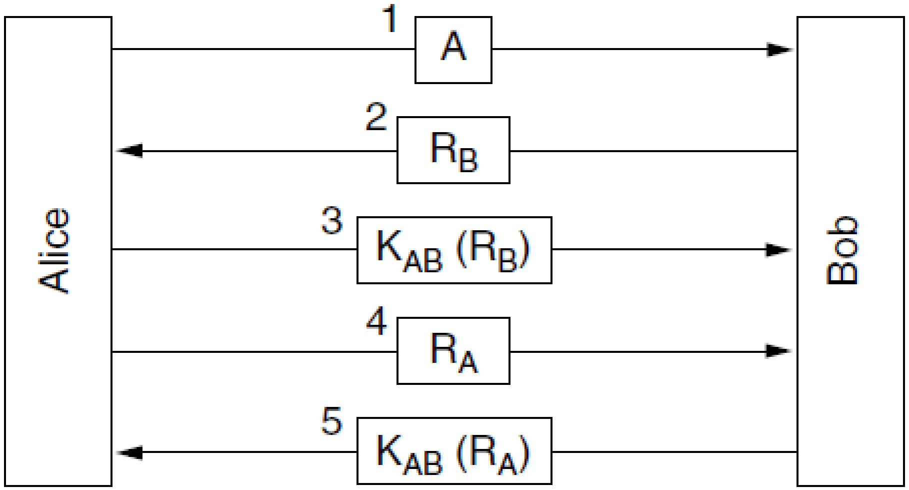
- Authentication is the technique by which a process verifies that its communication partner is who it is supposed to be and not imposter.
  - Verifying the identity of a remote process in the face of a malicious, active intruder is surprisingly difficult and requires complex protocols based on cryptography.
  - Authentication (验证) vs. authorization (授权)
  - Authentication deals with the question of whether you are actually communicating with a specific process.
  - Authorization is concerned with what the process is permitted to do.
  - For example, say a client process contacts a file server and says: “I am Scott’s process and I want to delete the file cookbook.old”.
    - Is this actually Scott’s process (authentication)?
    - Is Scott allowed to delete cookbook.old (authorization)?

Authentication Protocols

- The general model
  - A trusted **KDC** (Key Distribution Center)
  - Alice starts out by sending a message either to Bob or to a trusted KDC, which is expected to be honest.
  - Several other message exchanges follow in various directions.
  - As these messages are being sent, Trudy may intercept, modify, or replay them in order to trick Alice and Bob or just to gum up the works.
  - In most of the protocols, Alice and Bob will also have established **a secret session key** for use in the upcoming conversation.

Authentication based on a shared secret key (I)

- Assume that Alice and Bob already share a secret key K_{AB}.
- One party sends *a random number* to the other, who then transforms it in a special way and returns the result.
  - Such protocols are called **Challenge-response** protocols
  - This protocol contains five messages.



A, *B* are the identities of Alice and Bob.
R_i's are the challenges, where *i* identifies the challenger.
K_i's are keys, where *i* indicates the owner.
K_S is the session key.

Figure 8-32. Two-way authentication using a challenge-response protocol.

Authentication based on a shared secret key (II)

- A shorten two-way authentication protocol as illustrated in Fig 8-33.
  - Is this new protocol an improvement over the original one?
- Under certain circumstances, Trudy can defeat this protocol by using what is known as **a reflection attack**.
  - Trudy can break it if it is possible to open multiple sessions with Bob at once.

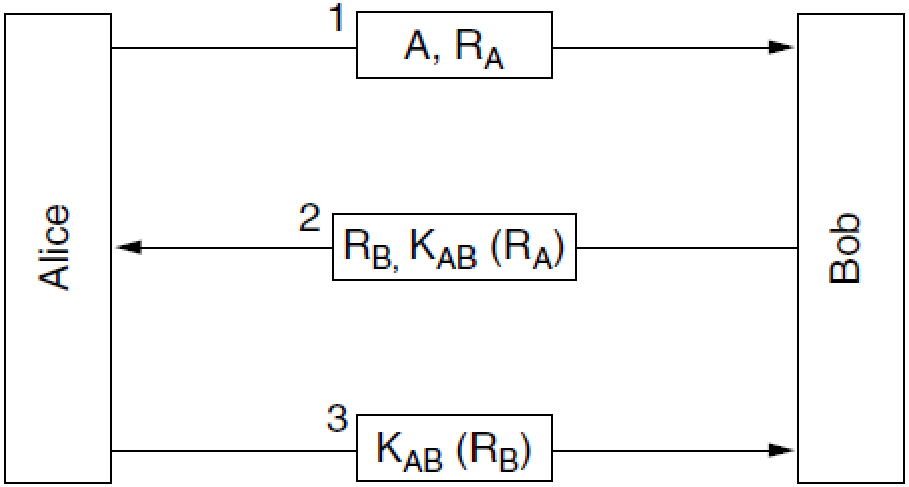


Figure 8-33. A shortened two-way authentication protocol.

Authentication based on a shared secret key (III)

- Trudy's **reflection attack** is shown in Fig. 8-34.
  - Trudy can open a second session with message 3, supplying the RB taken from message 2 as her challenge.

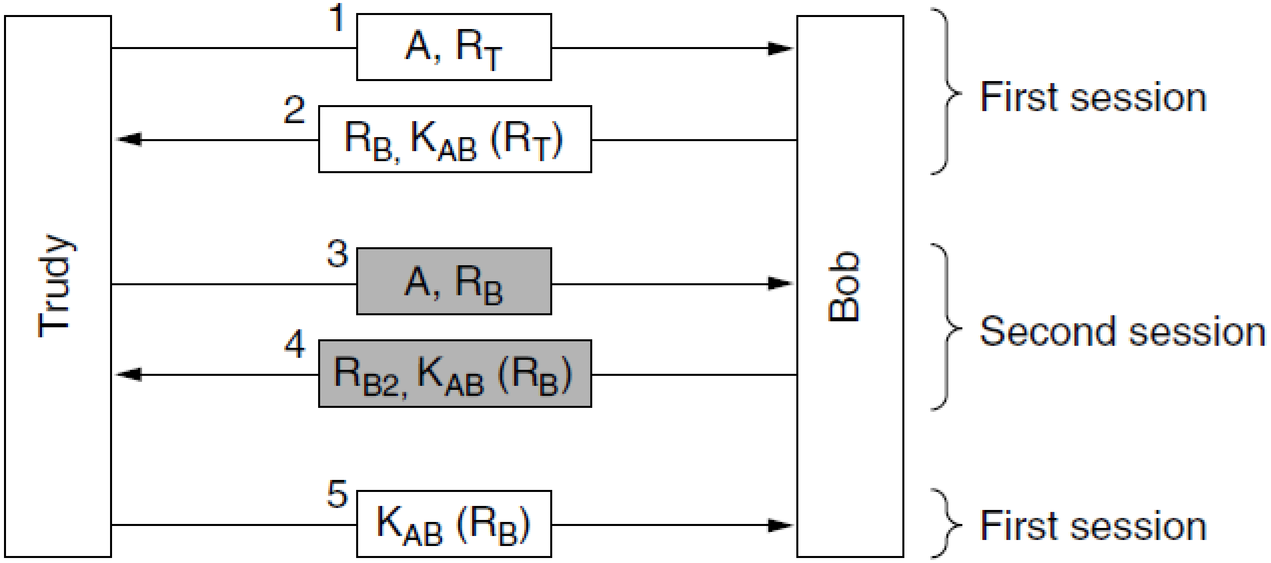
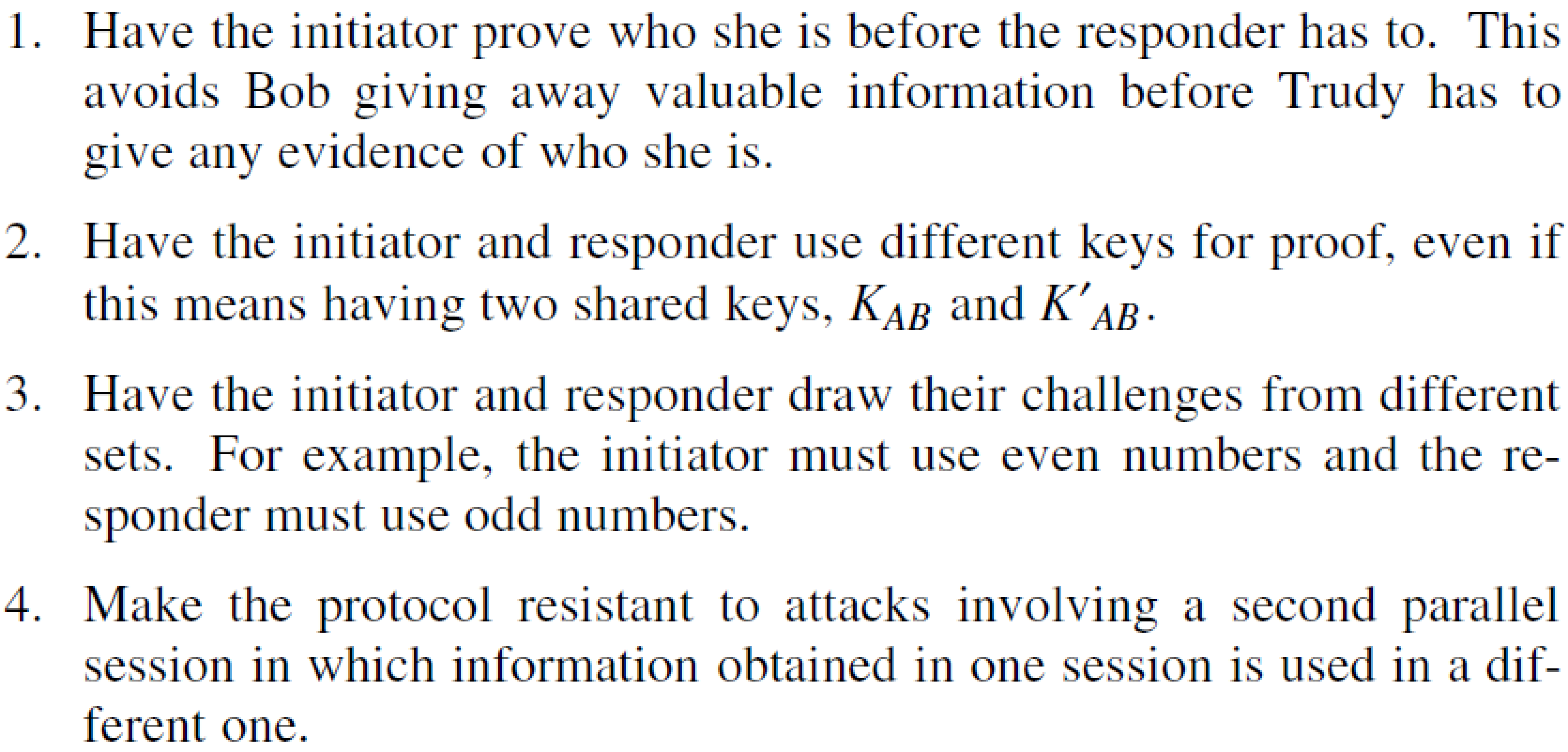


Figure 8-34. The reflection attack.

中间两个灰色交换信息中：Trudy用第一个session中R_B作为自己的随机数，然后Bob会用他与Alice共有的Secret Key: K_{AB}来加密R_B发给Trudy。然后message 5中Trudy就用K_{AB}(R_B)来回复Bob的message 2使Bob相信Trudy就是Alice。

Authentication based on a shared secret key (IV)

- The 4 general rules often help the designer avoid common pitfalls

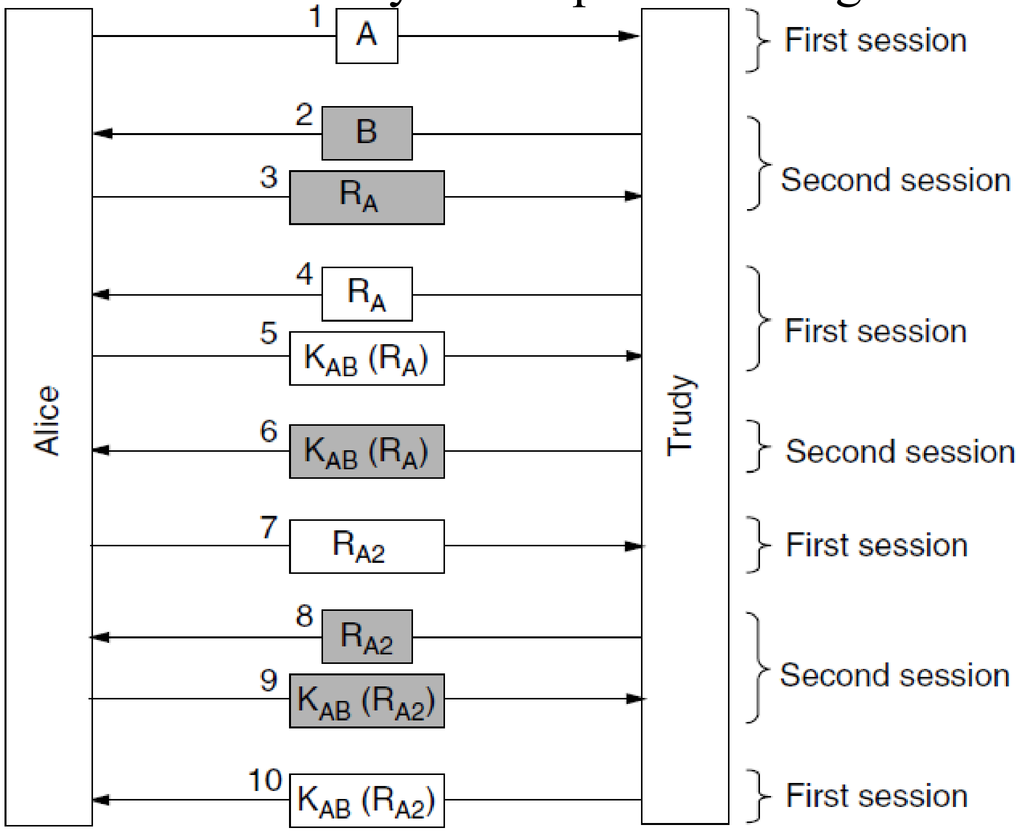


1. Have the initiator prove who she is before the responder has to. This avoids Bob giving away valuable information before Trudy has to give any evidence of who she is.
2. Have the initiator and responder use different keys for proof, even if this means having two shared keys, K_{AB} and K'_{AB}.
3. Have the initiator and responder draw their challenges from different sets. For example, the initiator must use even numbers and the responder must use odd numbers.
4. Make the protocol resistant to attacks involving a second parallel session in which information obtained in one session is used in a different one.

If even one of these rules is violated, the protocol can frequently be broken.

Authentication based on a shared secret key (V)

- What would happen if Alice is a general-purpose computer that also accepted *multiple sessions*?
  - This time Trudy intercept the messages from Alice, claiming to be “Bob”.



Trudy uses message 3 from Alice as the challenge to Alice (以子之矛攻子之盾)

Figure 8-35. A reflection attack on the protocol of Fig. 8-32.

Authentication based on a shared secret key (VI)

- The HMAC is formed by building a data structure consisting of Alice's nonce, Bob's nonce, their identities, and the shared secret key K_{AB}. This data structure is then hashed into the HMAC, for example, using SHA-1.
  - Trudy cannot subvert this protocol. Because she cannot force either party to encrypt or hash a value of her choice, as happened in Fig.8-34 and Fig.8-35.

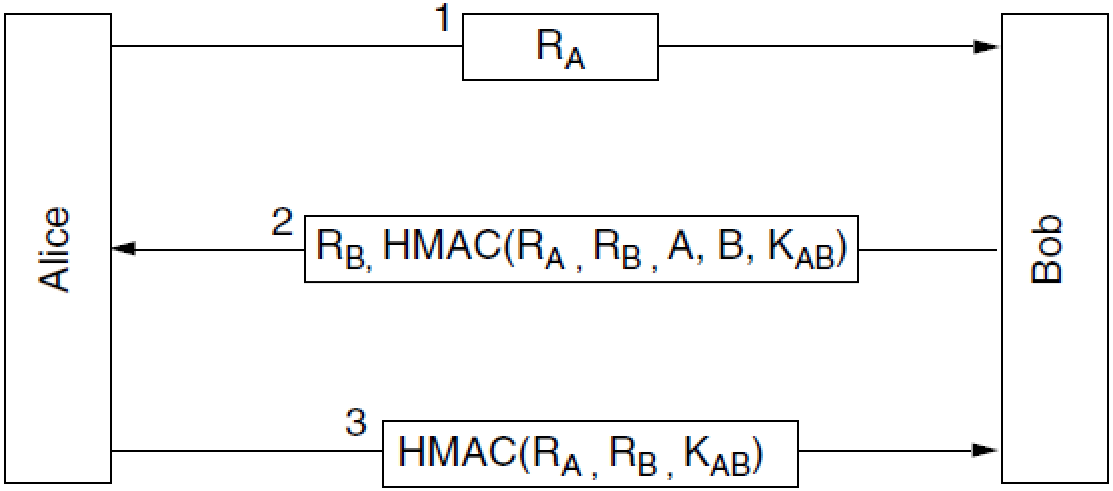

Alice
Bob
1
R_A
2
R_B, HMAC(R_A , R_B , A, B, K_{AB})
3
HMAC(R_A , R_B , K_{AB})

Figure 8-36. Authentication using HMACs.

Establishing a Shared Key: the Diffie-Hellman Key Exchange (I)

- The protocol that allows strangers to establish a shared secret key.
- The Diffie-Hellman Key exchange (Diffie and Hellman, 1976)
  - The two parties have to agree on two large numbers, n and g, where n is a prime, $(n - 1)/2$ is also a prime, and certain conditions apply to g.
  - One party (Alice) picks a large number x, and keeps it secret. Similarly, the other party (Bob) picks a large secret number y.
  - Alice initiates the key exchange protocol by sending Bob a message containing (n, g, g^x mod n).
  - Bob responds by sending Alice a message containing g^y mod n.
  - Alice raises the number Bob sent her to the xth power modulo n to get $(g^y \bmod n)^x \bmod n$. Bob performs a similar operation to get $(g^x \bmod n)^y \bmod n$.
  - By **the laws of modular arithmetic**, both calculations yield g^{xy} mod n (the shared key).

Establishing a Shared Key: the Diffie-Hellman Key Exchange (II)

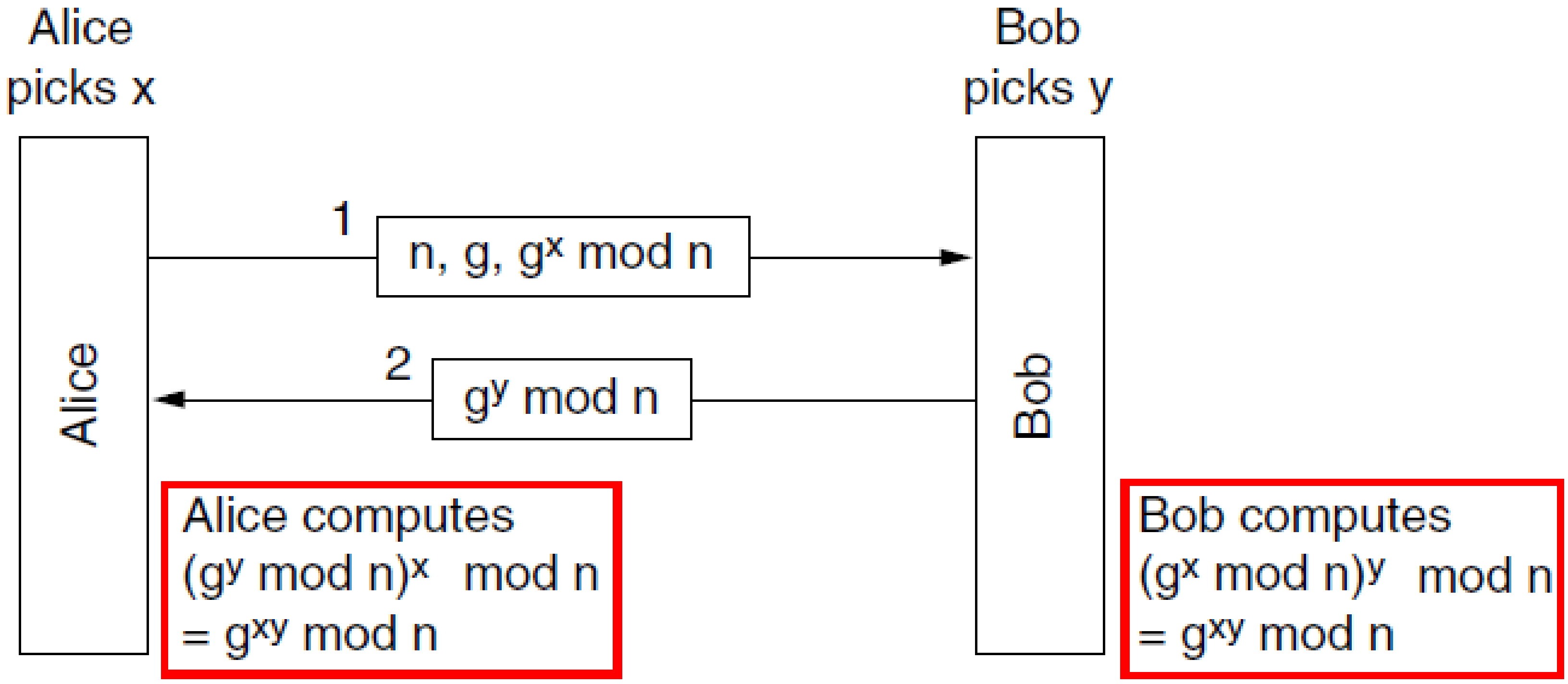
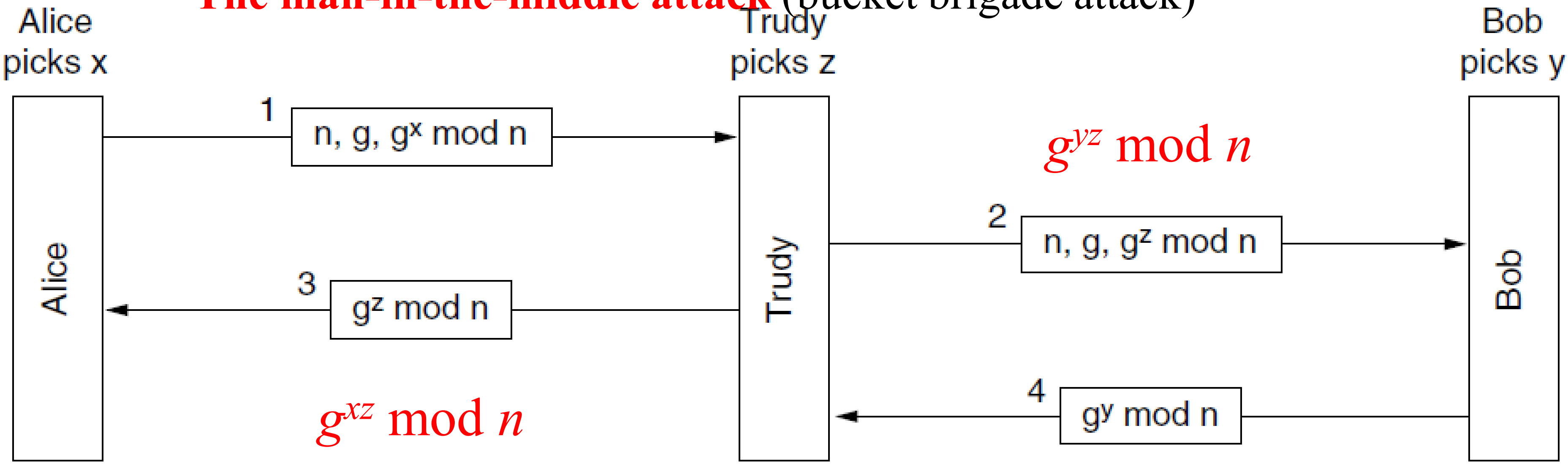


Figure 8-37. The Diffie-Hellman key exchange.

Of course, Trudy can see both messages, but given only g^x mod n, she cannot find x. No practical algorithm for computing discrete logarithm modulo a very large prime number is known.

Establishing a Shared Key: the Diffie-Hellman Key Exchange (III)

- Despite the elegance of the Diffie-Hellman algorithm, there is a problem: when Bob gets the triple (*n*, *g*, g^x mod *n*), how does he know it is from Alice and not from Trudy?
  - There is no way he can know. Unfortunately, Trudy can exploit this fact to deceive both Alice and Bob.
    - **The man-in-the-middle attack** (bucket brigade attack)



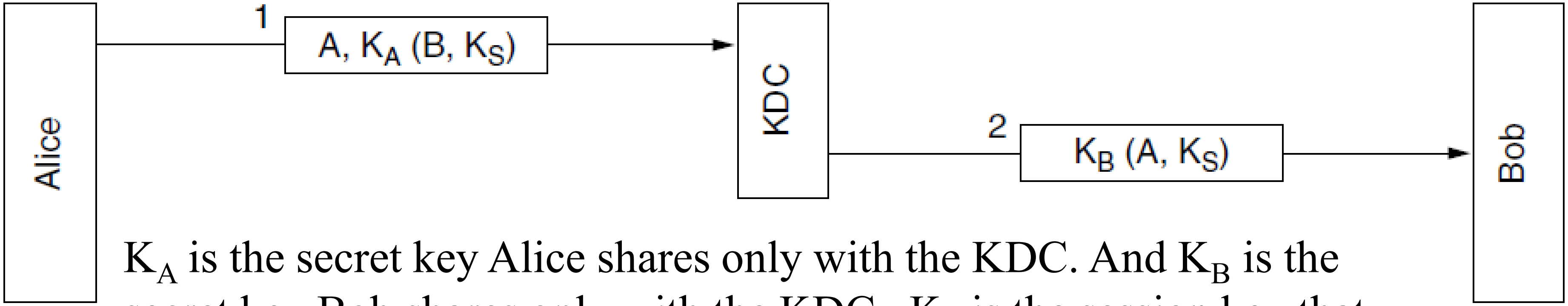
g^{yz} mod n

g^{xz} mod n

Figure 8-38. The man-in-the-middle attack.

Authentication Using a Key Distribution Center (I)

- For popular people, key management would become a real burden. A different approach is to introduce a trusted key distribution center.
  - In the protocol of Fig.8-39, each user has a single key shared with the KDC.
  - Authentication and session key management now go through the KDC.
  - But have the problem of **replay attack**.



K_A is the secret key Alice shares only with the KDC. And K_B is the secret key Bob shares only with the KDC. K_S is the session key that Alice want to use when she talk to Bob.

Figure 8-39. A first attempt at an authentication protocol using a KDC.

The Replay Attack

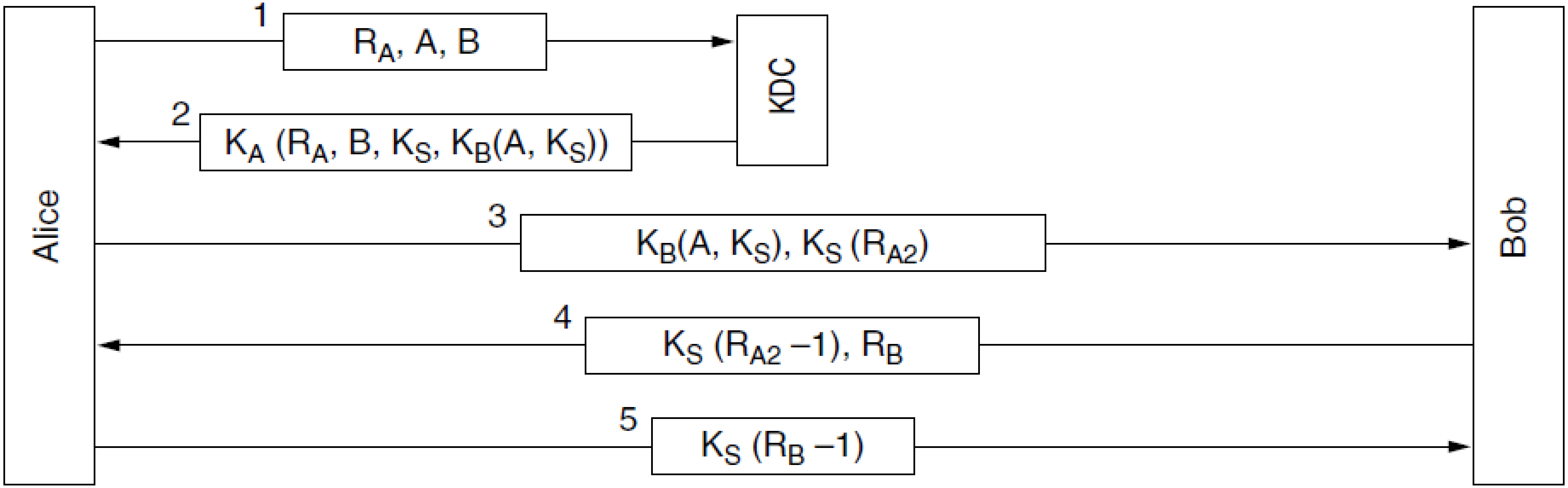
- Suppose Trudy is a secretary of Alice, and she requests Alice to pay by bank transfer. According to the above steps, Alice establishes a session key with her banker, Bob. Then she sends Bob a message requesting money to be transferred to Trudy's account.
- Now Trudy copies both message 2 in Fig.8-39 and the money transfer request that follows it. Trudy replays these message so to make Bob believe that Alice wants him to transfer money to Trudy.
  - **The reply attack**

Solutions to the Replay Attack (I)

- Several solutions to the replay attack are possible.
  - To include a **timestamp** in each message.
    - The trouble with this approach is that clocks are never exactly synchronized over a network.
  - To put a **nonce** in each message
    - Each party should remember all previously nonces.

Solutions to the Replay Attack (II)

- The Needham-Schroeder authentication protocol (1978)
  - A multiway challenge-response protocol
  - By having each party both generate a challenge and respond to one, the possibility of any kind of replay attack is eliminate.



Alice
KDC
Bob
1
R_A, A, B
2
K_A (R_A, B, K_S, K_B(A, K_S))
3
K_B(A, K_S), K_S (R_{A2})
4
K_S (R_{A2} –1), R_B
5
K_S (R_B –1)

Figure 8-40. The Needham-Schroeder authentication protocol.

Solutions to the Replay Attack (III)

- The Needham-Schroeder authentication protocol (1978)
  - Message 1: The large random number, R_A, is used as nonce.
  - Message 2: The KDC sends back to Alice a message containing Alice random number, a session key, and a ticket that she can send to Bob. R_A is to assure Alice that message 2 is fresh, and not a reply. Bob's identity is enclosed in case Trudy replaces B in message 1 with her own identity. K_B is included inside the encrypted message to prevent Trudy from replacing it with something else.

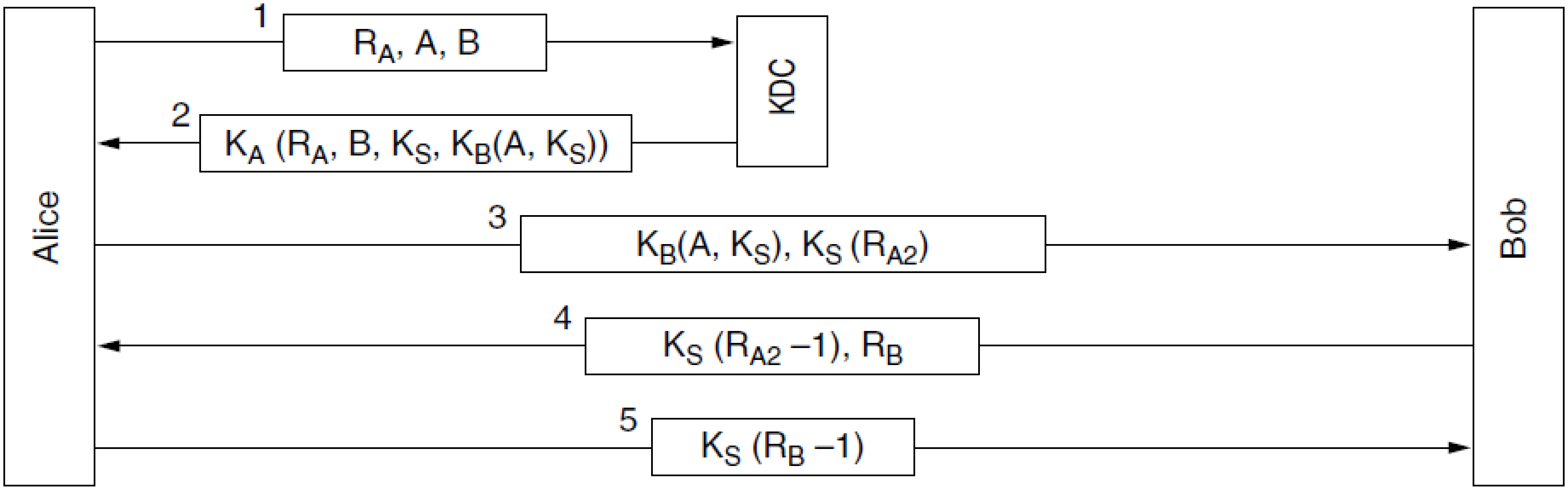

Alice
KDC
Bob
1
R_A, A, B
2
K_A (R_A, B, K_S, K_B(A, K_S))
3
K_B(A, K_S), K_S (R_{A2})
4
K_S (R_{A2} –1), R_B
5
K_S (R_B –1)

Figure 8-40. The Needham-Schroeder authentication protocol.

Solutions to the Replay Attack (IV)

- The Needham-Schroeder authentication protocol (1978)
  - Message 3: Alice now sends the ticket to Bob, along with a new random number, $R_{A2,}$ encrypted with the session key, K_S.
  - Message 4: Bob sends back $K_S(R_{A2} - 1)$ to prove Alice that she is talking to the real Bob.
    - Sending back $K_S(R_{A2})$ would not have worked, since Trudy could just have stolen it from message 3.

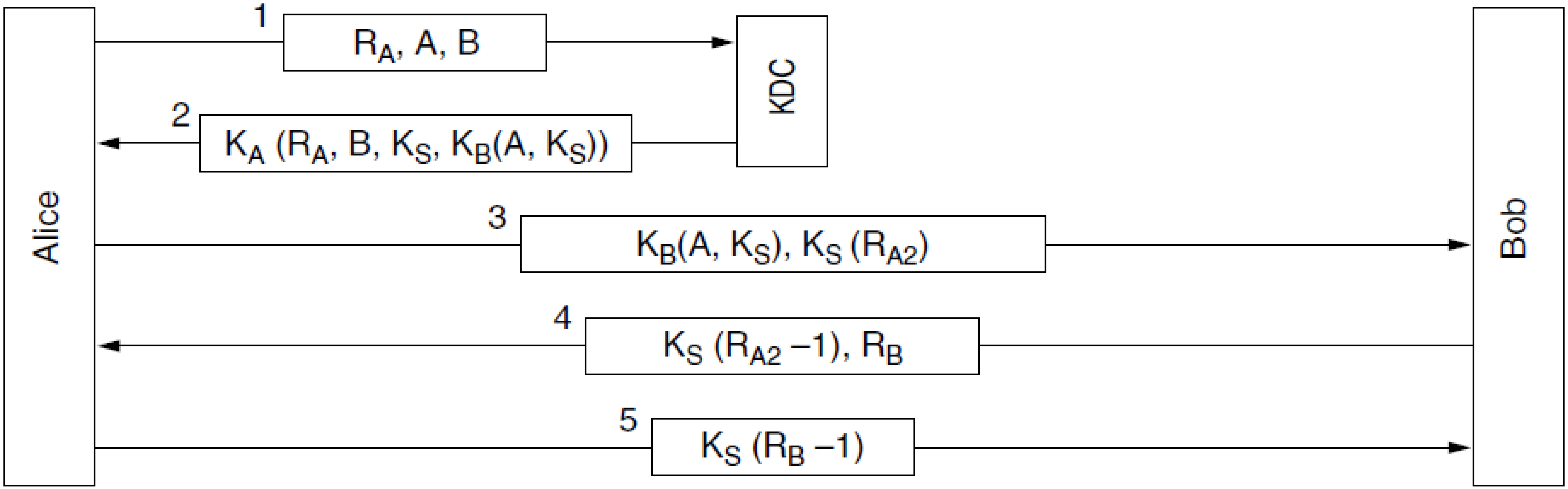

Alice
KDC
Bob
1
R_A, A, B
2
K_A (R_A, B, K_S, K_B(A, K_S))
3
K_B(A, K_S), K_S (R_{A2})
4
K_S (R_{A2} −1), R_B
5
K_S (R_B −1)

Figure 8-40. The Needham-Schroeder authentication protocol.

Solutions to the Replay Attack (V)

- The Needham-Schroeder authentication protocol (1978)
  - Message 5: is to convince Bob that it is indeed Alice he is talking to.
- This protocol does have a slight weakness. If Trudy ever manages to obtain an old session key in plaintext, she can initiate a compromised key and convince him that she is Alice.

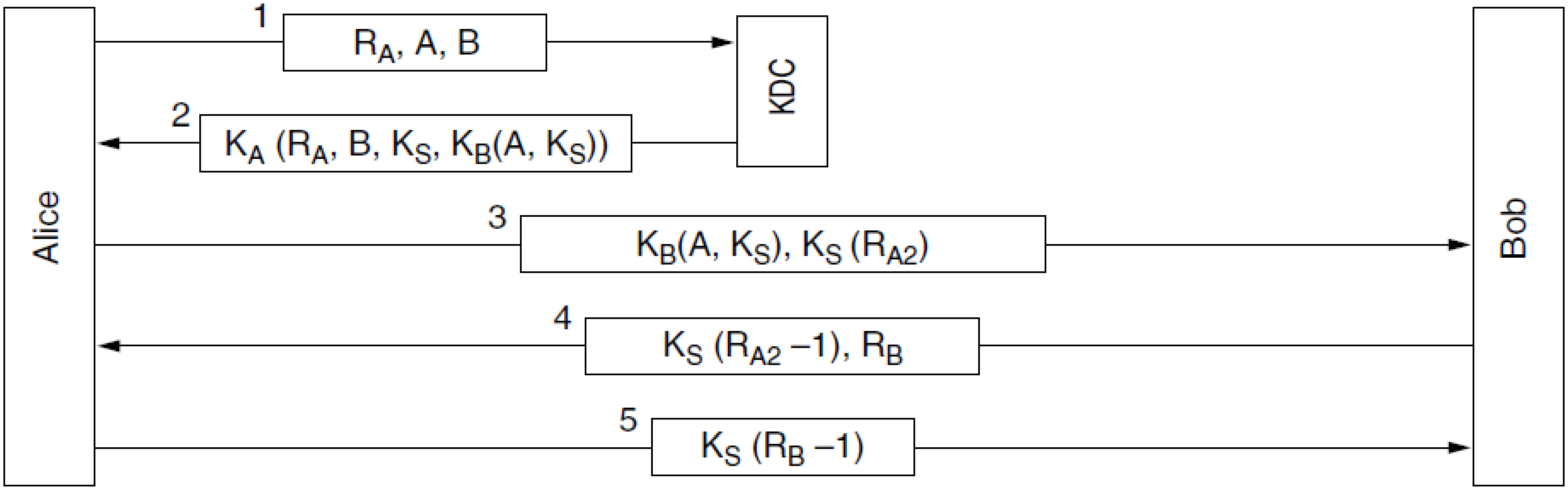


Figure 8-40. The Needham-Schroeder authentication protocol.

Solutions to the Replay Attack (VI)

- In the Otway-Rees protocol, Alice starts out by generating a pair of random numbers: R, which will be used as a common identifier, and R_A, which Alice will use to challenge Bob.
- When Bob gets this message, he construct a new message from the encrypted part of Alice's message and an analogous one of his own. Both the parts encrypted with K_A and K_B identify Alice and Bob, contain the common identifier, and contain a challenge.

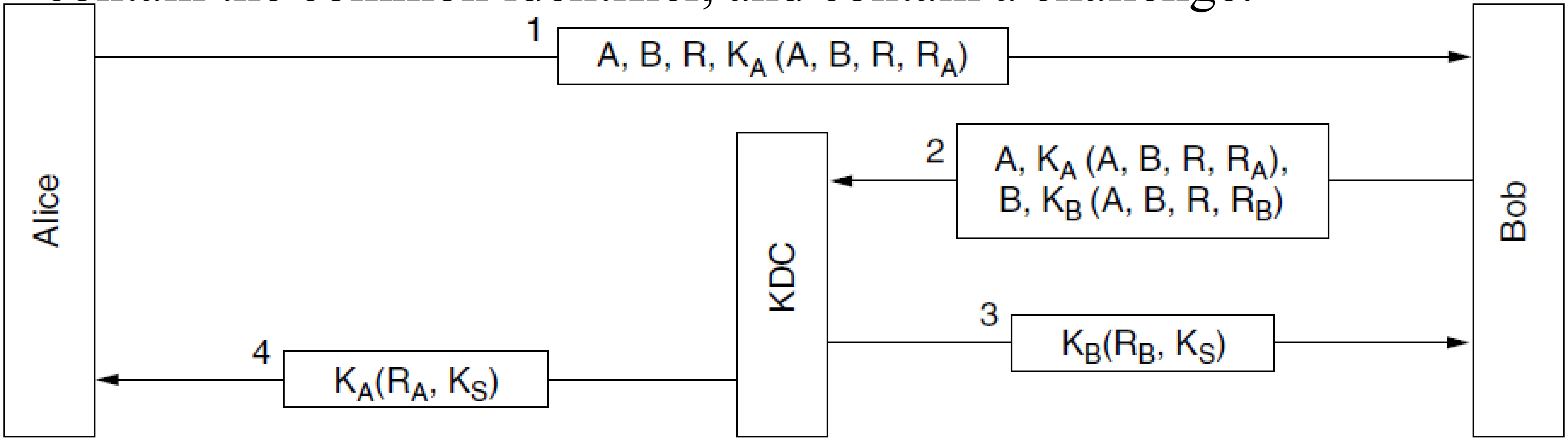

Alice
1
A, B, R, K_A (A, B, R, R_A)
KDC
2
A, K_A (A, B, R, R_A),
B, K_B (A, B, R, R_B)
Bob
3
K_B(R_B, K_S)
4
K_A(R_A, K_S)

Figure 8-41. The Otway-Rees authentication protocol (slightly simplified).

Solutions to the Replay Attack (VII)

- When the KDC checks to see if the R in both parts is the same, the KDC believes that the request message from Bob is valid. It then generates a session key and encrypts its twice, once for Alice and once for Bob. Each message contains the receiver's random number, as proof that the KDC, and not Trudy, generated the message.
- At this point, both Alice and Bob can use the session key to start communication.

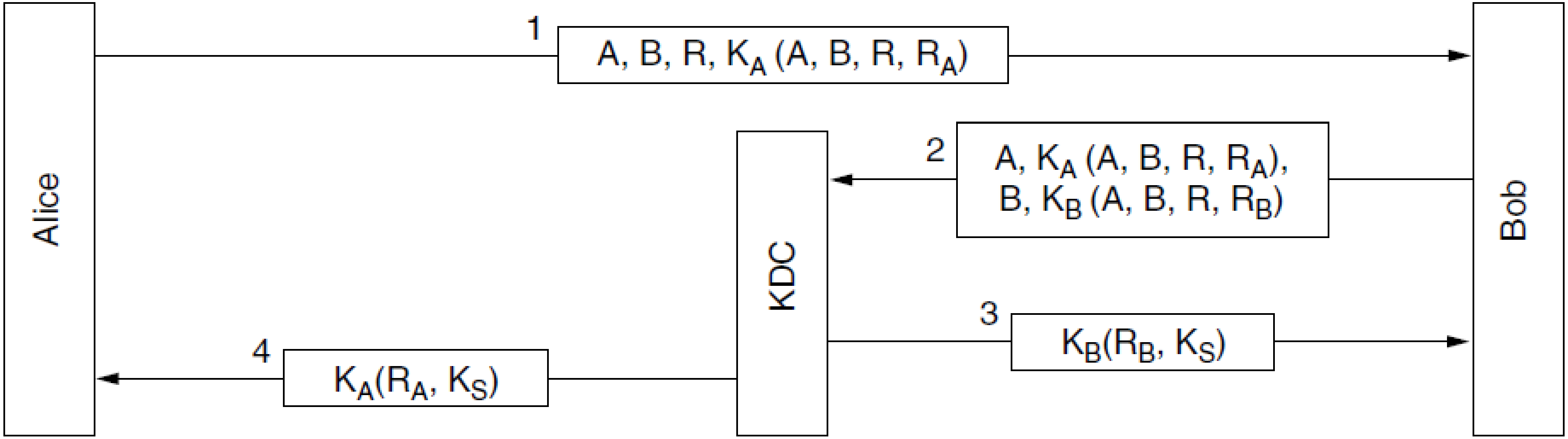

Alice
KDC
Bob
1
A, B, R, K_A (A, B, R, R_A)
2
A, K_A (A, B, R, R_A),
B, K_B (A, B, R, R_B)
3
K_B(R_B, K_S)
4
K_A(R_A, K_S)

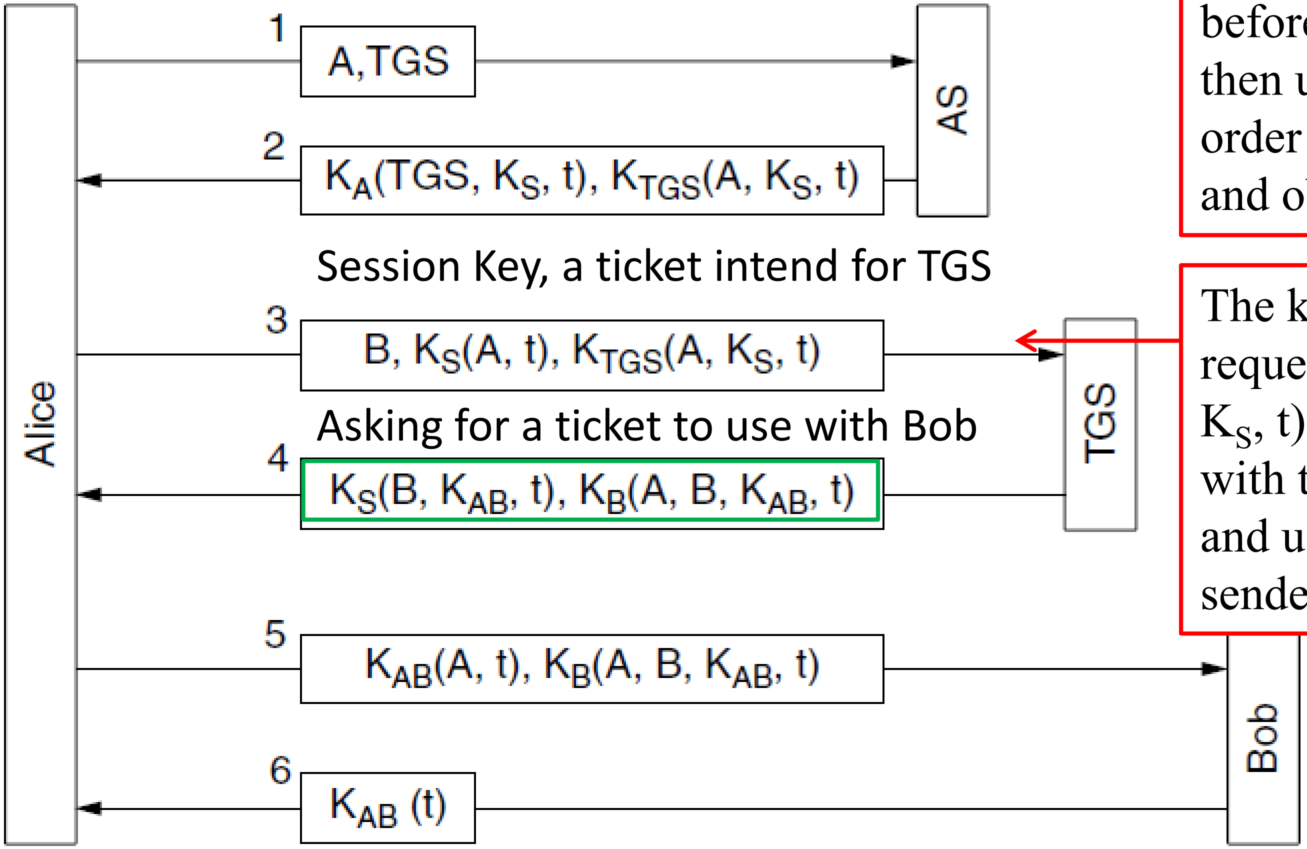
Figure 8-41. The Otway-Rees authentication protocol (slightly simplified).

Authentication Using Kerberos (I)

- Kerberos's biggest difference from Needham-Schroeder is its assumption that all clocks are fairly well synchronized.
  - RFC 4120
- Kerberos involves three servers in addition to Alice (a client workstations):
  - 1. Authentication Server (AS): Verifies users during login
  - 2. Ticket-Granting Server (TGS): Issues "proof of identity tickets"
  - 3. Bob the server: Actually does the work Alice wants performed.
- AS is similar to a KDC in that it shares a secret password with every user.
- TGS's job is to issue tickets that can convince the real servers that the bearer of a TGS ticket really is who he or she claim to be.

Authentication Using Kerberos (II)

- The operation of Kerberos V5



Alice

AS

TGS

Bob

1 A,TGS

2 $K_A(TGS, K_S, t), K_{TGS}(A, K_S, t)$

Session Key, a ticket intend for TGS

3 $B, K_S(A, t), K_{TGS}(A, K_S, t)$

Asking for a ticket to use with Bob

4 $K_S(B, K_{AB}, t), K_B(A, B, K_{AB}, t)$

5 $K_{AB}(A, t), K_B(A, B, K_{AB}, t)$

6 K_{AB} (t)

Figure 8-42. The operation of Kerberos V5.

Only when message 2 arrives does the workstation ask for Alice's password — not before then. The password is then used to generate K_A in order to decrypt message 2 and obtain **the session key**.

The key element in this request is the ticket K_{TGS}(A, K_S, t), which is encrypted with the TGS's secret key and used as proof that the sender really is Alice.

K_{AB} is a session key for Alice to use with Bob. Two versions of K_{AB}. The 1st is encrypted with onely KS, so Alice can read it. The 2nd is encrypted with Bob's key KB, so Bob can read it.

Authentication Using Public-Key Cryptography

- If a PKI (Public Key Infrastructure) exists with a directory server that hands out certificates for public keys, Alice can ask for Bob's, as shown in Fig.8-43 as message 1. The reply, in message 2, is an X.509 certificate containing Bob's public key.

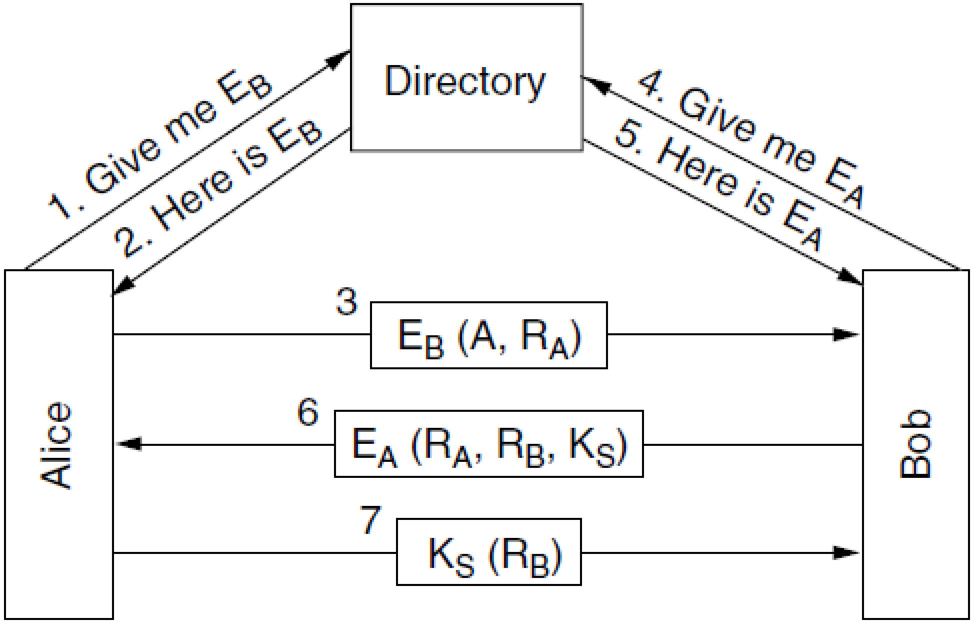


Figure 8-43. Mutual authentication using public-key cryptography.

Email Security (I)

- Secure email system PGP (Pretty Good Privacy, 1991, Phil Zimmermann)
  - Released in 1991, PGP is a complete email security package that provides privacy, authentication, digital signatures, and compression, all in an easy-to-use form.
  - PGP encrypts data by using a block cipher called **IDEA** (International Data Encryption Algorithm), which uses 128-bits keys.
  - Key management uses RSA and data integrity uses MD5.
  - It is like a preprocessor that takes plaintext as input and produces signed cipher text in base64 as output. This output can then be email.

Email Security (II)

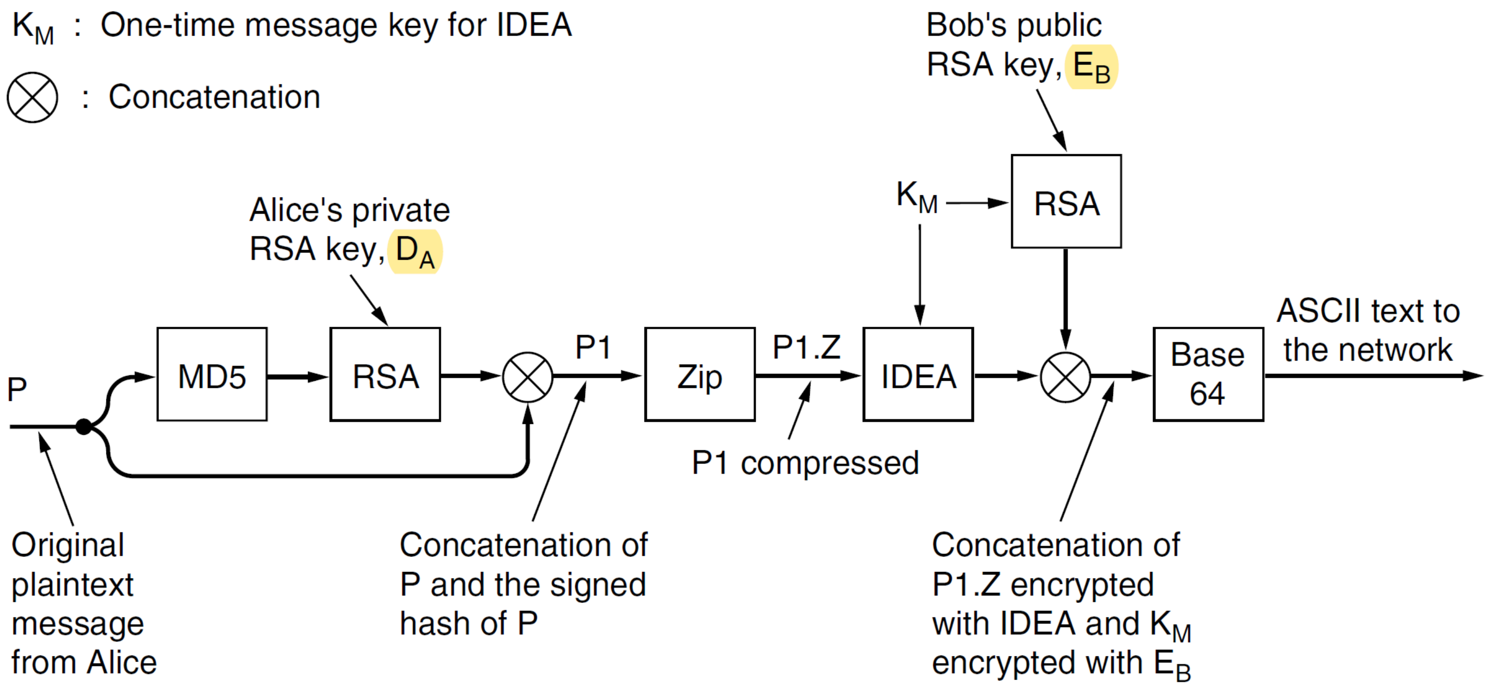


Figure 8-44. PGP in operation for sending a message.

1) Alice first hashes the original plaintext message P using MD5
2) Then encrypts the resulting hash using her private RSA key, D_A.
3) The encrypted hash and the original message are concatenated into a single message P1, and compressed using the ZIP program (The Ziv-Lempel algorithm, 1977).

Email Security (III)

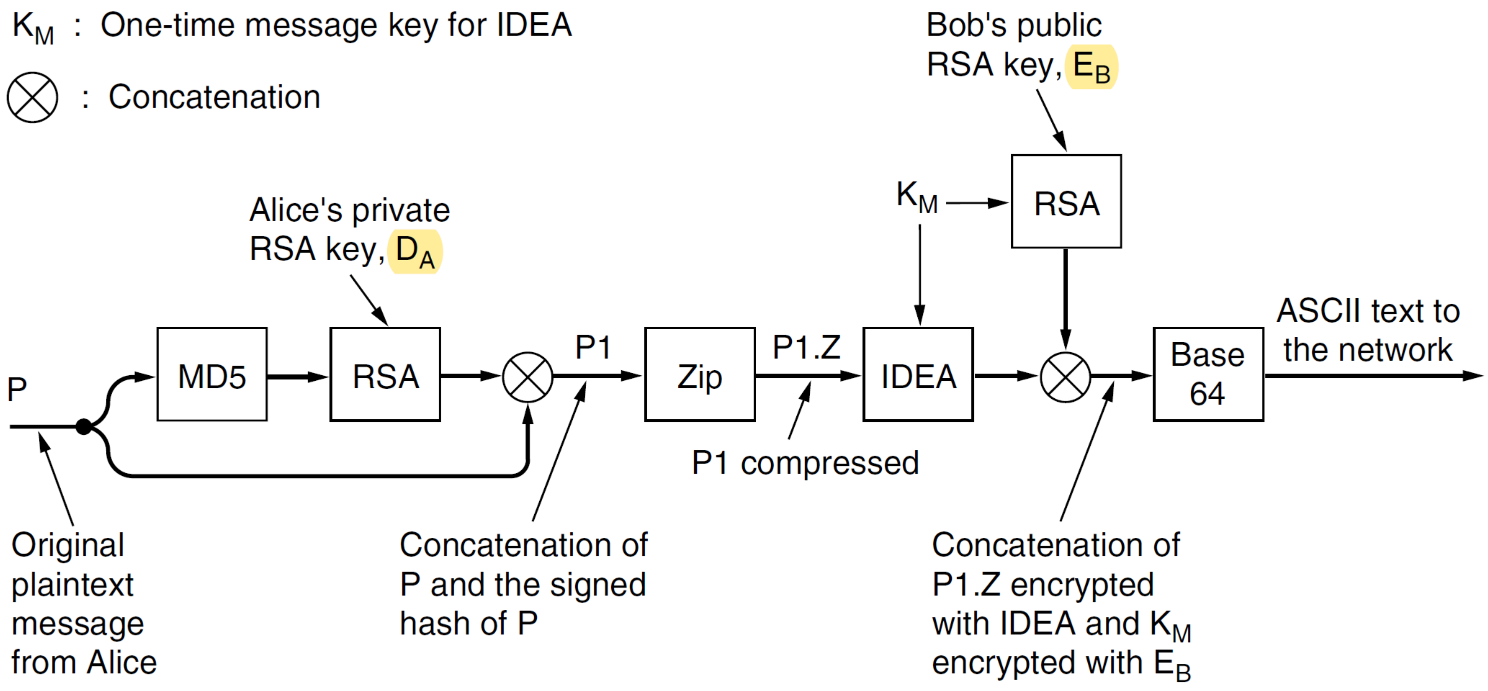

K_M : One-time message key for IDEA
⊗ : Concatenation
Bob's public RSA key, E_B
K_M
RSA
Alice's private RSA key, D_A
P
MD5
RSA
P1
Zip
P1.Z
IDEA
Base 64
ASCII text to the network
P1 compressed
Original plaintext message from Alice
Concatenation of P and the signed hash of P
Concatenation of P1.Z encrypted with IDEA and K_M encrypted with E_B

Figure 8-44. PGP in operation for sending a message.

4) PGP prompts Alice for some random input. Both the content and the typing speed are used to generated a 128-bit IDEA message key, K_M.

5) The K_M is used to encrypted P1.Z with IDEA in cipher feedback mode. In addition, K_M is encrypted with Bob's public key, E_B. These two components are concatenated and converted to base64.

Email Security (IV)

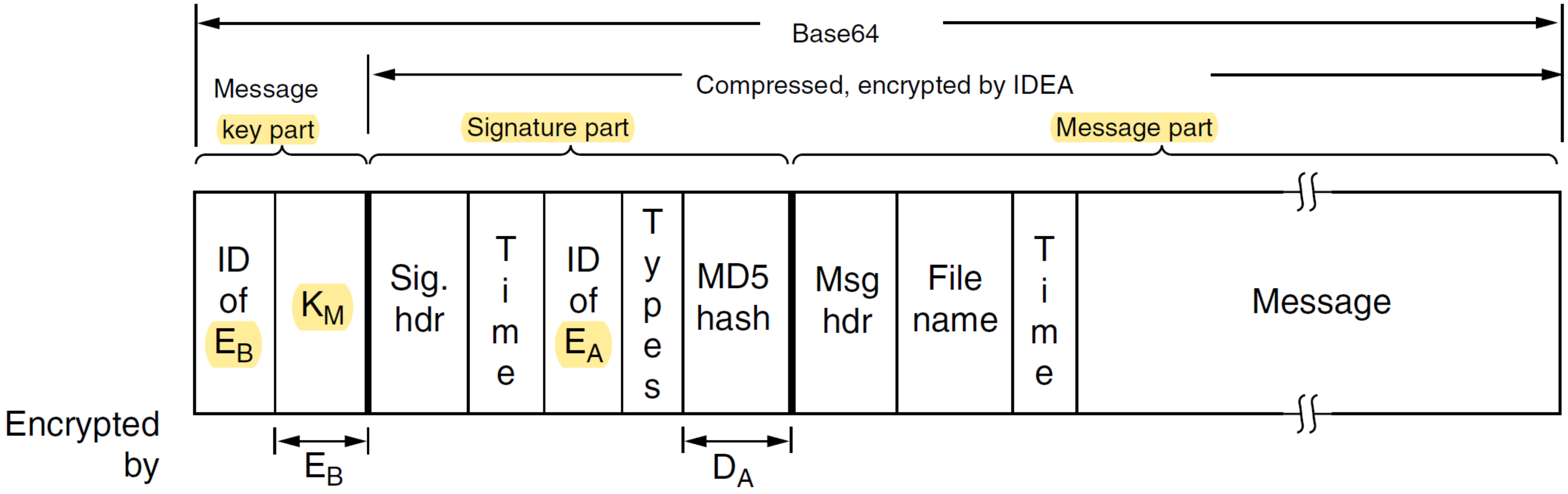


Figure 8-45. A PGP message.

In PGP, RSA is only used for two small computations. The heavy-duty encryption is done by IDEA, which is orders of magnitudes faster than RSA.

The message has three parts, containing the IDEA key, the signature, and the message respectively.

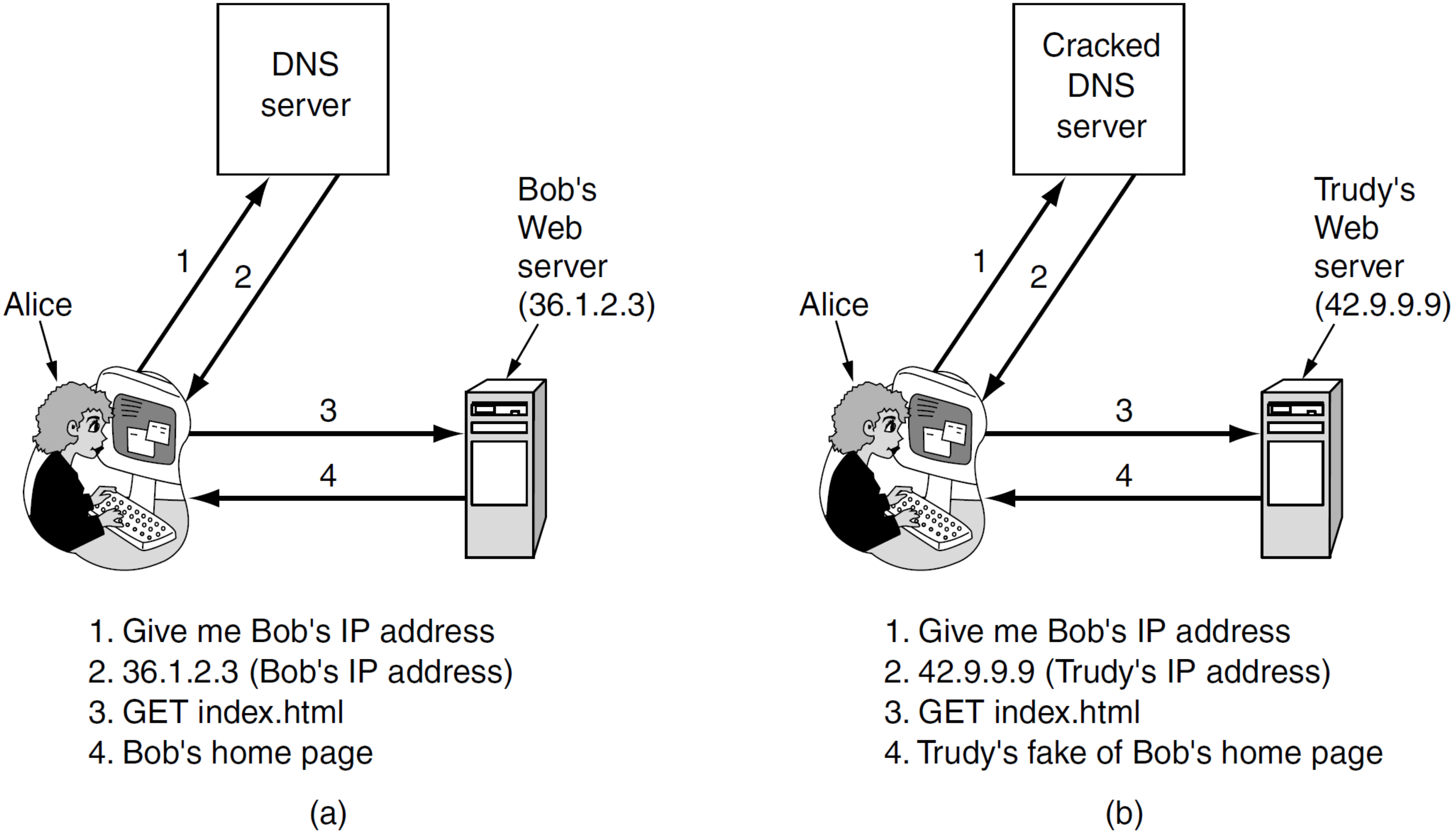
Web Security (I)

- Threats
  - Denial-of-service attacks, in which the cracker floods the site with traffic, rendering it unable to respond to legitimate queries.
  - To release false statement that will seriously affect a company’s stock.
  - Steal critical personal information, such as credit card number.

Web Security (II)

- Man-in-the-middle attack
  - Trudy might intercept all of Alice's outgoing packets and examine them, and return her fake page to Alice, and tricking Alice to send her critical information, such as credit card number.
  - One disadvantage of man-in-the-middle attack is that Trudy has to be in a position to intercept Alice's outgoing traffic and forge her incoming traffic, like to tap either Alice's phone line or Bob's, since to tap the fiber backbone is fairly difficult.
- DNS Spoofing
  - One way would be for Trudy to crack the DNS system or maybe just the DNS cache at Alice's ISP, and replace Bob's IP address with her (Trudy's) IP address.

DNS Spoofing (I)



1. Give me Bob's IP address
2. 36.1.2.3 (Bob's IP address)
3. GET index.html
4. Bob's home page

(a)

1. Give me Bob's IP address
2. 42.9.9.9 (Trudy's IP address)
3. GET index.html
4. Trudy's fake of Bob's home page

(b)

Figure 8-46. (a) Normal situation. (b) An attack based on breaking into a DNS server and modifying Bob's record.

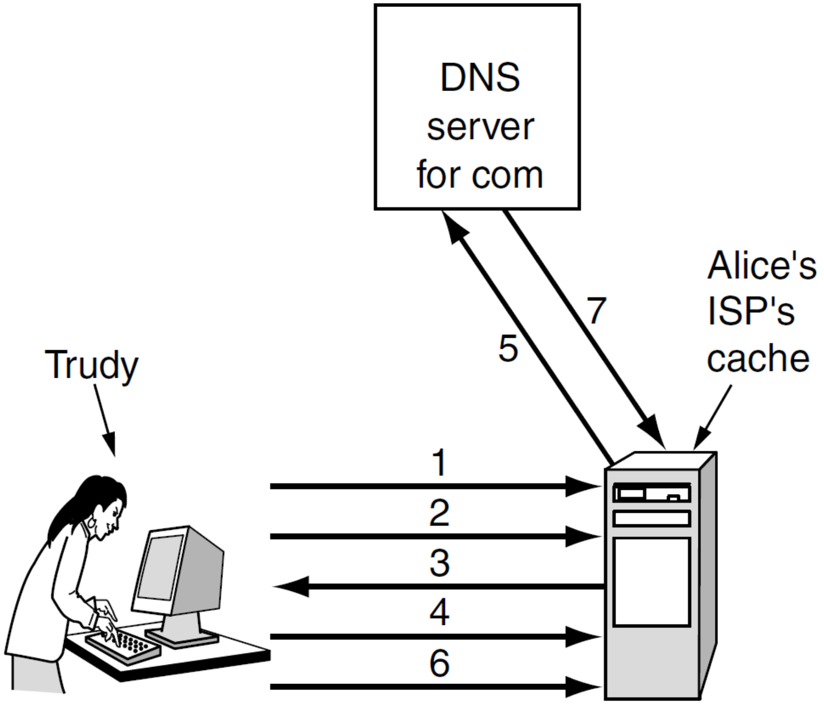
DNS Spoofing (II)

- The steps that Trudy fools DNS (DNS uses UDP, the DNS server has no real way of checking who supplied the answer)
  - For simplicity, we will assume that Alice's ISP does not initially have an entry for Bob's web site.
  - 1) Trudy sends a lookup request to Alice's ISP asking for the IP address of Bob's web site.
  - 2) Since there is no entry for this DNS name, the cache server queries the top-level server for the .com domain to get one. However, Trudy beats the com server to the punch and sends back a false reply saying: "Bob.com is 42.9.9.9," where that IP address is hers.
  - If the false reply gets back to Alice's ISP first, that one will be cached and the real reply will be rejected as an unsolicited replay to a query no longer outstanding.

DNS Spoofing (III)

- Actually, things are not quite that simple.
- 1) Alice's ISP checks to see that the reply bears the correct IP source address of the top-level server.
  - But this can be easily defeated since the IP addresses of the top-level servers have to be public.
- 2) To allow DNS servers to tell which replay goes with which request, all requests carry a sequence number.
  - To spoof Alice's ISP, Trudy has to know its current sequence number.

DNS Spoofing (IV)



1. Look up foobar.trudy-the-intruder.com (to force it into the ISP's cache)
2. Look up www.trudy-the-intruder.com (to get the ISP's next sequence number)
3. Request for www.trudy-the-intruder.com (Carrying the ISP's next sequence number, n)
4. Quick like a bunny, look up bob.com (to force the ISP to query the com server in step 5)
5. Legitimate query for bob.com with seq = n+1
6. Trudy's forged answer: Bob is 42.9.9.9, seq = n+1
7. Real answer (rejected, too late)

Figure 8-47. How Trudy spoofs Alice's ISP.

Secure DNS (I)

- **DNSsec** (DNS security) [RFC 2535]
  - It is based on public-key cryptography. Every DNS zone (Fig. 7-5) has a public/private key pair.
  - All information sent by a DNS server is signed with the originating zone's private key, so the receiver can verify its authenticity.
- DNSsec offers three fundamental services:
  - Proof of where the data originated
  - Public key distribution
    - For storing and retrieving public keys securely
  - Transaction and request authentication.
    - To guard against playback and spoofing attacks.

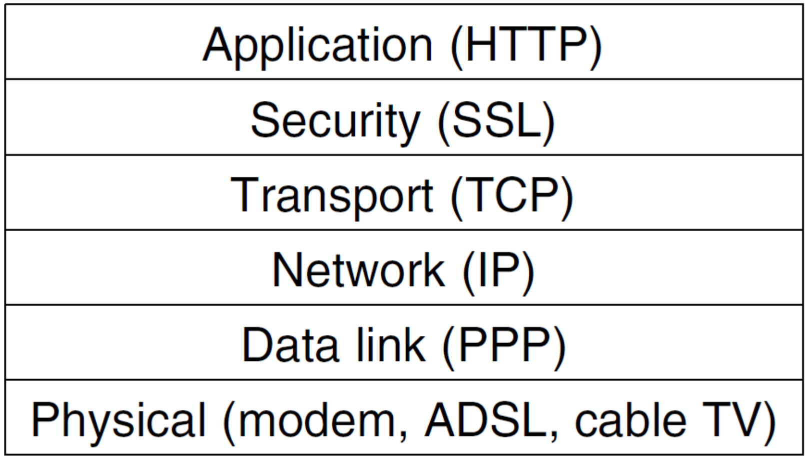
Secure DNS (II)

- DNS records are grouped into sets called **RRSets** (**Resource Record Sets**), with all the records having the same name, class and type being lumped together.
  - For example: An RRSet may contain multiple A records, for example, if a DNS name resolves to a primary IP address and a secondary IP address.
- DNSsec introduces several new record types
  - The key record (This records holds the public key of a zone, user, host, or other principal.)
  - The SIG record (It holds the signed hash according to the algorithm specified in the key record.)

SSL — The Secure Sockets Layer

- Some applications, such as purchasing merchandise by credit card, online banking, and electronic stock trading, demands for **secure connections**.
- SSL builds a secure connection between two sockets, including
  - 1. Parameter negotiation between client and server.
  - 2. Authentication of the server by the client
  - 3. Secret communication
  - 4. Data integrity protection

The Position of SSL in the Protocol Stack



Application (HTTP)

Security (SSL)

Transport (TCP)

Network (IP)

Data link (PPP)

Physical (modem, ADSL, cable TV)

Figure 8-49. Layers (and protocols) for a home user browsing with SSL.

Once the secure connection has been established, SSL's main job is handling compression and encryption.

When HTTP is used over SSL, it is called **HTTPS (Secure HTTP)**, even though it is the standard HTTP protocol. Sometimes it is available at a new port (**443**) instead of port 80. *SSL is not restricted to Web browsers*.

The SSL Protocol: Establishment

- SSL consists of two subprotocols, one for establishing a secure connection and one for using it.

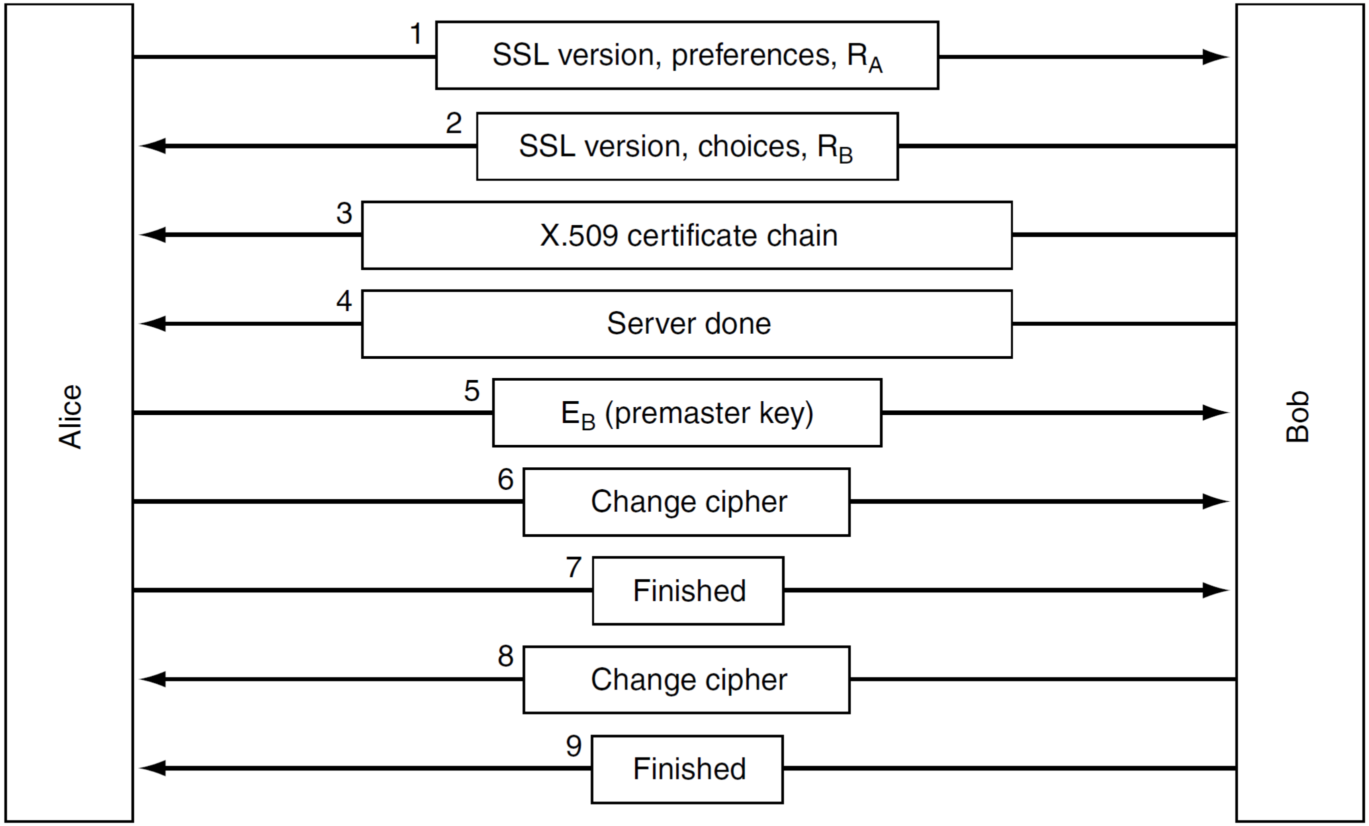


Figure 8-50. A simplified version of the SSL connection establishment subprotocol.

In message 3, he sends a certificate containing his public key.

In message 5, Alice responds by choosing a random 384-bit premaster key and sending it Bob encrypted with his public key.

The actual session key used for encrypting data is derived from the premaster key combined with both nonces in a complex way.

The SSL Protocol: Transmission

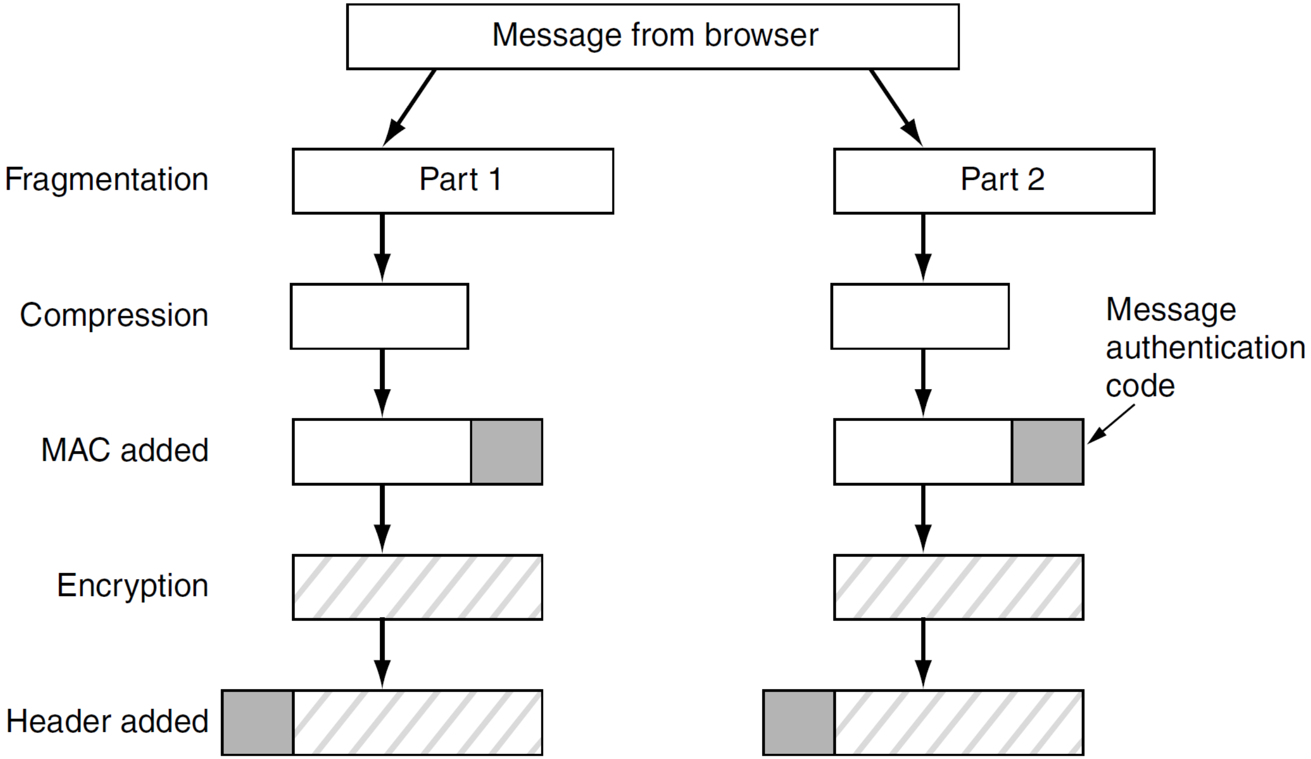
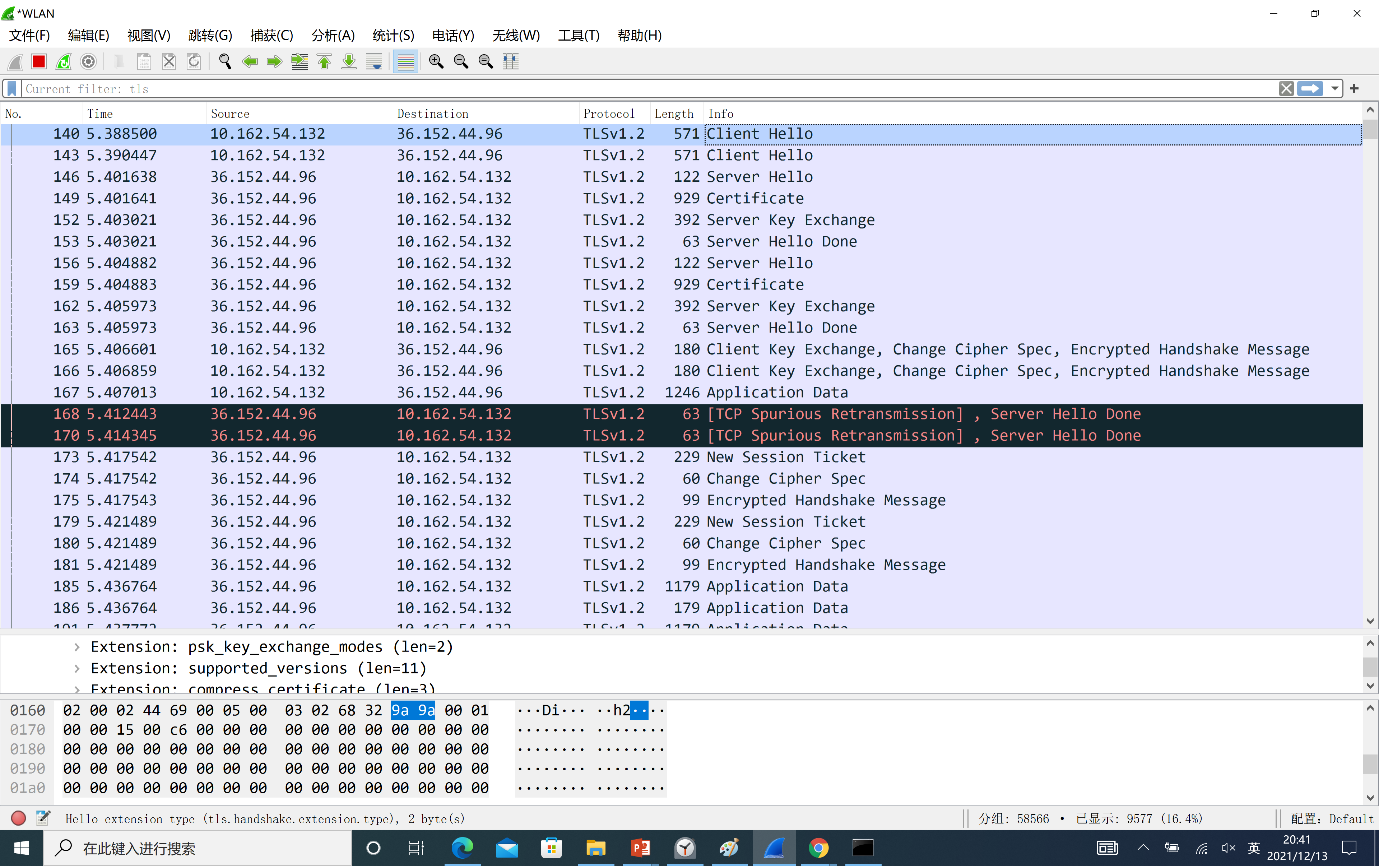


Figure 8-51. Data transmission using SSL.

Messages from the browser are first broken into units of up to 16 KB. If compression is enabled, each unit is then separately compressed. A secret key derived from the two nonces and premaster key is concatenated with the compressed text and the result is hashed with the agreed-on hashing algorithm. This hash is appended to each fragment as the MAC. The compressed fragment plus MAC is then encrypted with the agree-on symmetric encrypted algorithm. Finally, a header is added.


*WLAN
文件(F) 编辑(E) 视图(V) 跳转(G) 捕获(C) 分析(A) 统计(S) 电话(Y) 无线(W) 工具(T) 帮助(H)

Current filter: tls

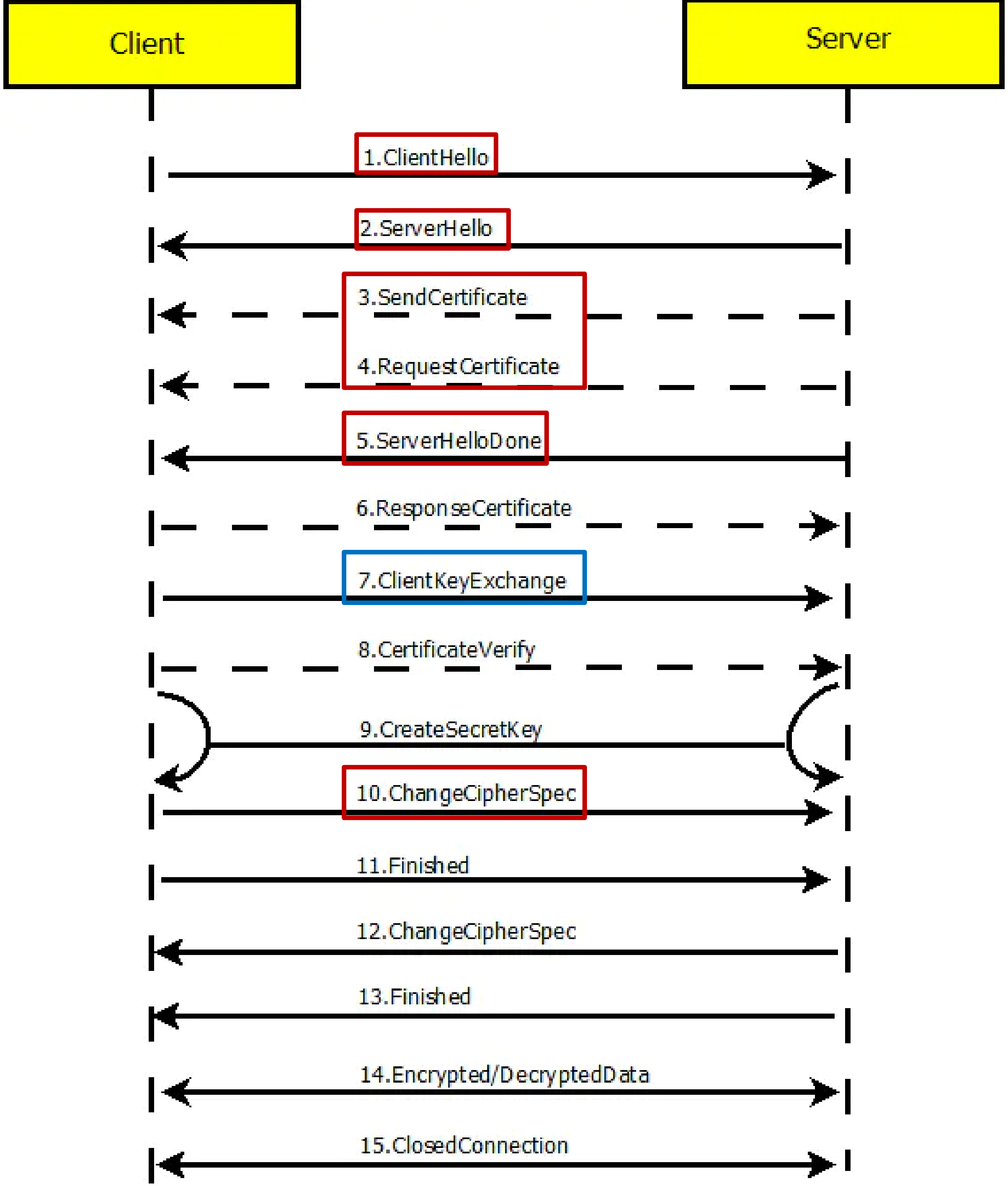
```
No.   Time      Source         Destination    Protocol Length Info
  140 5.388500  10.162.54.132  36.152.44.96   TLSv1.2   571 Client Hello
  143 5.390447  10.162.54.132  36.152.44.96   TLSv1.2   571 Client Hello
  146 5.401638  36.152.44.96   10.162.54.132  TLSv1.2   122 Server Hello
  149 5.401641  36.152.44.96   10.162.54.132  TLSv1.2   929 Certificate
  152 5.403021  36.152.44.96   10.162.54.132  TLSv1.2   392 Server Key Exchange
  153 5.403021  36.152.44.96   10.162.54.132  TLSv1.2    63 Server Hello Done
  156 5.404882  36.152.44.96   10.162.54.132  TLSv1.2   122 Server Hello
  159 5.404883  36.152.44.96   10.162.54.132  TLSv1.2   929 Certificate
  162 5.405973  36.152.44.96   10.162.54.132  TLSv1.2   392 Server Key Exchange
  163 5.405973  36.152.44.96   10.162.54.132  TLSv1.2    63 Server Hello Done
  165 5.406601  10.162.54.132  36.152.44.96   TLSv1.2   180 Client Key Exchange, Change Cipher Spec, Encrypted Handshake Message
  166 5.406859  10.162.54.132  36.152.44.96   TLSv1.2   180 Client Key Exchange, Change Cipher Spec, Encrypted Handshake Message
  167 5.407013  10.162.54.132  36.152.44.96   TLSv1.2  1246 Application Data
  168 5.412443  36.152.44.96   10.162.54.132  TLSv1.2    63 [TCP Spurious Retransmission] , Server Hello Done
  170 5.414345  36.152.44.96   10.162.54.132  TLSv1.2    63 [TCP Spurious Retransmission] , Server Hello Done
  173 5.417542  36.152.44.96   10.162.54.132  TLSv1.2   229 New Session Ticket
  174 5.417542  36.152.44.96   10.162.54.132  TLSv1.2    60 Change Cipher Spec
  175 5.417543  36.152.44.96   10.162.54.132  TLSv1.2    99 Encrypted Handshake Message
  179 5.421489  36.152.44.96   10.162.54.132  TLSv1.2   229 New Session Ticket
  180 5.421489  36.152.44.96   10.162.54.132  TLSv1.2    60 Change Cipher Spec
  181 5.421489  36.152.44.96   10.162.54.132  TLSv1.2    99 Encrypted Handshake Message
  185 5.436764  36.152.44.96   10.162.54.132  TLSv1.2  1179 Application Data
  186 5.436764  36.152.44.96   10.162.54.132  TLSv1.2   179 Application Data
  191 5.437773  36.152.44.96   10.162.54.132  TLSv1.2  1179 Application Data
```

```
    > Extension: psk_key_exchange_modes (len=2)
    > Extension: supported_versions (len=11)
    > Extension: compress_certificate (len=3)
```

```
0160  02 00 02 44 69 00 05 00  03 02 68 32 9a 9a 00 01   ···Di··· ··h2····
0170  00 00 15 00 c6 00 00 00  00 00 00 00 00 00 00 00   ········ ········
0180  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ········ ········
0190  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ········ ········
01a0  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ········ ········
```

Hello extension type (tls.handshake.extension.type), 2 byte(s)　　分组：58566 · 已显示：9577 (16.4%)　　配置：Default

2021年12月13日在实验室输入百度网址，通过nslookup查到百度的DNS服务器IP地址为36.152.44.96。


Client
Server
1.ClientHello
2.ServerHello
3.SendCertificate
4.RequestCertificate
5.ServerHelloDone
6.ResponseCertificate
7.ClientKeyExchange
8.CertificateVerify
9.CreateSecretKey
10.ChangeCipherSpec
11.Finished
12.ChangeCipherSpec
13.Finished
14.Encrypted/DecryptedData
15.ClosedConnection

[3]

References

- [1] A.S. Tanenbaum, and D.J. Wetherall, Computer Networks, 5th Edition, Prentice Hall, 2011.
- [2] https://en.wikipedia.org/wiki/Replay_attack
- [3] https://www.jianshu.com/p/1fc7130eb2c2