Cryptography and Network Security

Third Edition

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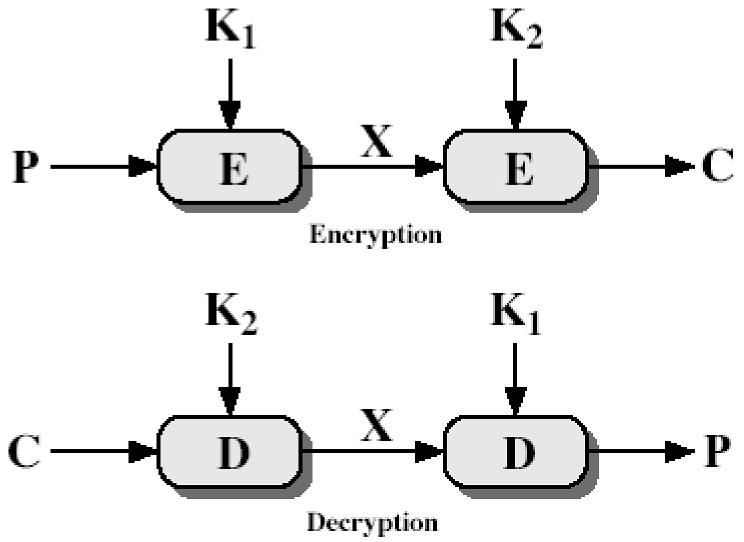
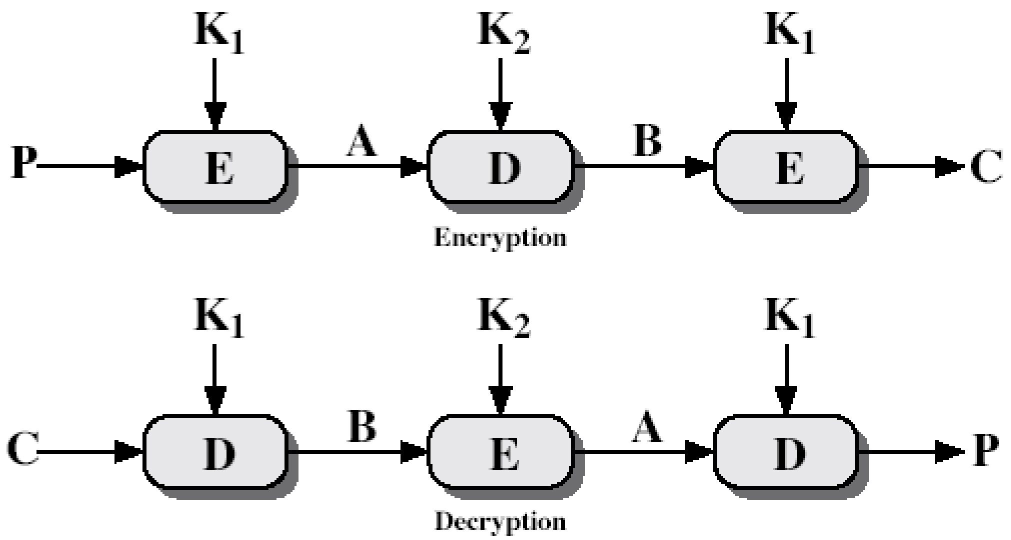
Lecture slides by Lawrie Brown



(a) Double Encryption



(b) Triple Encryption

- $C=E_{K2}[E_{K1}[P]]$
- $P=D_{K2}[D_{K1}[C]]$
- Key Length = 56*2 = 112 bits.
- $E_{K2}[E_{K1}[P]] = E_{K3}[P]]$ – then the scheme becomes useless.
- It does not hold.

- Because Plaintext mapping is
- $2^{64}! = 10^{10\text{^}20}$
- DES mapping with different key is
- $2^{56} = 10^{17}$

Meet in the Middle attack

- It is based on the observation that, if we have
- C=E K2 [EK1[P]]
- Then (see Fig 6.1a)
- X= EK1[P]= D K2 [C]
- Given a known pair, (P,C), the attack proceeds as follows.

- First, encrypt P for all possible 256 values of K1. Store these results in the table and then sort the table by the values of X. Next, decrypt C using all 256 possible values of K2. As each decryption is produced, check the result against the table for match. If a match occurs, then test two resulting keys against a new known plaintext-ciphertext pair. If the two keys produce the correct ciphertext, accept them as the correct keys.

Triple DES

- clear a replacement for DES was needed
  - theoretical attacks that can break it
  - demonstrated exhaustive key search attacks
- AES is a new cipher alternative
- prior to this alternative was to use multiple encryption with DES implementations
- Triple-DES is the chosen form

Why Triple-DES?

- why not Double-DES?
  - NOT same as some other single-DES use, but have
- meet-in-the-middle attack
  - works whenever use a cipher twice
  - since $X = E_{K1}[P] = D_{K2}[C]$
  - attack by encrypting P with all keys and store
  - then decrypt C with keys and match X value
  - can show takes $O(2^{56})$ steps

Triple-DES with Two-Keys

- hence must use 3 encryptions
  - would seem to need 3 distinct keys
- but can use 2 keys with E-D-E sequence
  - $C = E_{K1}[D_{K2}[E_{K1}[P]]]$
  - encrypt & decrypt equivalent in security
  - if `K1=K2` then can work with single DES
- standardized in ANSI X9.17 & ISO8732
- no current known practical attacks
- slower

Triple-DES with Three-Keys

- although are no practical attacks on two-key Triple-DES have some indications
- can use Triple-DES with Three-Keys to avoid even these
  - $C = E_{K3}[D_{K2}[E_{K1}[P]]]$
- has been adopted by some Internet applications, eg PGP, S/MIME

Blowfish

- a symmetric block cipher designed by Bruce Schneier in 1993/94
- characteristics
  - fast implementation on 32-bit CPUs
  - compact in use of memory
  - simple structure eases analysis/implemention
  - variable security by varying key size
- has been implemented in various products

- **Password Management**
- Archiving tools
- E-commerce software
- Email Encryption
- Filetransfer
- openssl

Products using blowfish

- 96Crypt
- Advanced Encryption Package Professional
- Ashampoo WinOptimizer
- Bcrypt
- BestCrypt
- Kryptel
- LexiGuard
- MySecret
- PC-Encrypt
- SafeHouse
- Scramdisk
- Sentry 2020
- ShareCrypt

- Blow-RAU
- BlowTorch
- CodedDrag
- CryptArchiver
- Citecq
- CryptoDisk
- CryptoForge
- CuteCipher for Mac
- Cypher Millennium
- Cypherix
- DigiShield
- DOSFish
- dozeCrypt
- DriveCrypt
- EncryptIt
- GnuPG

- Fast: encrypts data on 32 bit MP at a rate of 18 clock cycles per byte.
- Compact: can run in less than 5K of Memory
- Simple: easy to implement.
- Variably secure: key length is variable and can be long as 448 bits.

- Block cipher: 64-bit block
- Variable key length: 32 bits to 448 bits
- Designed by Bruce Schneier
- Much faster than DES and IDEA
- Unpatented and royalty-free
- No license required

Applications

- Bulk encryption. The algorithm should be efficient in encrypting data files or a continuous data stream.
- Random bit generation. The algorithm should be efficient in producing single random bits.
- Packet encryption. (An ATM packet has a 48- byte data field.)
- Hashing

Platform

- Special hardware – VLSI
- Large processors. The algorithm should be efficient on 32-bit microprocessors with 4 kbyte program and data caches.
- Medium-size processors. Small processors. It should be possible to implement the algorithm on smart cards,

- Blowfish is a variable-length key block cipher.
- It is only suitable for applications where the key does not change often, like a communications link or an automatic file encryptor.
- It is significantly faster than DES when implemented on 32-bit microprocessors with large data caches

Blowfish Key Schedule

- uses a 32 to 448 bit key [1 to 14 32-bit word]
- used to generate
  - 18 32-bit subkeys stored in K-array K_j
  - four 8x32 S-boxes stored in $S_{i,j}$
  - Totalling 18+1024 = 1042*8 = 4168 bytes
- key schedule consists of:
  - initialize P-array and then 4 S-boxes using pi
  - XOR P-array with key bits (reuse as needed)
  - loop repeatedly encrypting data using current P & S and replace successive pairs of P then S values
  - requires 521 encryptions, hence slow in rekeying

- The keys are stored in a K-array:
- K1, K2, .., Kj, j=1,2,..,14
- The sub-keys are stored in the P-array:
- P1, P2,.., P18
- There are four S-boxes, each with 256 32-bit entries:
- S1,0, S1,1, .., S1,255
- S2,0, S2,1, .., S2,255
- S3,0, S3,1, .., S3,255
- S4,0, S4,1, .., S4,255

Blowfish Encryption

- uses two primitives: addition & XOR
- data is divided into two 32-bit halves L_0 & R_0

```
for $i$ = 1 to 16 do
    $R_i = L_{i-1}$ XOR $P_i$;
    $L_i = F[R_i]$ XOR $R_{i-1}$;
$L_{17} = R_{16}$ XOR $P_{18}$;
$R_{17} = L_{16}$ XOR $i_{17}$;
```

- where

$$F[a,b,c,d] = ((S_{1,a} + S_{2,b}) \text{ XOR } S_{3,c}) + S_{4,a}$$

Blowfish

- a symmetric block cipher designed by Bruce Schneier in 1993/94
- characteristics
  - fast implementation on 32-bit CPUs
  - compact in use of memory
  - simple structure eases analysis/implemention
  - variable security by varying key size
- has been implemented in various products

- Fast: encrypts data on 32 bit MP at a rate of 18 clock cycles per byte.
- Compact: can run in less than 5K of Memory
- Simple: easy to implement.
- Variably secure: key length is variable and can be long as 448 bits.

Blowfish Key Schedule

- uses a 32 to 448 bit key [1 to 14, 32 bit word]
- keys stored in K-array: $K_{1,}\ K_{2,}\dots.\ K_{14}$
- used to generate
  - 18 32-bit subkeys stored in P-array $P_{1,}\ P_{2,}\dots.\ P_{18}$
  - four S-boxes each with 256 32-bit entries in $S_{i,j}$

$S_{1,0;}\ S_{1,1;}\ \dots.\ S_{1,255}$

$S_{2,0;}\ S_{2,1;}\ \dots.\ S_{2,255}$

$S_{3,0;}\ S_{3,1;}\ \dots.\ S_{3,255}$

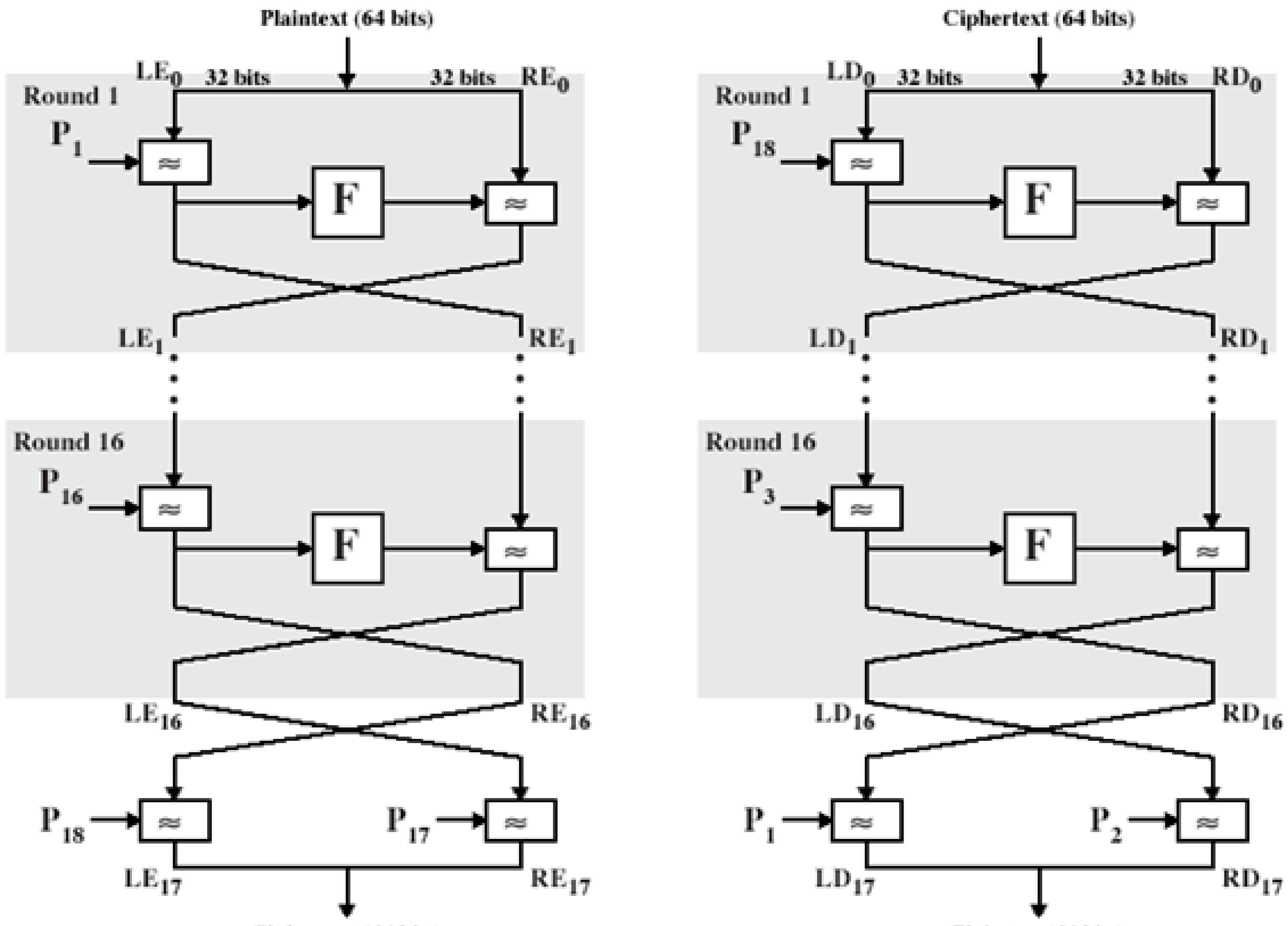
$S_{4,0;}\ S_{4,1;}\ \dots.\ S_{4,255}$

Contd…

- key schedule consists of:
  - initialize P-array and then 4 S-boxes using pi fractional part
    - P1 = 243F6A88
    - P2 = 85A308D3
    - ….
    - S4,254 = 578FDFE3
    - S4,255 = 3AC372E6
  - XOR P-array with key bits (reuse as needed)
  - $P1 = P1 \oplus K1$, $P2 = P2 \oplus K2$, $P3 = P3 \oplus K3$
  - $P14 = P14 \oplus K14$, P15 = P15 Xor K1, … ,P18 = P18 Xor K4

Contd…

- loop repeatedly encrypting data using current P & S and replace successive pairs of P then S values
- requires 521 encryptions, hence slow in rekeying
- P1, P2 = Ep,s[0];
- P3, P4 = Ep,s[P1||P2];
- P5, P6 = Ep,s[P3||P4];
- ….
- P_{17},P_{18}= Ep,s[P16||P17];
- $S_{1,0}$,$S_{1,1}$ = Ep,s[P17||P18];
- …
- $S_{4,254}$,$S_{4,255}$ = Ep,s[$S_{4,252}$||$S_{4,253}$];
- Hence not suitable for application that changes key frequently.



(a) Encryption

(b) Decryption

Figure 6.3 Blowfish Encryption and Decryption

Blowfish Encryption

- uses two primitives: addition (add by modulo 2^{32} & XOR
- data is divided into two 32-bit halves L_0 & R_0

```
for $i$ = 1 to 16 do
    $R_i = L_{i-1}$ XOR $P_i$;
    $L_i = F[R_i]$ XOR $R_{i-1}$;
$L_{17} = R_{16}$ XOR $P_{18}$;
$R_{17} = L_{16}$ XOR $P_{17}$;
```

- where

$$F[a,b,c,d] = ((S_{1,a} + S_{2,b}) \text{ XOR } S_{3,c}) + S_{4,d}$$

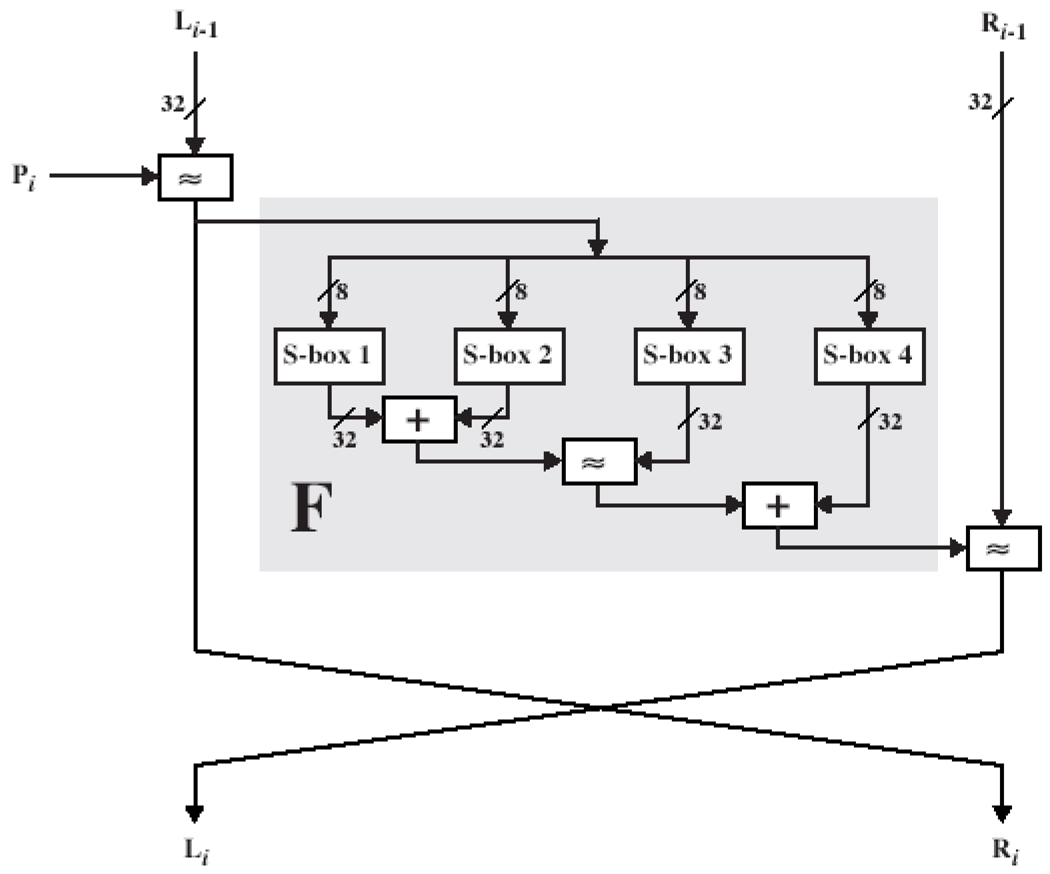


Figure 6.4 Detail of Single Blowfish Round

The Blowfish Algorithm

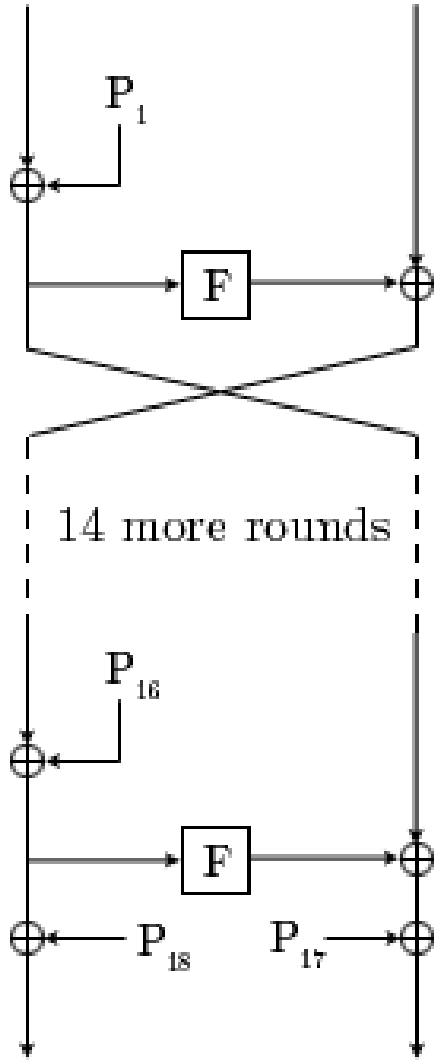
- **There are two parts to this algorithm;**
  - A part that handles the expansion of the key.
  - A part that handles the encryption of the data.
- **The expansion of the key:** break the original key into a set of subkeys. Specifically, a key of no more than 448 bits is separated into 4168 bytes. There is a P-array and four 32-bit S-boxes. The P-array contains 18 32-bit subkeys, while each S-box contains 256 entries.
- **The encryption of the data:** 64-bit input is denoted with an x, while the P-array is denoted with a Pi (where i is the iteration).

The Blowfish Algorithm: Key Expansion (cont)

- Blowfish has a 64-bit block size and a key length of anywhere from 32 bits to 448 bits (32-448 bits in steps of 8 bits; default 128 bits).
- It is a 16-round Feistel cipher and uses large key-dependent S-boxes. It is similar in structure to CAST-128, which uses fixed S-boxes.

The Blowfish Algorithm: Key Expansion (cont)

- The diagram to shows the action of Blowfish. Each line represents 32 bits. The algorithm keeps two subkey arrays: the 18-entry P-array and four 256-entry S-boxes.
- The S-boxes accept 8-bit input and produce 32-bit output. One entry of the P-array is used every round, and after the final round, each half of the data block is XORed with one of the two remaining unused P-entries.



The Blowfish Algorithm: Key Expansion (cont)

- Initialize the P-array and S-boxes
- XOR P-array with the key bits. For example, P1 XOR (first 32 bits of key), P2 XOR (second 32 bits of key), ...
- Use the above method to encrypt the all-zero string
- This new output is now P1 and P2
- Encrypt the new P1 and P2 with the modified subkeys
- This new output is now P3 and P4
- Repeat 521 times in order to calculate new subkeys for the P-array and the four S-boxes

The Blowfish Algorithm: Encryption (cont)

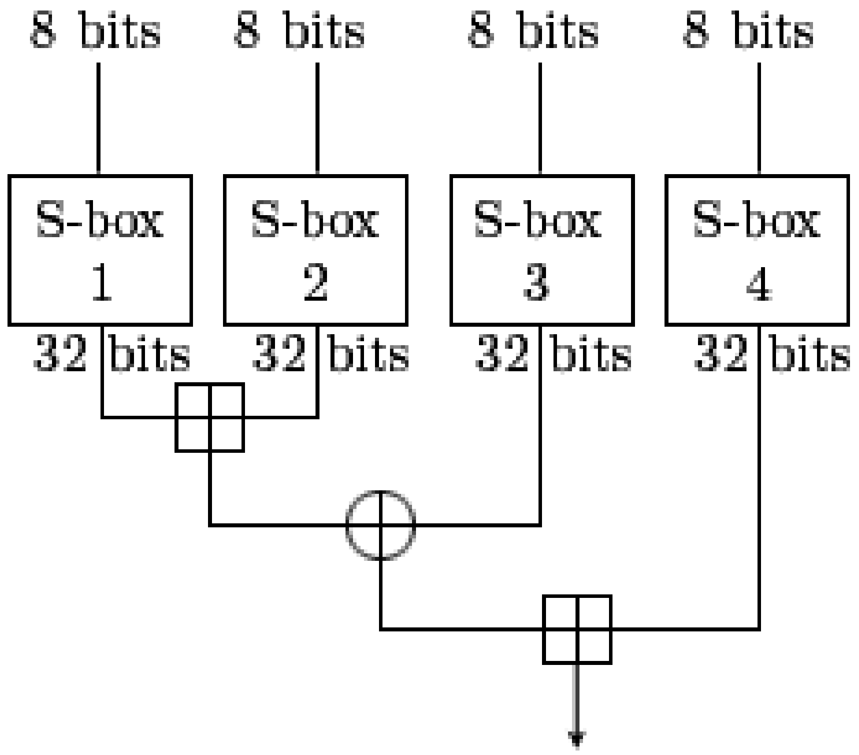
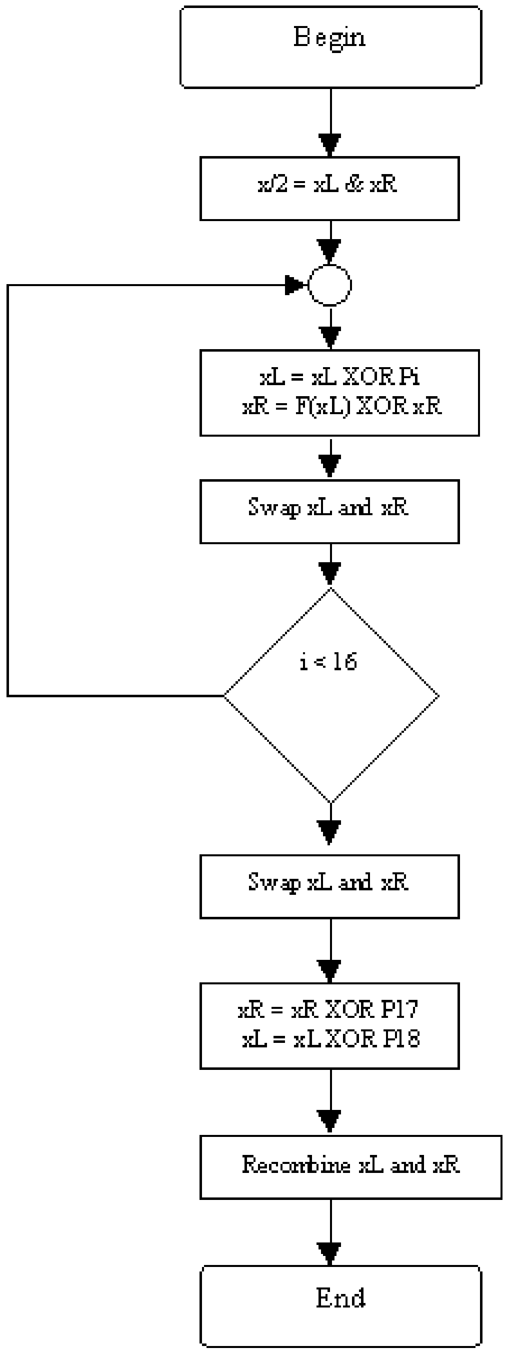


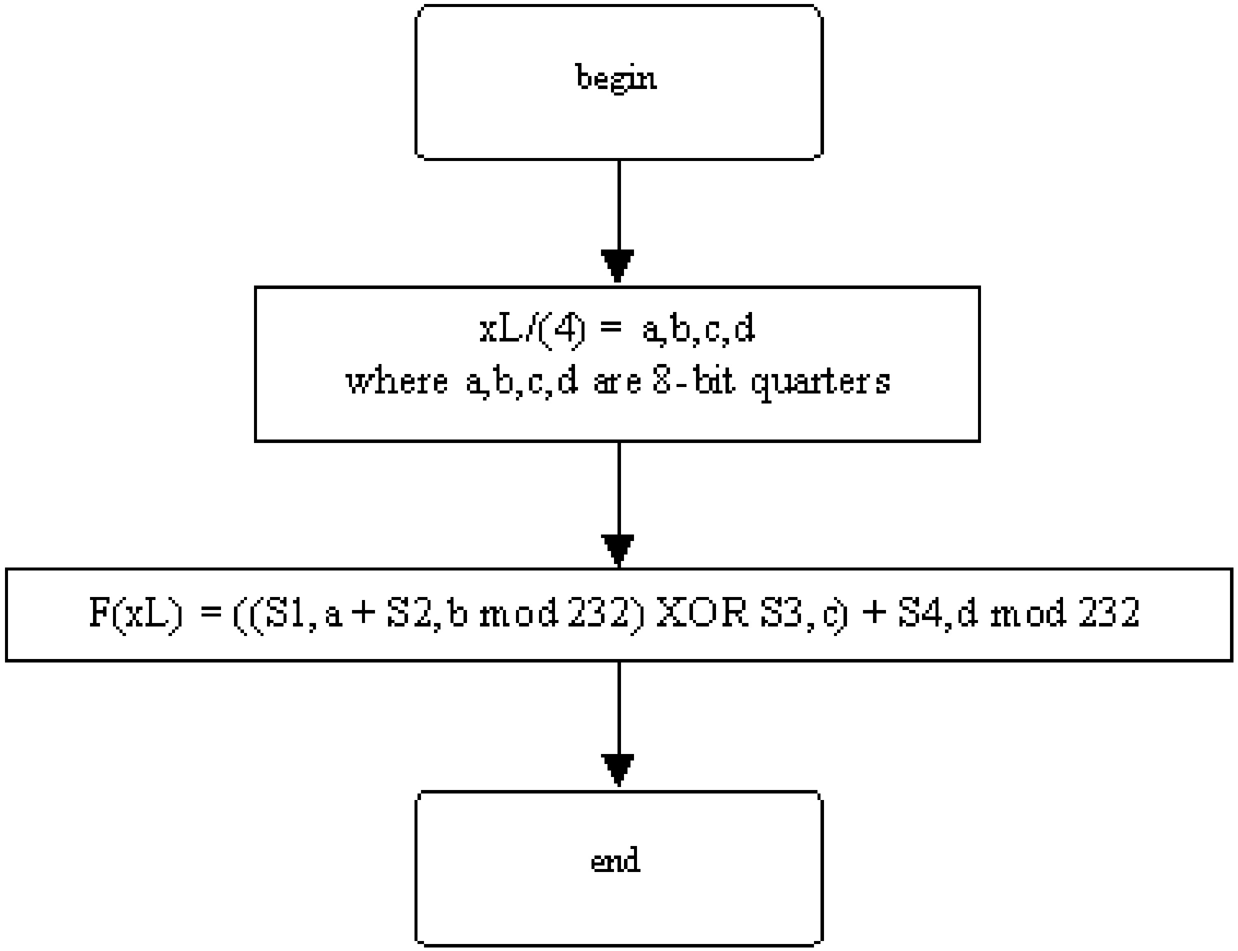
Diagram of Blowfish's F function

The Blowfish Algorithm



The Blowfish Algorithm: Encryption (cont)

- The diagram to the right shows Blowfish's F-function. The function splits the 32-bit input into four eight-bit quarters, and uses the quarters as input to the S-boxes. The outputs are added modulo 2^{32} and XORed to produce the final 32-bit output.
- Since Blowfish is a Feistel network, it can be inverted simply by XORing P17 and P18 to the ciphertext block, then using the P-entries in reverse order.


begin
xL/(4) = a,b,c,d
where a,b,c,d are 8-bit quarters
F(xL) = ((S1,a + S2,b mod 232) XOR S3,c) + S4,d mod 232
end

The Function F

The Blowfish Algorithm (cont)

- Blowfish's key schedule starts by initializing the P-array and S-boxes with values derived from the hexadecimal digits of pi, which contain no obvious pattern.
- The secret key is then XORed with the P-entries in order (cycling the key if necessary). A 64-bit all-zero block is then encrypted with the algorithm as it stands.
- The resultant ciphertext replaces P1 and P2. The ciphertext is then encrypted again with the new subkeys, and P3 and P4 are replaced by the new ciphertext. This continues, replacing the entire P-array and all the S-box entries.
- In all, the Blowfish encryption algorithm will run 521 times to generate all the subkeys - about 4KB of data is processed.

DECRYPTION

- Cipher text data is divided into two 32-bit halves LD_0 & RD_0

```
for $i$ = 1 to 16 do
    $RD_i$ = $LD_{i-1}$ XOR $P_{19-i}$;
    $LD_i$ = F[$RD_i$] XOR $RD_{i-1}$;
$LD_{17}$ = $RD_{16}$ XOR $P_1$;
$RD_{17}$ = $LD_{16}$ XOR $P_2$;
```

- Blowfish is a formidable symmetric cipher. Unlike DES, the S-boxes in Blowfish are key dependent. Both the sub-keys and S-boxes are produced by a process of repeated applications of Blowfish. This thoroughly mangles the bits and makes cryptanalysis very difficult. Another interesting aspect of the Blowfish design is that operations are performed on both halves of the data in each round, compared to performing operation on just half of the data in each round in the classic Feistel cipher. Blowfish is very fast.

Discussion

- key dependent S-boxes and subkeys, generated using cipher itself, makes analysis very difficult
- changing both halves in each round increases security
- provided key is large enough, brute-force key search is not practical, especially given the high key schedule cost

RC5

- symmetric encryption algorithm developed by Ron Rivest in 1994.
- It has following characteristics:
- Suitable for hardware or software
- Fast
- Adaptable to processors of different word lengths
- Variable number of rounds

- Variable-length key
- Simple
- Low memory requirement
- High security
- Data-dependent rotations
- RC5 has been incorporated into RSA Data Security, Inc's major products including BSAFE, JSAFE, and S/MAIL.

RC5

- a proprietary cipher owned by RSADSI
- designed by Ronald Rivest (of RSA fame)
- used in various RSADSI products
- can vary key size / data size / no rounds
- very clean and simple design
- easy implementation on various CPUs
- yet still regarded as secure

Parameter	Definition	Allowable values
W	Word size in bits. RC5 encrypts 2-word blocks	16,32,64
R	Number of rounds	0,1,..,255
B	Number of 8-bit bytes (octets) in the secret key K	0,1,.., 255

RC5 Ciphers

- RC5 is a family of ciphers RC5-w/r/b
  - w = word size in bits (16/32/64) nb data=2w
  - r = number of rounds (0..255)
  - b = number of bytes in key (0..255)
- nominal version is RC5-32/12/16
  - ie 32-bit words so encrypts 64-bit data blocks
  - using 12 rounds
  - with 16 bytes (128-bit) secret key

- consider the problem of replacing DES with an equivalent RC5algorithm –

  RC5 -32/16/7

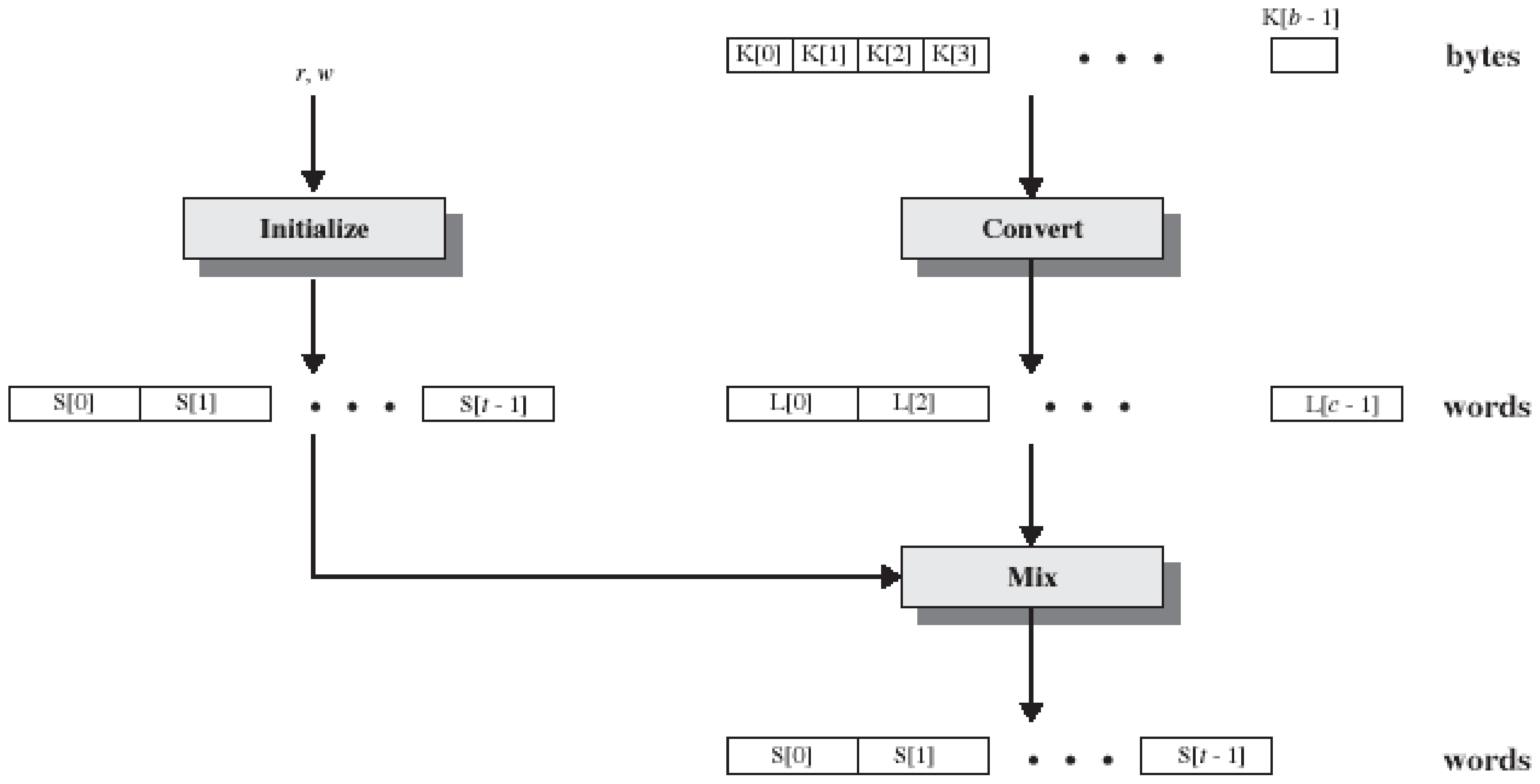


Figure 6.5 RC5 Key Expansion

- RC5 performs a complex set of operations on the secret key to produce a total of *t* sub-keys. Two sub-keys are used in each round, and two sub-keys are used on an additional operation that is not part of any round, so $t=2r+2$. Each sub-key is one word (*w* bits) in length.

- The sub-keys are stored in a *t*-word array labeled *S[0], S[1], .., S[t-1].* Using the parameters *r* and *w* as inputs, this array is initialized to a particular fixed pseudorandom bit pattern.

- Then the *b*-byte key, *K*[*0..b-1*], is converted into a *c*-word array *L*[*0..c-1*]. On a little-endian machine, this is accomplished by zeroing out the array L and copying the string K directly into the memory positions represented by *L*. If *b* is not an integer multiple of *w*, then a portion of *L* at the right end remains zero. Finally, a mixing operation is performed that applies the contents of *L* to the initialized values of *S* to produce a final value for the array *S*.

1. Two's complement addition of words, denoted by "+". This is modulo-2^w addition. The inverse operation, subtraction, is denoted "$-$".
2. Bit-wise exclusive-OR of words, denoted by $\oplus$.
3. A left-rotation (or "left-spin") of words: the cyclic rotation of word x left by y bits is denoted $x \lll y$. Here y is interpreted modulo w, so that when w is a power of two, only the $\lg(w)$ low-order bits of y are used to determine the rotation amount. The inverse operation, right-rotation, is denoted $x \ggg y$.

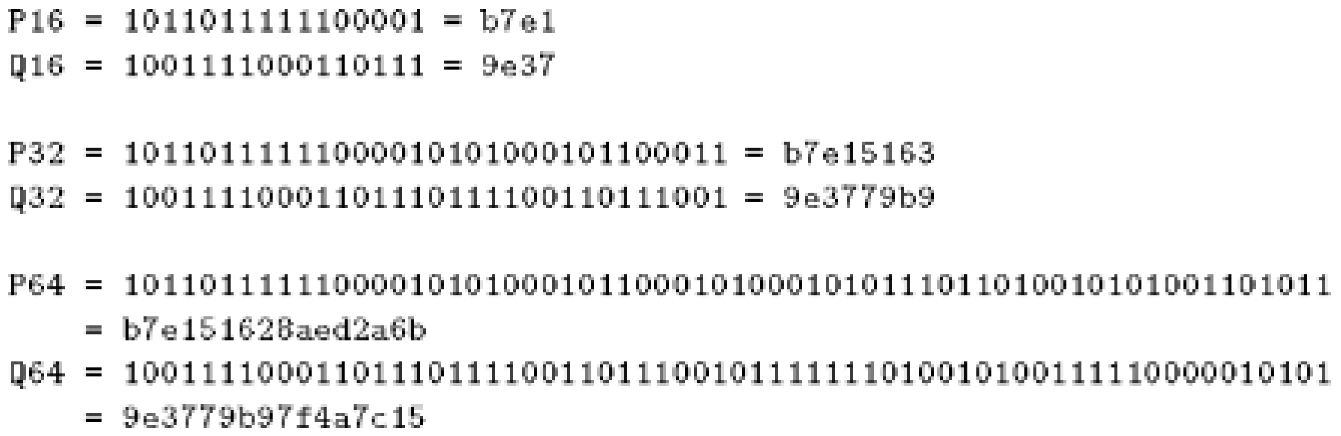
Detail

- The initialize operation makes use of two word-length constants defined as follows:
- $Pw=Odd[(e-2)2^{w}]$
- $Qw=Odd[(phi\ \phi\ -1)2^{w}]$
- e=2.718281828459.. (base of natural logarithms)
- =1.618033988749.. (golden ratio= $\frac{1+\sqrt{5}}{2}$

- *Odd[x]* is the odd integer nearest to *x* (rounded to *x+1* if *x* is an even)
- For example, Odd[3]=3, and Odd[ϕ]=1.

allowable values of *w*

W	16	32	64
Pw	B7e1	B7e15163	**B7e151638aed 2a6b**
Qw	**9e37**	**9e3779b9**	**9e3779b97f4a7 c15**



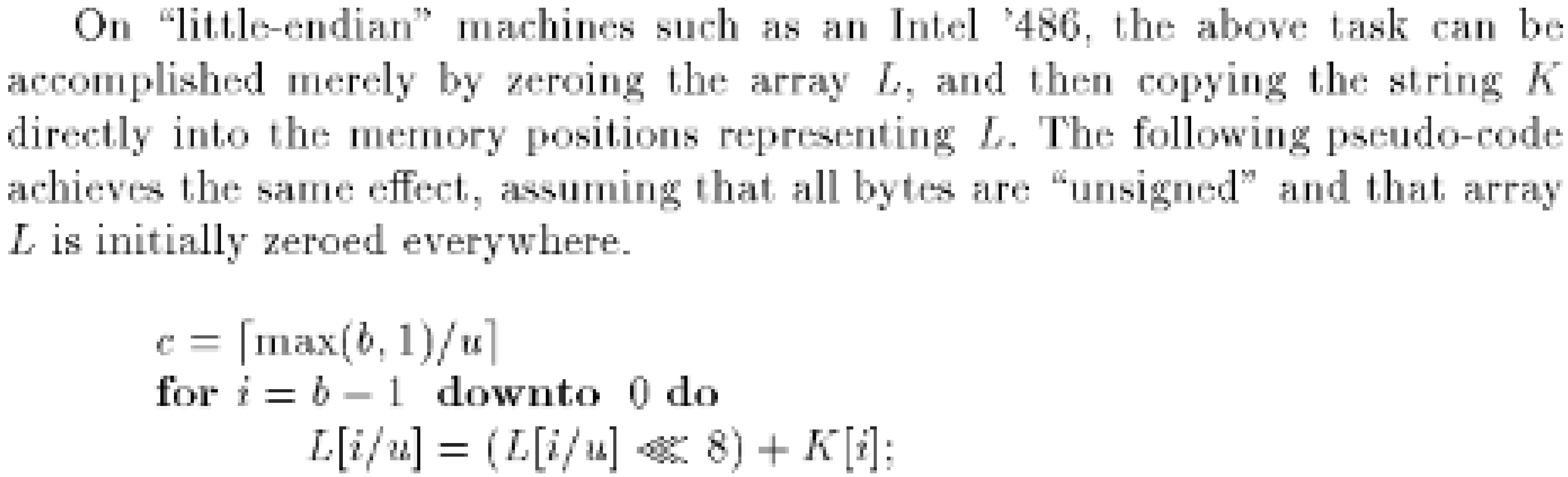
```
P16 = 1011011111100001 = b7e1
Q16 = 1001111000110111 = 9e37

P32 = 10110111111000010101000101100011 = b7e15163
Q32 = 10011110001101110111100110111001 = 9e3779b9

P64 = 1011011111100001010100010110001010001010111011010010101001101011
    = b7e151628aed2a6b
Q64 = 1001111000110111011110011011100101111111010010100111110000010101
    = 9e3779b97f4a7c15
```

S-Array Initialised

- the array S is initialized in the following manner:
- *S[0]=Pw;*
- *For i=1 to t-1*
- *S[i]=S[i-1]+Qw,* where addition is performed modulo 2^w

Converting the Secret Key from Bytes to Words. The first algorithmic step of key expansion is to copy the secret key $K[0...b-1]$ into an array $L[0...c-1]$ of $c = \lceil b/u \rceil$ words, where $u = w/8$ is the number of bytes/word. This operation is done in a natural manner, using u consecutive key bytes of K to fill up each successive word in L, low-order byte to high-order byte. Any unfilled byte positions of L are zeroed. In the case that $b = c = 0$ we reset c to 1 and set $L[0]$ to zero.

Bytes to word



On "little-endian" machines such as an Intel '486, the above task can be accomplished merely by zeroing the array L, and then copying the string K directly into the memory positions representing L. The following pseudo-code achieves the same effect, assuming that all bytes are "unsigned" and that array L is initially zeroed everywhere.

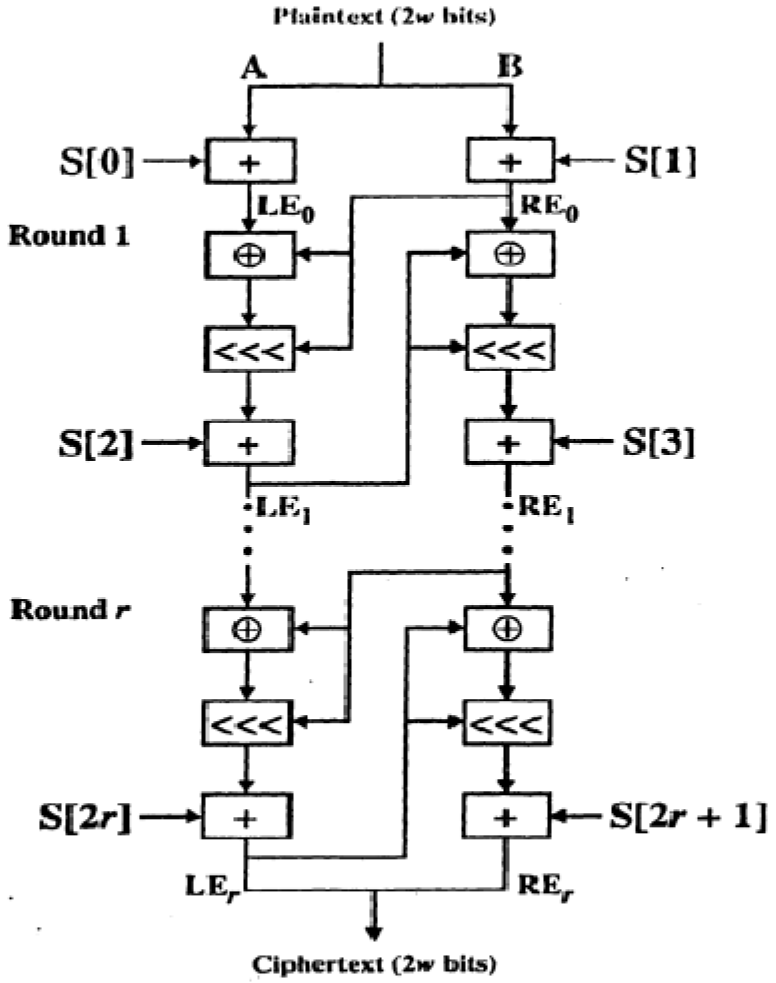
```
$c = \lceil \max(b, 1)/u \rceil$
for $i = b - 1$ downto $0$ do
    $L[i/u] = (L[i/u] \lll 8) + K[i];$
```

Mixing in the Secret Key. The third algorithmic step of key expansion is to mix in the user's secret key in three passes over the arrays S and L. More precisely, due to the potentially different sizes of S and L, the larger array will be processed three times, and the other may be handled more times.

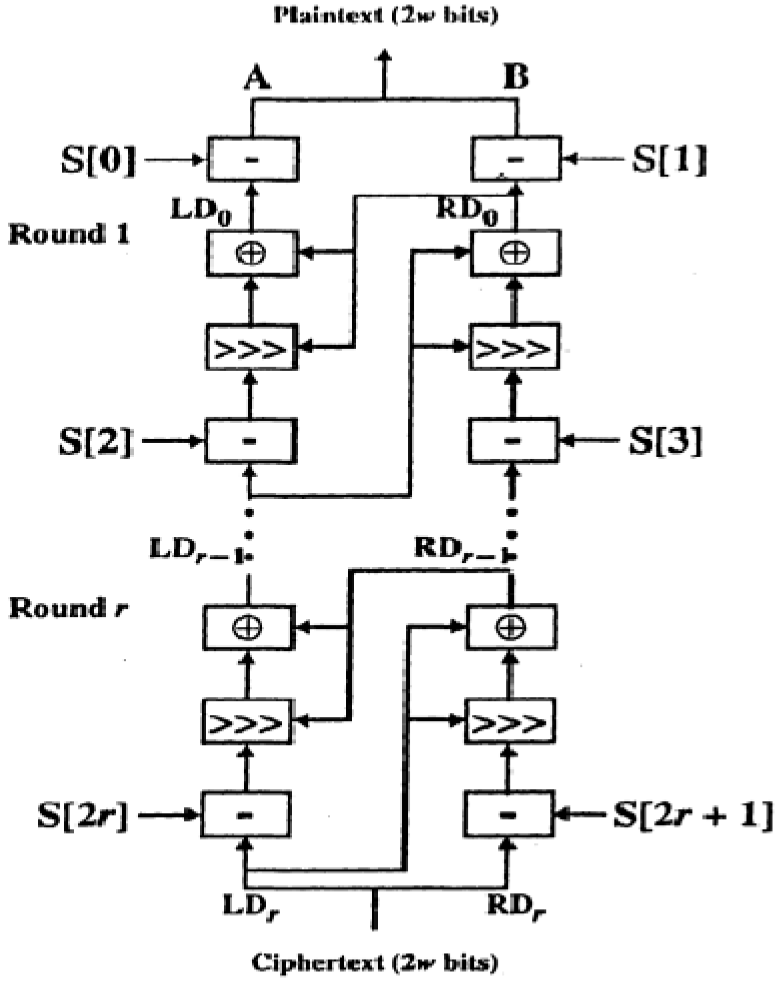
```
$i = j = 0;$
$A = B = 0;$
**do** $3 * \max(t, c)$ **times:**
        $A = S[i] = (S[i] + A + B) \lll 3;$
        $B = L[j] = (L[j] + A + B) \lll (A + B);$
        $i = (i + 1) \bmod(t);$
        $j = (j + 1) \bmod(c);$
```

The key-expansion function has a certain amount of "one-wayness": it is not so easy to determine K from S.

RC5 encryption



(a) Encryption



(b) Decryption

RC5 Key Expansion

- RC5 uses 2r+2 subkey words (w-bits)
- subkeys are stored in array `S[i]`, i=0..t-1
- then the key schedule consists of
  - initializing S to a fixed pseudorandom value, based on constants e and phi
  - the byte key is copied (little-endian) into a c-word array L
  - a mixing operation then combines L and S to form the final S array

RC5 Encryption

- split input into two halves A & B

```
$L_0 = A + S[0];$
$R_0 = B + S[1];$
for $i = 1$ to $r$ do
    $L_i = ((L_{i-1} \text{ XOR } R_{i-1}) <<< R_{i-1}) + S[2 \times i];$
    $R_i = ((R_{i-1} \text{ XOR } L_i) <<< L_i) + S[2 \times i + 1];$
```

- each round is like 2 DES rounds
- note rotation is main source of non-linearity
- need reasonable number of rounds (eg 12-16)

Decryption

The decryption routine is easily derived from the encryption routine.

```
**for** $i = r$ **downto** 1 **do**
        $B = ((B - S[2*i+1]) \ggg A) \oplus A;$
        $A = ((A - S[2*i]) \ggg B) \oplus B;$
$B = B - S[1];$
$A = A - S[0];$
```

RC5 Modes

- RFC2040 defines 4 modes used by RC5
  - RC5 Block Cipher, is ECB mode
  - RC5-CBC, is CBC mode
  - RC5-CBC-PAD, is CBC with padding by bytes with value being the number of padding bytes
  - RC5-CTS, a variant of CBC which is the same size as the original message, uses ciphertext stealing to keep size same as original

Block Cipher Characteristics

- features seen in modern block ciphers are:
  - variable key length / block size / no rounds
  - mixed operators, data/key dependent rotation
  - key dependent S-boxes
  - more complex key scheduling
  - operation of full data in each round
  - varying non-linear functions

Stream Ciphers

- process the message bit by bit (as a stream)
- typically have a (pseudo) random **stream key**
- combined (XOR) with plaintext bit by bit
- randomness of **stream key** completely destroys any statistically properties in the message
  - $C_i = M_i$ XOR $StreamKey_i$
- what could be simpler!!!!
- but must never reuse stream key
  - otherwise can remove effect and recover messages

Stream Cipher Properties

- some design considerations are:
  - long period with no repetitions
  - statistically random
  - depends on large enough key
  - large linear complexity
  - correlation immunity
  - confusion
  - diffusion
  - use of highly non-linear boolean functions

RC4

- a proprietary cipher owned by RSA DSI
- another Ron Rivest design, simple but effective
- variable key size, byte-oriented stream cipher
- widely used (web SSL/TLS, wireless WEP)
- key forms random permutation of all 8-bit values
- uses that permutation to scramble input info processed a byte at a time

RC4 Key Schedule

- starts with an array S of numbers: 0..255
- use key to well and truly shuffle
- S forms **internal state** of the cipher
- given a key k of length l bytes

```
for i = 0 to 255 do
    S[i] = i
j = 0
for i = 0 to 255 do
    j = (j + S[i] + k[i mod l]) (mod 256)
    swap (S[i], S[j])
```

RC4 Encryption

- encryption continues shuffling array values
- sum of shuffled pair selects "stream key" value
- tXOR with next byte of message to en/decrypt

```
i = j = 0
for each message byte $M_i$
    i = (i + 1) (mod 256)
    j = (j + S[i]) (mod 256)
    swap(S[i], S[j])
    t = (S[i] + S[j]) (mod 256)
    $C_i$ = $M_i$ XOR S[t]
```

RC4 Security

- claimed secure against known attacks
  - have some analyses, none practical
- result is very non-linear
- since RC4 is a stream cipher, must **never reuse a key**
- have a concern with WEP, but due to key handling rather than RC4 itself

Summary

- have considered:
  - some other modern symmetric block ciphers
  - Triple-DES
  - Blowfish
  - RC5
  - briefly introduced stream ciphers
  - RC4