Symmetric Key Crypto

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Some slides are written by Mark Stamp.

(Modern) Symmetric Key Crypto

- Stream cipher
  - generalize one-time pad
  - Except that key is relatively short → works on one bit/byte at a time
  - Key is stretched into a long keystream
  - Keystream is used just like a one-time pad
- Block cipher
  - More popular than stream cipher
  - Works on larger chunks of data (blocks) at a time
  - Can even combine blocks for additional security

Stream Ciphers

Generates keystream of any length from **random seed**

- Keystream is pseudorandom
- ~~Key is truly uniformly random~~
- Key is only used once, ever

$$Enc_{seed}(M) = K_{seed} \oplus M$$

Stream Ciphers

- Stream ciphers were the king of crypto
- Today, not as popular as block ciphers
- We'll discuss two stream ciphers:
- A5/1
  - Based on shift registers → hardware
  - Used in GSM mobile phone system
- RC4 → Rivest Cipher 4
  - Based on a changing lookup table
  - Used many places
  - *Note: RC5 is a block cipher*
  - *RSA*
    - *Shamir*

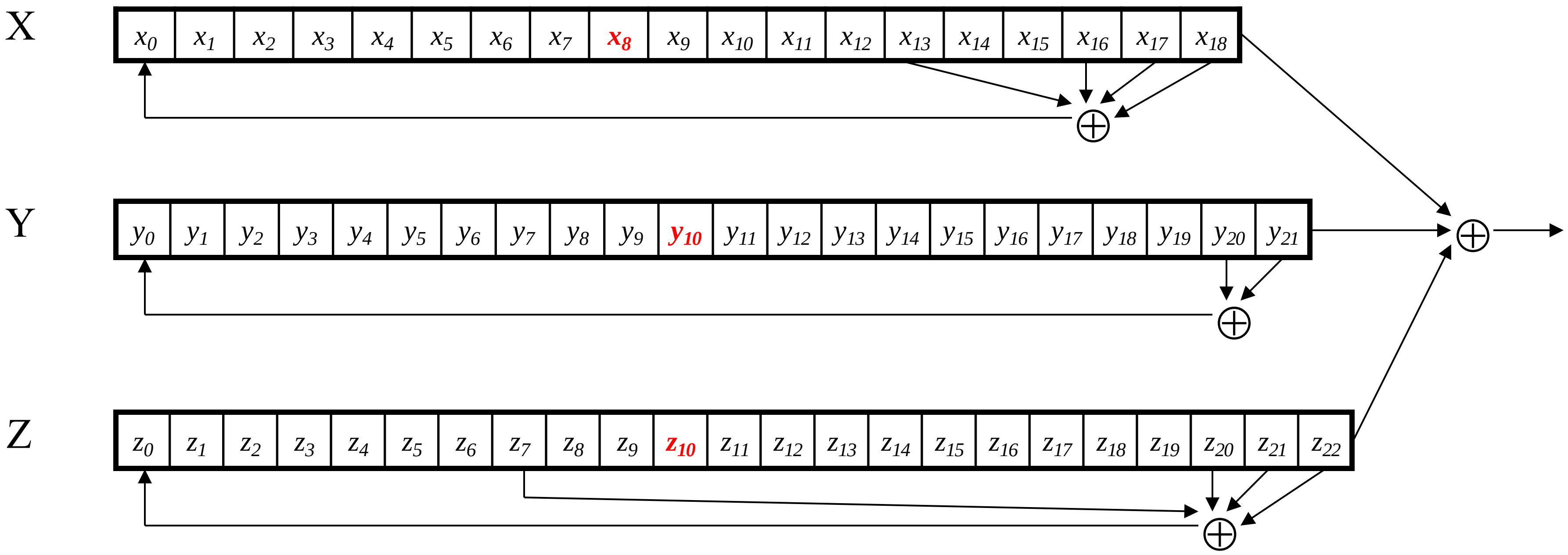
A5/1: Shift Registers

- A5/1 uses 3 *shift registers*
  - X: 19 bits $(x_0,x_1,x_2, \ldots,x_{18})$
  - Y: 22 bits $(y_0,y_1,y_2, \ldots,y_{21})$
  - Z: 23 bits $(z_0,z_1,z_2, \ldots,z_{22})$
- Use these bits to generate as many bits as we want to serve as One Time Pad.

A5/1: Keystream

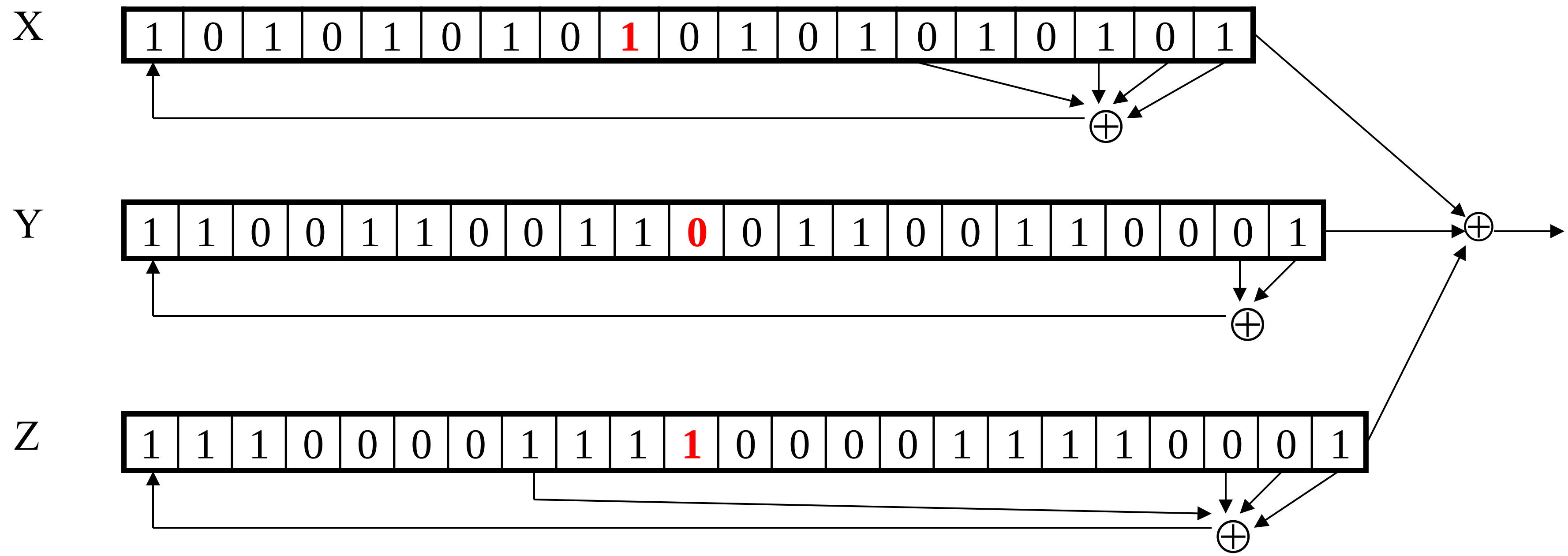
- At each iteration: $m = \mathrm{maj}(x_8, y_{10}, z_{10})$
  - Examples: $\mathrm{maj}(0,1,0) = 0$ and $\mathrm{maj}(1,1,0) = 1$
- If $x_8 = m$ then X *steps*
  - $t = x_{13} \oplus x_{16} \oplus x_{17} \oplus x_{18}$
  - $x_i = x_{i-1}$ for $i = 18,17,\ldots,1$ and $x_0 = t$
- If $y_{10} = m$ then Y *steps*
  - $t = y_{20} \oplus y_{21}$
  - $y_i = y_{i-1}$ for $i = 21,20,\ldots,1$ and $y_0 = t$
- If $z_{10} = m$ then Z *steps*
  - $t = z_7 \oplus z_{20} \oplus z_{21} \oplus z_{22}$
  - $z_i = z_{i-1}$ for $i = 22,21,\ldots,1$ and $z_0 = t$
- Keystream **bit** is $x_{18} \oplus y_{21} \oplus z_{22}$

A5/1



- Each variable here is a single bit
- Key is used as **initial fill** of registers
- Each register steps (or not) based on $\mathrm{maj}(x_8, y_{10}, z_{10})$
- Keystream bit is XOR of rightmost bits of registers

A5/1



- In this example, $m = \text{maj}(x_8, y_{10}, z_{10}) = \text{maj}(\mathbf{1},\mathbf{0},\mathbf{1}) = \mathbf{1}$
- Register X steps, Y does not step, and Z steps
- Keystream bit is XOR of right bits of registers
- Here, keystream bit will be $0 \oplus 1 \oplus 0 = 1$

Shift Register Crypto

- Shift register crypto efficient in hardware
- Often, slow if implemented in software
- In the past, very, very popular
- Today, more is done in software due to fast processors
- Shift register crypto still used some
  - E.g. in resource-constrained devices; embedded devices.

RC4

- A self-modifying lookup table
- Table always contains a permutation of the byte values 0,1,…,255
- Initialize the permutation using key
- At each step, RC4 does the following
  - Swaps elements in current lookup table
  - Selects a keystream byte from table
- Each step of RC4 produces a **byte**
- Each step of A5/1 produces only a bit
  - Efficient in hardware

RC4 Initialization

- S[] is permutation of 0,1,...,255
- key[] contains N bytes of key

```
for i = 0 to 255
        S[i] = i
        K[i] = key[i (mod N)]  ← any key length!
next i
j = 0
for i = 0 to 255
        j = (j + S[i] + K[i]) mod 256
        swap(S[i], S[j])
next i
i = j = 0
```

RC4 Keystream

- At each step, swap elements in table and select keystream byte

```
i = (i + 1) mod 256
j = (j + S[i]) mod 256
swap(S[i], S[j])
t = (S[i] + S[j]) mod 256
keystreamByte = S[t]
```

- Use keystream bytes like a one-time pad
- **Note:** first 256 bytes should be discarded
  - Otherwise, attack exists

Stream Ciphers

- Stream ciphers were popular in the past
  - Efficient in hardware → speed
  - Speed was needed to keep up with voice, etc.
    - Less memory consumption as well.
  - Today, processors are fast, so software-based crypto is usually more than fast enough
- Future of stream ciphers?
  - "the death of stream ciphers"?

Block Ciphers

Block Cipher

- Plaintext and ciphertext consist of fixed-sized blocks → bits
- Ciphertext obtained from plaintext by iterating a **round function**
- Input to round function consists of ***key*** and ***output*** of previous round
- Usually implemented in software
  - Used to be slow, but it's fine for modern CPUs
  - Intel has specific hardware instructions to speedup AES
    - AES-NI
    - AESENC AESDEC

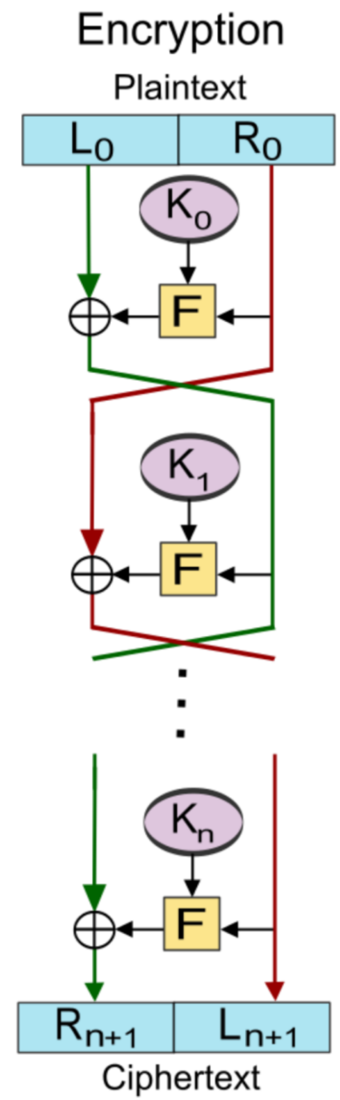
Feistel Cipher: Encryption

- **Feistel cipher** is a "type" of block cipher
  - ***Not*** a specific block cipher but a framework
  - Instances: DES; blowfish; RC5; TEA; Twofish…
- Split plaintext block into left and right components: $P = (L_0, R_0)$
- For each round $i = 0, 1, \ldots, n$, compute

  $L_{i+1} = R_i$

  $R_{i+1} = L_i \oplus F(R_i, K_i)$

  where F is round function and K_i is subkey
- Ciphertext: $C = (R_{n+1}, L_{n+1})$



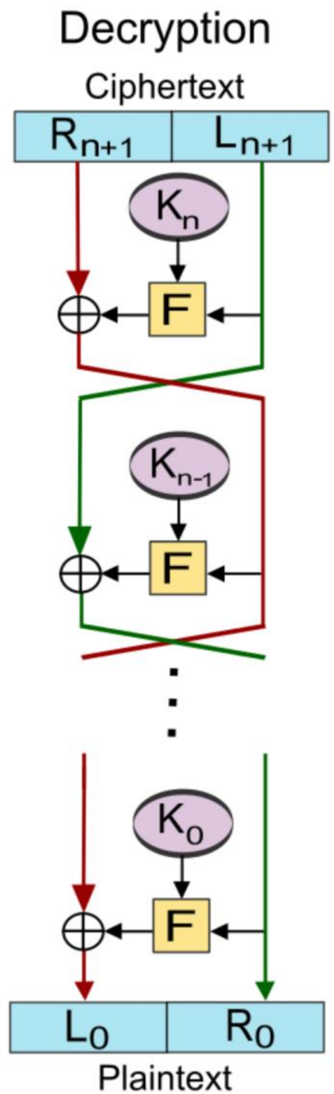
Feistel Cipher: Decryption

- Start with ciphertext $C = (R_{n+1}, L_{n+1})$
- For each round $i = n+1, n, \ldots, 1$, compute

  $R_{i-1} = L_i$

  $L_{i-1} = R_i \oplus F(L_i, K_{i-1})$

  where F is round function and K_i is subkey
- Plaintext: $P = (L_0, R_0)$
- Decryption works for any function F
  - But only secure for certain functions F
  - What about $F = 0$?

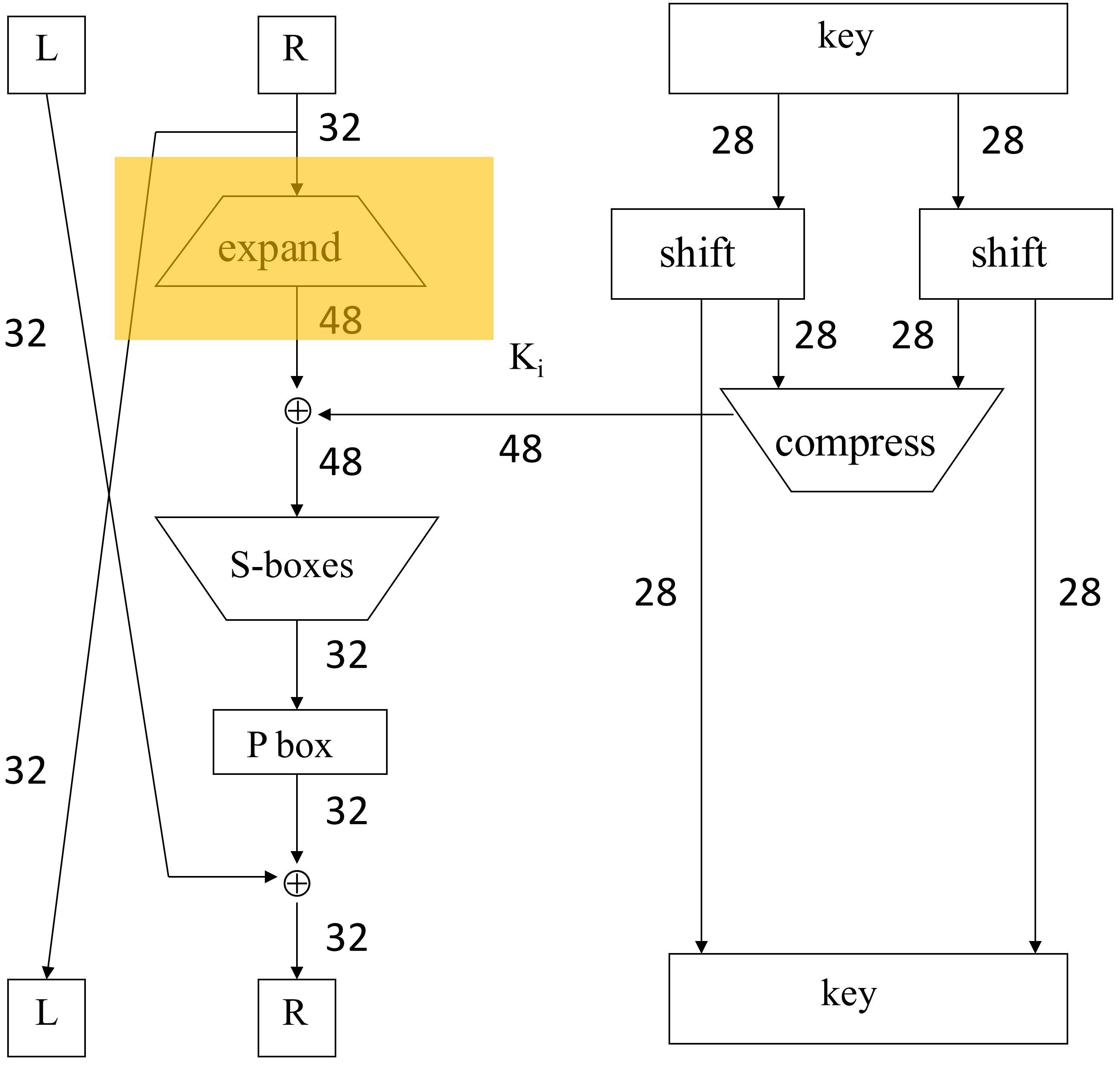


Data Encryption Standard

- **DES** developed in 1970's
- An implementation of Feistel Cipher
- DES was U.S. government standard
  - NSA "secured" the algorithm.
  - But it has been cracked in 1998
- Many successors
  - Triple DES; AES; G-DES; …

DES

- DES is a Feistel cipher with…
  - 64 bit block length
  - 56 bit key length
  - 16 rounds
  - 48 bits of key used each round (subkey)
- Round function is simple (for block cipher)
- Security depends heavily on “S-boxes”
  - Each S-box maps 6 bits to 4 bits



One Round of DES

DES Expansion Permutation

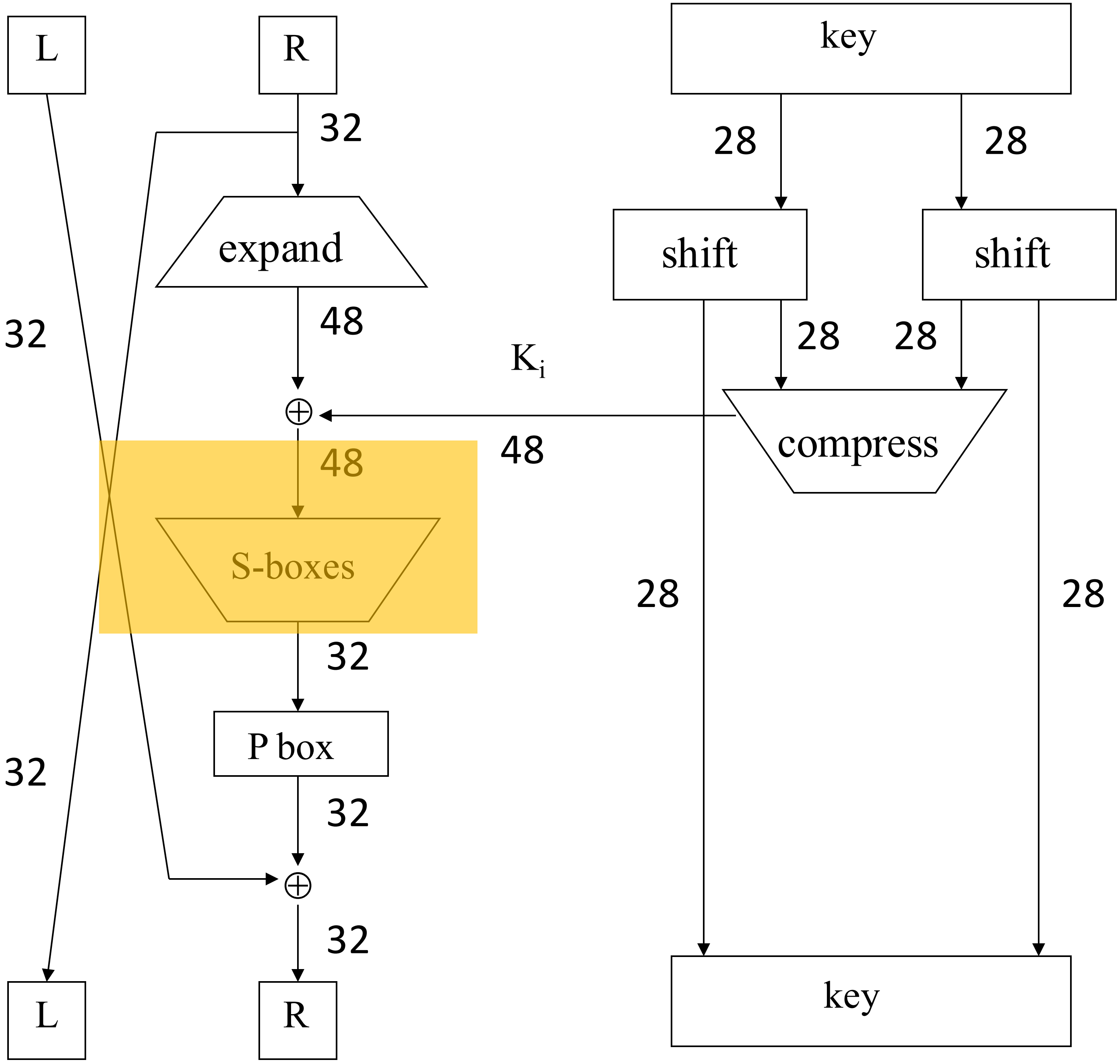
- Input 32 bits

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31

- Output 48 bits

31	0	1	2	3	4	3	4	5	6	7	8
7	8	9	10	11	12	11	12	13	14	15	16
15	16	17	18	19	20	19	20	21	22	23	24
23	24	25	26	27	28	27	28	29	30	31	0

- Output contains eight 6-bit (8 * 6 = 48 bits) pieces



One Round of DES

DES S-box

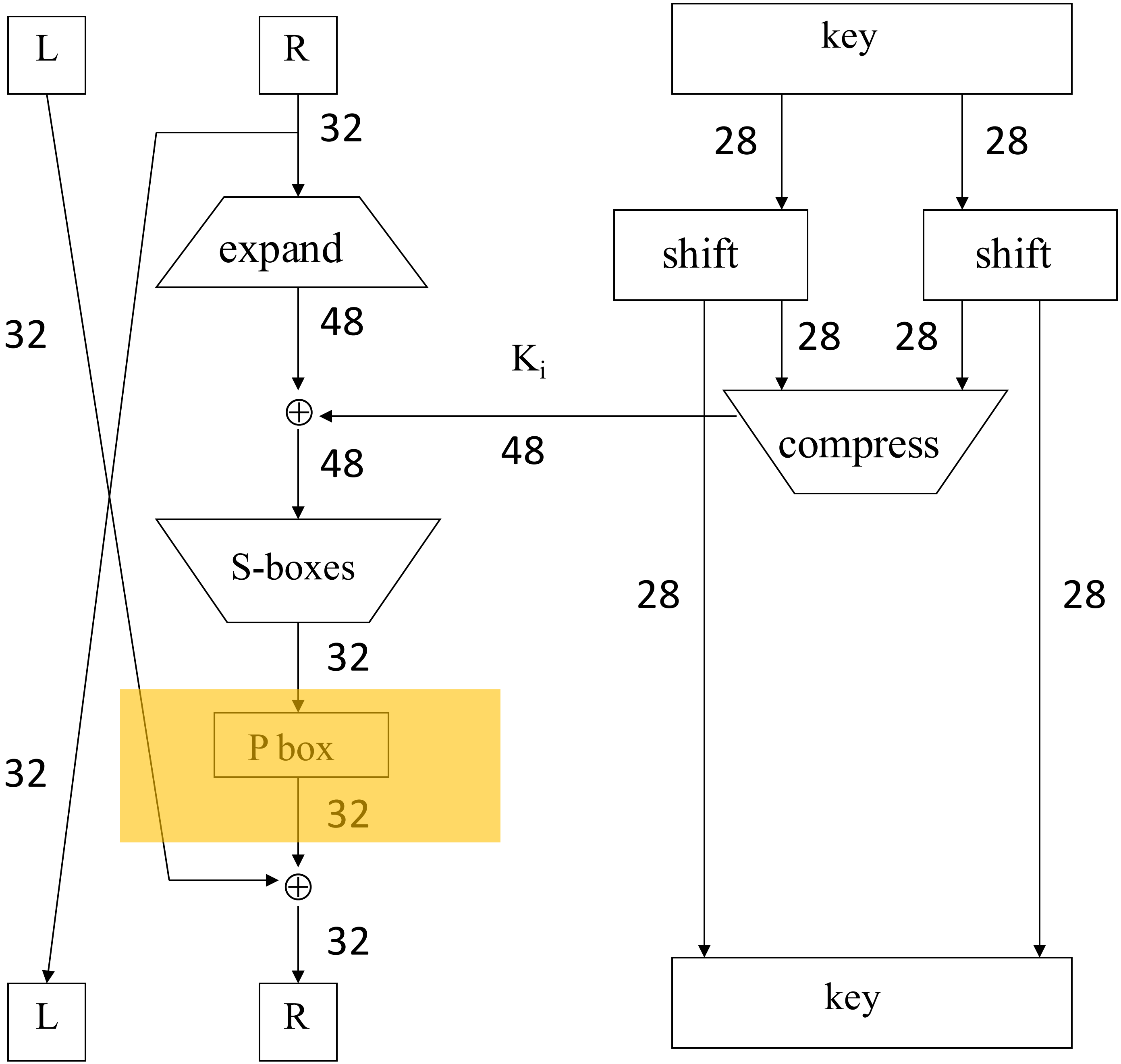
- 8 "substitution boxes" or S-boxes
  - In DES S-boxes are carefully chosen to resist cryptanalysis.
  - Thus, that is where the security comes from.
- Each S-box maps 6 bits to 4 bits

input bits (0,1,2,3,4,5)

↓ Middle four bits of the input bits

	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
00	1110	0100	1101	0001	0010	1111	1011	1000	0011	1010	0110	1100	0101	1001	0000	0111
01	0000	1111	0111	0100	1110	0010	1101	0001	1010	0110	1100	1011	1001	0101	0011	1000
10	0100	0001	1110	1000	1101	0110	0010	1011	1111	1100	1001	0111	0011	1010	0101	0000
11	1111	1100	1000	0010	0100	1001	0001	0111	0101	1011	0011	1110	1010	0000	0110	1101

non-linear transformation, provided in the form of a lookup table



One Round of DES

DES P-box

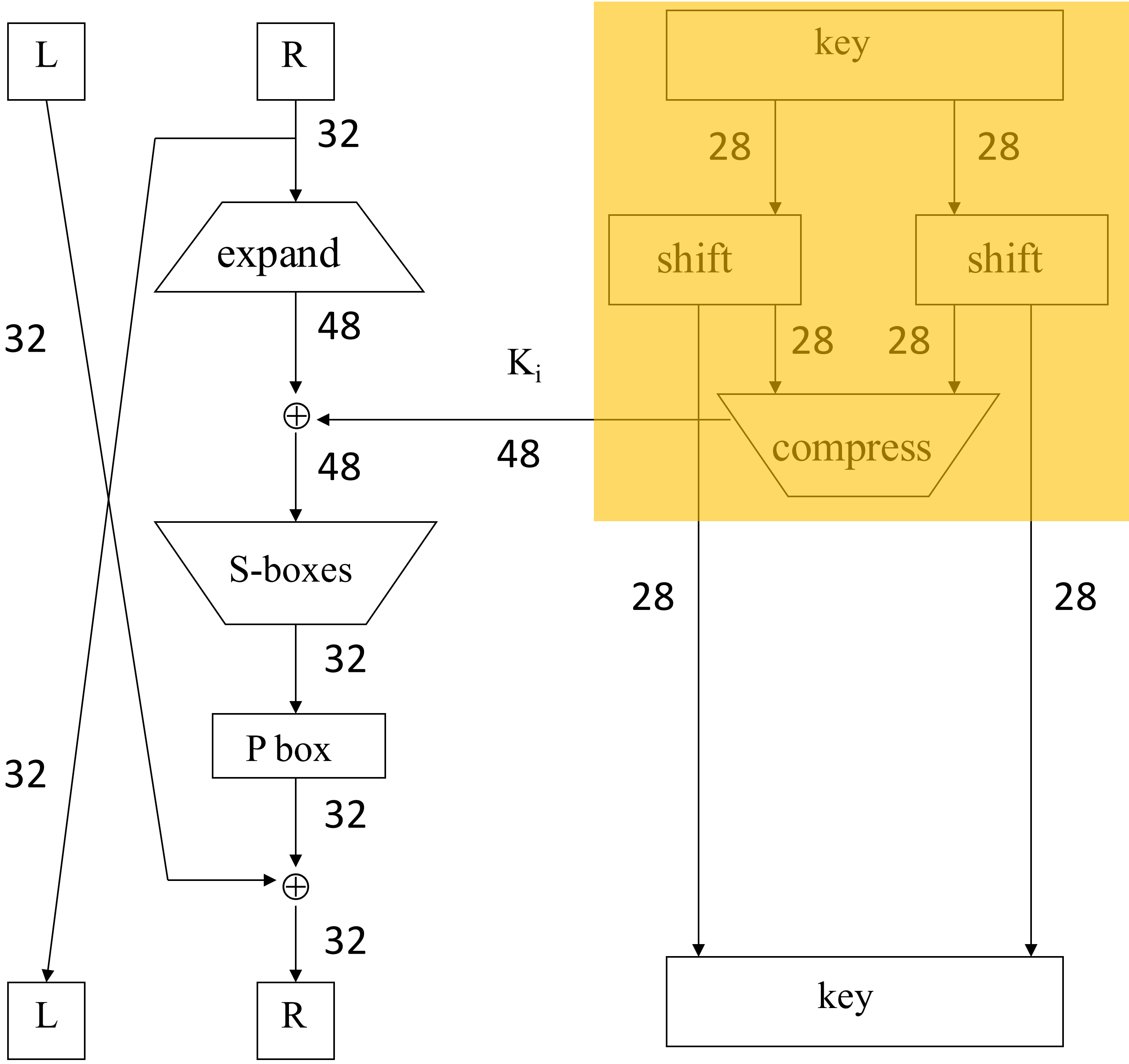
- Basically we further permutate the output of S-box.

- Input 32 bits

```
 0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
```

- Output 32 bits

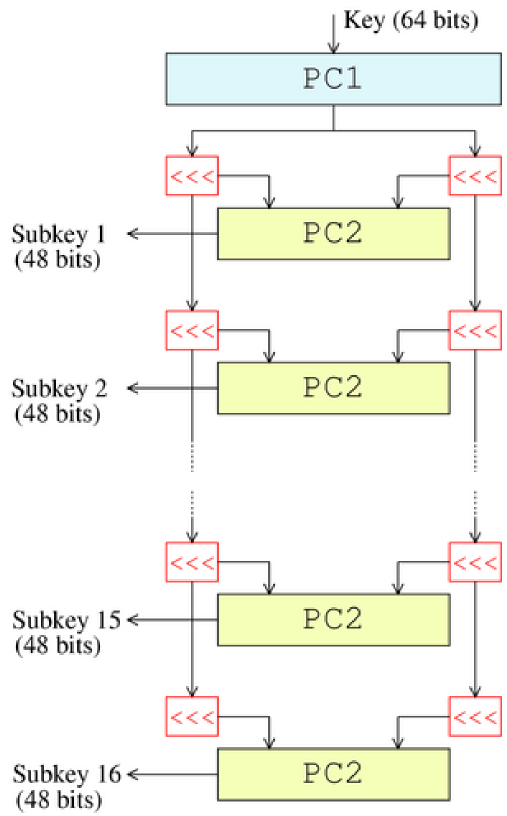
```
15  6 19 20 28 11 27 16  0 14 22 25  4 17 30  9
 1  7 23 13 31 26  2  8 18 12 29  5 21 10  3 24
```



One Round of DES

DES Subkey

- 56 bit DES key out of 64-bit, numbered 0,1,2,…,55
  - 24 * 2 bits of key are eventually extracted from 28 * 2 bits.

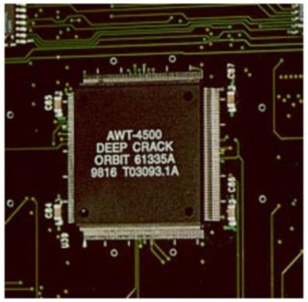


DES: Prologue and Epilogue

- An initial permutation before round 1
- Halves are swapped after last round
- A final permutation (inverse of initial perm) applied to (R_{16}, L_{16})
- None of this serves any security purpose
    - But this is how the algorithm is designed…

Security of DES

- Security depends heavily on S-boxes
- Attacks by exhaustive key search
  - given message x and a ciphertext c such that $DES_k(x)$=c → find k
  - Wiener: $1,000,000 - 3.5 hours; never built in public
  - 1998, the EFF DES Cracker, which was built for less than $250,000 < 3 days
  - 1999, Distributed.Net (*idle time of your computer*), 22 hours and 15 minutes (over many machines)
  - You can assume that NSA and agencies likely can crack DES in milliseconds



"Deep crack" DES cracker

Triple DES

- Today, 56 bit DES key is too small
  - As aforementioned, exhaustive key search is feasible
- **Triple DES** or **3DES** (with 112 bit key, why?)
  - $C = E(D(E(P,K_1),K_2),K_1)$
  - $P = D(E(D(C,K_1),K_2),K_1)$
- Why Encrypt-Decrypt-Encrypt with 2 keys?
  - Why not encrypt-encrypt-encrypt mode?
    - Backward compatible: $E(D(E(P,K),K),K) = E(P,K)$
  - And 112 is a lot of bits

3DES

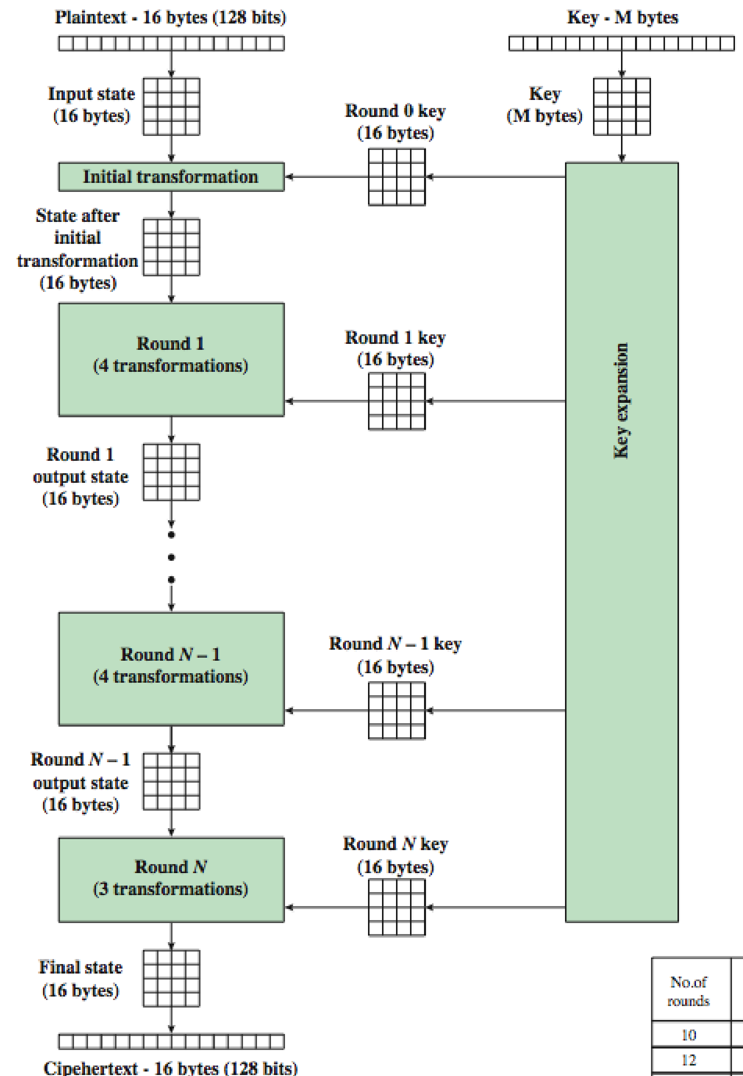
- Why not $C = E(E(P,K),K)$ instead?
  - still just 56 bit key
- But why not $C = E(E(P,K_1),K_2)$ instead?
  - Unfortunately, brute force search difficulty can be reduced from 2^112 to 2^57
- Meet-in-the-middle attack

Advanced Encryption Standard

- Replacement for DES
  - The de-facto symmetric cipher since late 1990
- Not a Feistel cipher (unlike DES)
  - Variable key lengths
  - Fast implementation in hardware and software
  - Small code and memory footprint → but still too much
- We will provide a (simplified) implementation of AES after today's class.
  - Just for your reference, you are NOT required to remember its implementation.

AES: Executive Summary

- **Block size:** 128 bits
- **Key length:** 128, 192 or 256 bits
- 10 to 14 rounds (depends on key length)
- Each round uses 4 functions
  - ByteSub (S-box layer)
  - ShiftRow
  - MixColumn
  - AddRoundKey (key addition layer)

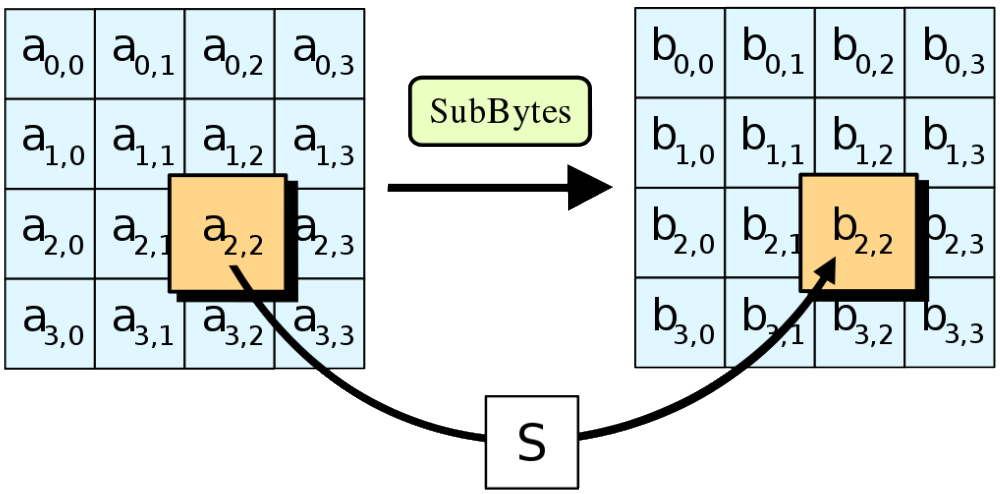


No.of rounds	Key Length (bytes)
10	16
12	24
14	32

You don’t need to remember this figure!!!!!

AES ByteSub

- Treat 128 bit block as 4x4 byte array



ByteSub is AES's "S-box"

- No fixed point $a_{i,j} = S(a_{i,j})$

AES “S-box”

Last 4 bits of input

First 4 bits of input

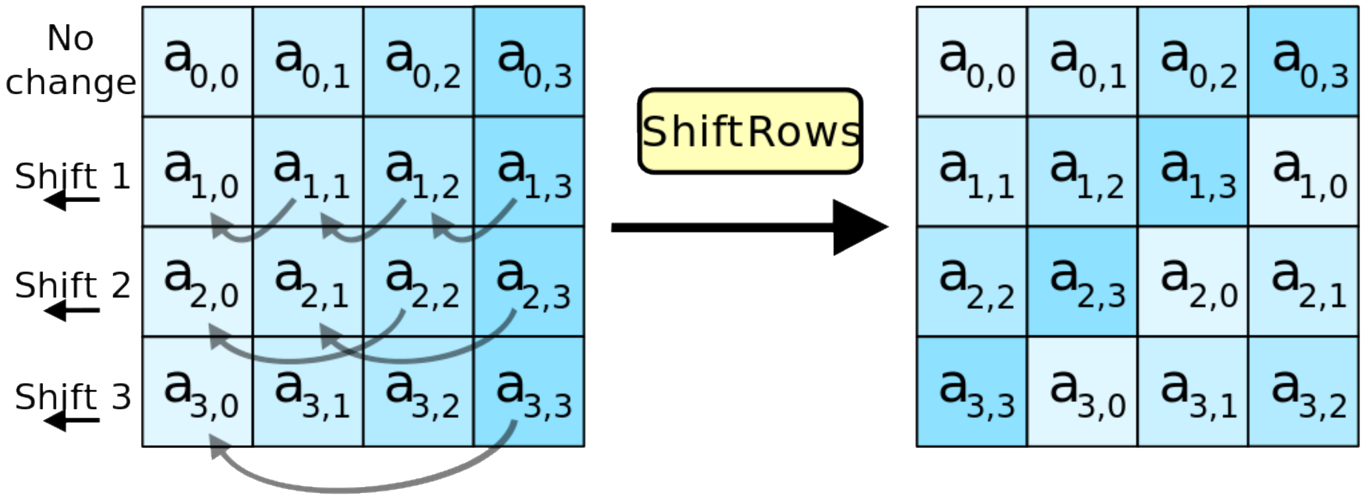
	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7c	77	7b	f2	6b	6f	c5	30	01	67	2b	fe	d7	ab	76
1	ca	82	c9	7d	fa	59	47	f0	ad	d4	a2	af	9c	a4	72	c0
2	b7	fd	93	26	36	3f	f7	cc	34	a5	e5	f1	71	d8	31	15
3	04	c7	23	c3	18	96	05	9a	07	12	80	e2	eb	27	b2	75
4	09	83	2c	1a	1b	6e	5a	a0	52	3b	d6	b3	29	e3	2f	84
5	53	d1	00	ed	20	fc	b1	5b	6a	cb	be	39	4a	4c	58	cf
6	d0	ef	aa	fb	43	4d	33	85	45	f9	02	7f	50	3c	9f	a8
7	51	a3	40	8f	92	9d	38	f5	bc	b6	da	21	10	ff	f3	d2
8	cd	0c	13	ec	5f	97	44	17	c4	a7	7e	3d	64	5d	19	73
9	60	81	4f	dc	22	2a	90	88	46	ee	b8	14	de	5e	0b	db
a	e0	32	3a	0a	49	06	24	5c	c2	d3	ac	62	91	95	e4	79
b	e7	c8	37	6d	8d	d5	4e	a9	6c	56	f4	ea	65	7a	ae	08
c	ba	78	25	2e	1c	a6	b4	c6	e8	dd	74	1f	4b	bd	8b	8a
d	70	3e	b5	66	48	03	f6	0e	61	35	57	b9	86	c1	1d	9e
e	e1	f8	98	11	69	d9	8e	94	9b	1e	87	e9	ce	55	28	df
f	8c	a1	89	0d	bf	e6	42	68	41	99	2d	0f	b0	54	bb	16

Then, how to invert this table? (need another table)

- 0x62 → 0xaa ➔ 0xaa → 0x62

AES ShiftRow

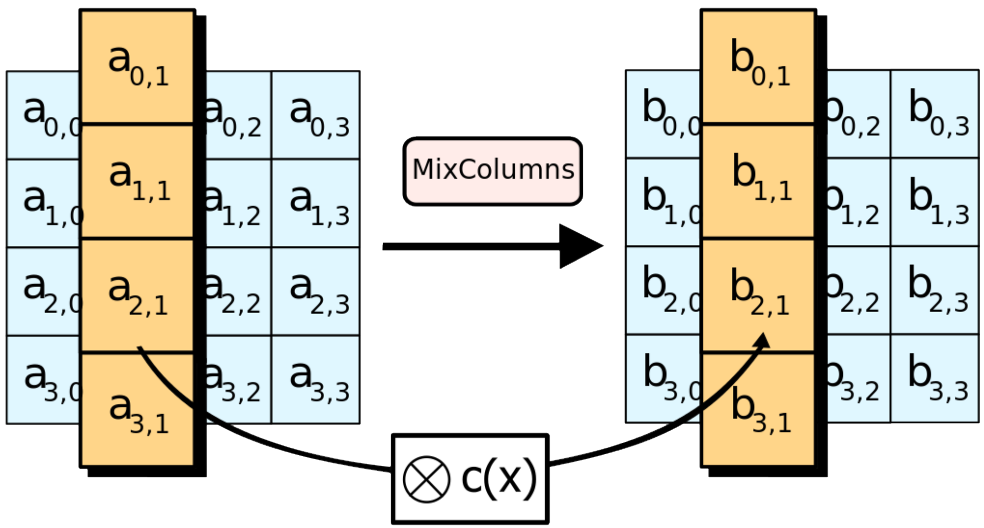
- Cyclic shift rows



To avoid the columns being encrypted independently

AES MixColumn

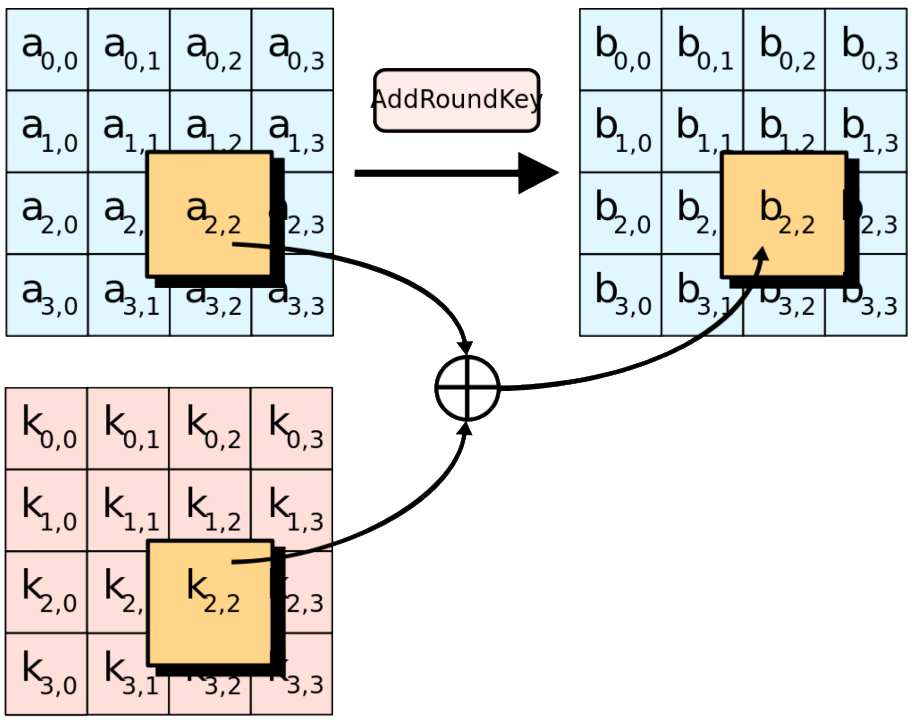
- Invertible operation applied to each column



- It's a matrix multiplication.
  - Implemented as a (big) lookup table

AES AddRoundKey

- XOR subkey with block



AES Comments

- Can be effectively implemented in 8-bit and 32-bit CPU.
    - One key reason it is becoming so popular
        - The franchise player in block cipher
    - Specific hardware instructions.
        - AES-NI
        - AESENC AESDEC
- Some other good properties
    - Avalanche effect: one bit difference in plaintext causes a big change in cipher text.
        - Talk about that later..

Tiny Encryption Algorithm

- 64 bit block, 128 bit key
- Assumes 32-bit arithmetic
- Number of rounds is variable (32 is considered secure)
- Uses “weak” round function, so large number of rounds required

TEA Encryption

Assuming 32 rounds:

$(K[0], K[1], K[2], K[3]) = 128$ bit key

(L,R) = plaintext (64-bit block)

delta = 0x9e3779b9

Magic number!

sum = 0

for i = 1 to 32

sum += delta

$L \mathrel{+}= ((R \ll 4)+K[0]) \oplus (R+sum) \oplus ((R \gg 5)+K[1])$

$R \mathrel{+}= ((L \ll 4)+K[2]) \oplus (L+sum) \oplus ((L \gg 5)+K[3])$

ciphertext = (L,R)

Again, you don't need to remember this detailed algorithm

TEA Decryption

Assuming 32 rounds:

$(K[0], K[1], K[2], K[3])$ = 128 bit key

(L,R) = ciphertext (64-bit block)

delta = 0x9e3779b9

sum = delta << 5

for i = 1 to 32

$\quad R \mathrel{-}= ((L \ll 4)+K[2]) \oplus (L+\text{sum}) \oplus ((L \gg 5)+K[3])$

$\quad L \mathrel{-}= ((R \ll 4)+K[0]) \oplus (R+\text{sum}) \oplus ((R \gg 5)+K[1])$

$\quad$ sum −= delta

plaintext = (L,R)

Again, you don't need to remember this detailed algorithm

TEA Comments

- **"Almost"** a Feistel cipher?
  - Uses + and - instead of $\oplus$ (XOR)
  - Each step both left and right halves are used.
- Simple, easy to implement, fast, low memory requirement, etc.
  - Can you memorize the implementation like how you memorize quick sort algorithm?
    - Well, that's why it's called "tiny".
- Possibly enable attacks?
  - four different keys that all give the exact same encrypted output
  - $2^{128} \rightarrow 2^{126}$
  - X-box attacks.

Overview of Linear Cryptanalysis

Linear Cryptanalysis

- Non-linear functions (i.e., s-box) are the primary contribution of security of block ciphers.
- To attack, we approximate the nonlinearity with **linear equations**
- How well can we do this?

Vulnerable S-box Linear Analysis

- Input $x_0x_1x_2$ where x_0 is row and x_1x_2 is column
- Output y_0y_1

row	column 00	01	10	11
0	10	01	11	00
1	00	10	01	11

Linear Analysis

- For example,
  $y_1 = x_1$
  with prob. 3/4
- And
  $y_0 = x_0 \oplus x_2 \oplus 1$
  with prob. 1
- And
  $y_0 \oplus y_1 = x_1 \oplus x_2$
  with prob. 3/4

row	column 00	01	10	11
0	10	01	11	00
1	00	10	01	11

Linear Cryptanalysis of DES

- DES is linear except for S-boxes
- How well can we approximate S-boxes with linear functions?
- DES S-boxes designed so there are no good linear approximations to any one output bit
- But there **are** linear combinations of output bits that can be approximated by linear combinations of input bits
  - Still not very practical, requires a huge amount of plaintext

Block Cipher Modes

Multiple Blocks

- How to encrypt multiple blocks?
  - What's the block size of AES/DES/TEA?
  - How large it is?
- Do we need a new key for each block?
  - If so, as impractical as a one-time pad!
- So, what can we do?
  - Encrypt each block individually?
  - Make encryption depends on previous block?
    - Then "chain" them together?
    - Partial block? Not considered in this course

Modes of Operation

- Many modes — we discuss 3 most popular
- Electronic Codebook (**ECB**) mode
  - Encrypt each block independently
  - Most obvious approach, but a bad idea
- Cipher Block Chaining (**CBC**) mode
  - Chain the blocks together
  - More secure than ECB, a little bit extra work
- Counter (**CTR**) mode
  - Block ciphers acts like a stream cipher
  - Popular for random access

ECB Mode

- Notation: $C = E(P, K)$
- Given plaintext $P_0, P_1, \ldots, P_m, \ldots$
- Most obvious way to use a block cipher:

Encrypt	**Decrypt**
$C_0 = E(P_0, K)$	$P_0 = D(C_0, K)$
$C_1 = E(P_1, K)$	$P_1 = D(C_1, K)$
$C_2 = E(P_2, K) \ \ldots$	$P_2 = D(C_2, K) \ \ldots$

- For fixed key K, this is "electronic" version of a codebook cipher (without additive)
  - With a different codebook for each key

ECB Cut and Paste

- Suppose plaintext is

  `Eva. pings Bob. Ted. pings Tom.`

- Assuming 64-bit blocks and 8-bit ASCII:

  $P_0 =$ "`Eva. pin`", $P_1 =$ "`gs Bob. `",

  $P_2 =$ "`Ted. pin`", $P_3 =$ "`gs Tom. `"

- Ciphertext: C_0, C_1, C_2, C_3
- Attacker cuts and pastes: C_0, C_3, C_2, C_1
- Decrypts as

  `Eva. pings Tom. Ted. pings Bob.`

Principles of CIA

Confidentiality:

- No one is supposed to read what data or information is sent unless he is authorized.

Integrity:

- The ability to ensure that data is an accurate and unchanged representation of the original secure information.

Availability:

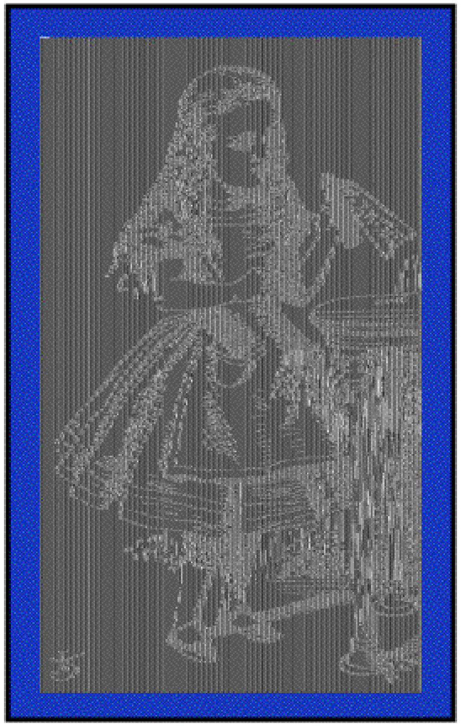
- the information concerned is readily accessible to the authorised viewer at all times

ECB Weakness

- Suppose $P_i = P_j$
- Then $C_i = C_j$ and attacker knows $P_i = P_j$
- This gives attacker some information, even if he does not know P_i or P_j
- Attacker might know P_i
- Is this a serious issue?
  - Any information can be leaked?

Alice Hates ECB Mode

- Alice’s uncompressed image, and ECB encrypted (TEA)



- ❑ Why does this happen?
- ❑ Same plaintext yields same ciphertext!

CBC Mode

- Blocks are "chained" together
- A random initialization vector, or IV, is required to initialize CBC mode
- IV is random, but not secret

Encryption

$$C_0 = E(IV \oplus P_0, K),$$
$$C_1 = E(C_0 \oplus P_1, K),$$
$$C_2 = E(C_1 \oplus P_2, K),\ldots$$

Decryption

$$P_0 = IV \oplus D(C_0, K),$$
$$P_1 = C_0 \oplus D(C_1, K),$$
$$P_2 = C_1 \oplus D(C_2, K),\ldots$$

- Analogous to classic codebook *with additive*

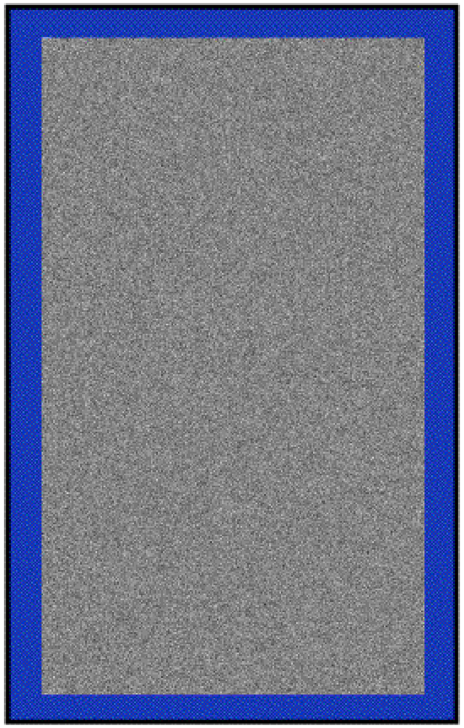
CBC Mode

- Identical plaintext blocks yield different ciphertext blocks — this is very good!
- But what about errors in transmission?
  - If C_1 is garbled to, say, G then

    $$P_1 \neq C_0 \oplus D(G, K),\ P_2 \neq G \oplus D(C_2, K)$$
  - But $P_3 = C_2 \oplus D(C_3, K)$, $P_4 = C_3 \oplus D(C_4, K)$, …
  - “G” can only influence limited decryptions!
- Cut and paste is still possible
  - Talk more on “integrity” later today.

Alice Likes CBC Mode

- Alice's uncompressed image, Alice CBC encrypted (TEA)



- ❑ Why does this happen?
- ❑ Same plaintext yields different ciphertext!

Counter Mode (CTR)

- CTR is popular for random access
- Use block cipher like a stream cipher

Encryption

$C_0 = P_0 \oplus E(IV, K),$

$C_1 = P_1 \oplus E(IV+1, K),$

$C_2 = P_2 \oplus E(IV+2, K), \ldots$

Decryption

$P_0 = C_0 \oplus E(IV, K),$

$P_1 = C_1 \oplus E(IV+1, K),$

$P_2 = C_2 \oplus E(IV+2, K), \ldots$

Integrity

Data Integrity

- **Integrity** — detect unauthorized writing (i.e., detect unauthorized mod of data)
- Example: Inter-bank fund transfers
  - Confidentiality may be nice, integrity is ***critical***
- Encryption provides **confidentiality** (prevents unauthorized disclosure)
- Encryption alone does **not** provide integrity
  - One-time pad, ECB cut-and-paste, etc., etc.

MAC

- Message Authentication Code (MAC)
  - Used for data **integrity**
  - Integrity not the same as confidentiality
- MAC is computed as **CBC residue**
  - That is, compute CBC encryption, saving only final ciphertext block, the MAC
  - The MAC serves as a cryptographic checksum for data
    - Any tempering of data will be detected.

MAC Computation

- MAC computation (assuming N blocks)

  $C_0 = E(IV \oplus P_0, K)$,

  $C_1 = E(C_0 \oplus P_1, K)$,

  $C_2 = E(C_1 \oplus P_2, K), \ldots$

  $C_{N-1} = E(C_{N-2} \oplus P_{N-1}, K) = MAC$

- Send IV, P_0, P_1, …, P_{N-1} and MAC
- Receiver does same computation and verifies that result agrees with MAC
- Both sender and receiver must know K

Does a MAC work?

- Suppose Alice has 4 plaintext blocks
- Alice computes

  $\mathbf{C_0} = E(IV \oplus P_0, K)$, $\mathbf{C_1} = E(\mathbf{C_0} \oplus P_1, K)$,

  $\mathbf{C_2} = E(\mathbf{C_1} \oplus P_2, K)$, $\mathbf{C_3} = E(\mathbf{C_2} \oplus P_3, K) = \mathbf{MAC}$
- Alice sends IV, P_0, P_1, P_2, P_3 and $\mathbf{MAC}$ to Bob
- Suppose the attacker changes P_1 to X
- Bob computes

  $\mathbf{C_0} = E(IV \oplus P_0, K)$, $\boldsymbol{C_1} = E(\mathbf{C_0} \oplus X, K)$,

  $\boldsymbol{C_2} = E(\boldsymbol{C_1} \oplus P_2, K)$, $\boldsymbol{C_3} = E(\boldsymbol{C_2} \oplus P_3, K) = \boldsymbol{MAC} \neq \mathbf{MAC}$
- It works since error <u>propagates</u> into $\mathbf{MAC}$
- The attacker can't make $\boldsymbol{MAC} == \mathbf{MAC}$ without K

Confidentiality and Integrity

- Encrypt with one key, MAC with another key
- Why not use the same key?
  - Send last encrypted block (MAC) twice?
  - This cannot add any security!

Confidentiality and Integrity

- Using different keys to encrypt and compute MAC works, even if keys are related
  - But, twice as much work as encryption alone
  - Can do a little better — about 1.5 “encryptions”
- Confidentiality *and* integrity with same work as one encryption is a still research topic…
  - Authenticated encryption (AE)
  - Optional reading materials on this topic.

Quantum Computers and Symmetric Ciphers

- Quantum computers use weird properties of quantum mechanics
- These use “quantum bits” or “qubits”
  - Bits are either 0 or 1, but…
  - Qubits both 0 and 1? Or range 0 to 1?
- With N bits, in one of 2^N states
- With N qubits, 2^N quantum amplitudes
  - Which are continuous, not discrete, values, so potential for vastly more computing power

Quantum Computers and Symmetric Ciphers

- Quantum computers are challenging to build and to program
- Special algorithms needed to take advantage of qubits
  - Need to use reversible logic operations
  - Results generally only probabalistic
- Today, quantum computers are small
  - IBM claims to have one with 433 qubits
  - Engineering challenges are immense

Quantum Computers and Symmetric Ciphers

- Assuming big quantum computers are built, are they a threat to symmetric ciphers?
- Best quantum algorithm for exhaustive search is due to Grover (1996)
- Grover's algorithm is square root faster
- For n bit symmetric key…
  - Conventional computer: Work factor 2^{n-1}
  - Grover's algorithm: Work factor about $2^{n/2}$

Quantum Computers and Symmetric Ciphers

- Assuming big quantum computers are built, are they a threat to symmetric ciphers?
- Not really a serious threat
- If we double the length of the key, work factor for Grover's algorithm is same
- For AES, most common to use 128-bit key
  - But, we can use 256-bit keys
  - Just a little slower with 256 than 128-bit key

Uses for Symmetric Crypto

- Confidentiality
  - Transmitting data over insecure channel
  - Secure storage on insecure media
- Integrity (MAC)
- Authentication protocols (later…)
- Hash function