04 Cryptography II

@Andrew: assign groups!

Engr 399/599: Hardware Security

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Adapted from: Mark Tehranipoor of University of Florida

Course Website

engr599.github.io

4111 Room Code:
2-3-5

Write that down!

Last Time: Caesar Cypher Example

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
D E F G H I J K L M N O P Q R S T U V W X Y Z A B C

H E L L O W O R L D ← plaintext

K H O O R . . . ← cypher text

1-grams (Unigrams) for English

a	0.080	h	0.060	n	0.070	t	0.090
b	0.015	i	0.065	o	0.080	u	0.030
c	0.030	j	0.005	p	0.020	v	0.010
d	0.040	k	0.005	q	0.002	w	0.015
e	0.130	l	0.035	r	0.065	x	0.005
f	0.020	m	0.030	s	0.060	y	0.020
g	0.015					z	0.002

[cf. Barbara Endicott-Popovsky, U. Washington]

Polyalphabetic Substitution - Examples

– Example:

	A	B	C	D	E	F	G	H	I	J	K	L	M
Key1:	a	d	g	j	m	p	s	v	y	b	e	h	k
Key2:	n	s	x	c	h	m	r	w	b	g	l	q	v

	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Key1:	n	q	t	w	z	c	f	i	l	o	r	u	x
Key2:	a	f	k	p	u	z	e	j	o	t	y	d	i

– **Plaintext: TOUGH STUFF**

– **Ciphertext: ffirv zfjpm**

use n (=2) keys in turn for consecutive P chars in P

- Note:
  - Different chars mapped into the same one: **T, O → f**
  - Same char mapped into different ones: **F → p, m**
  - '**f**' most frequent in C (0.30); in English: f(**f**) = 0.02 << f(**e**) = 0.13

[cf. J. Leiwo, VU, NL]

Vigenere Tableaux (1)

Note: Row A – shift 0 (a->a)
Row B – shift 1 (a->b)
Row C – shift 2 (a->c)
…
Row Z – shift 25 (a->z)

[cf. J. Leiwo, VU, NL]

	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	p
A	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	0
B	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	a	1
C	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	2
D	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	3
E	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	4
F	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	5
G	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	6
H	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	7
I	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	8
J	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	9
K	k	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	10
L	l	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	11
M	m	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	12
N	n	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	13
O	o	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	14
P	p	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	15
Q	q	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	16
R	r	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	17
S	s	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	18
T	t	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	19
U	u	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	20
V	v	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	21
W	w	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	22
X	x	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	23
Y	y	z	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v	w	x	24
Z	z	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	25

Vigenère Tableaux (2)

- Example

  Key:

  EXODUS

  Plaintext P:

  YELLOW SUBMARINE FROM YELLOW RIVER

  Extended keyword (re-applied to mimic words in P):

  YELLOW SUBMARINE FROM YELLOW RIVER

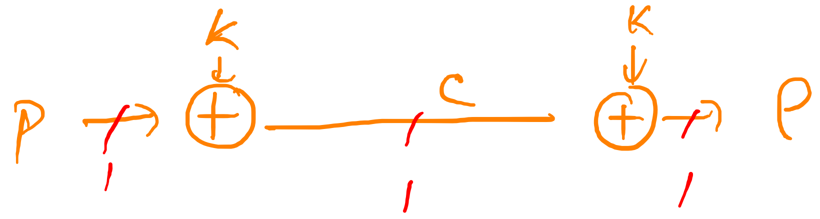
  EXODUS EXODUSEXO DUSE XODUSE XODUS

  Ciphertext:

  cbxoio wlppujmks ilgq vsofhb owyyj

[cf. J. Leiwo, VU, NL]

Stream and Block Ciphers (1)



a. Stream ciphers

b. Problems with stream ciphers

c. Block ciphers

d. Pros / cons for stream and block ciphers

Stream Ciphers (1)

- **Stream cipher**: 1 char from P → 1 char for C
  - Example: polyalphabetic cipher
    - P and K (repeated 'EXODUS'):
      YELLOWSUBMARINEFROMYELLOWRIVER
      EXODUSEXODUSEXODUSEXODUSEXODUS
    - Encryption (char after char, using Vigenère Tableaux):
      (1) E(**Y**, **E**) → **c**   (2) E(**E**, **X**) → **b**   (3) E(**L**, **O**) → **z** . . .
    - C: **cbzoiowlppujmksilgqvsofhbowyyj**
    - C as sent (in the right-to-left order):

Stream Ciphers (2)

– Example: polyalphabetic cipher - cont.

- C as received (in the right-to-left order):

Sender S → **jyywobhfosvqgliskmjupplwoiozbc** → Receiver R

- C and K for decryption:

  cbzoiowlppujmksilgqvsofhbowyyj

  EXODUSEXODUSEXODUSEXODUSEXODUS

- Decryption:

  (1) D(**c**, **E**) → **Y** (2) D(**b**, **X**) → **E** (3) D(**z**, **O**) → **L** . . .

- Decrypted P:

  YEL. . .

Q: Do you know how D uses Vigenère Tableaux?

A: Finds c under column e → Y

Problems with Stream Ciphers (1)

- Problems with stream ciphers
  - Dropping a char from key K results in wrong decryption
  - Example:
    - P and K (repeated 'EXODUS') with a char in K missing:

YELLOWSUBMARINEFROMYELLOWRIVER
EODUSEXODUSEXODUSEXODUSEXODUSE

missing X in K ! (no errors in repeated K later)

- Encryption

(using VT):

1) E(**Y**,**E**) → **c**
2) E(**E**,**O**) → **s**
3) E(**L**,**D**) → **o**

...

- Ciphertext: **cso...**

C in the order as sent (right-to-left):

...osc

Problems with Stream Ciphers (2)

- C as received (in the right-to-left order):

  ...osc →

- C and correct K ('EXODUS') for decryption:

  cso...

  EXO...

- Decryption (using VT, applying correct key):

  1) D(c, E) → Y

  2) D(s, X) → V

  3) D(o, O) → A

  ...

- Decrypted P:

  YVA... - Wrong!

  – We know it's wrong, Receiver might not know it *yet*!

What if message is corrupted in a noisy area?

Problems with Stream Ciphers (3)

- The problem might be recoverable
  - Example:

    If R had more characters decoded, R might be able to detect that S dropped a key char, and R could recover
    - E.g., suppose that R decoded:

      YELLOW SUBMAZGTR

      - R could guess, that the 2nd word should really be:

        SUBMARINE

      - => R would know that S dropped a char from K after sending "**SUBMA**"
      - => R could go back 4 chars, drop a char from K ("recalibrate K with C"), and get "resynchronized" with S

Block Ciphers (1)

- We can do better than using recovery for stream ciphers
  - Solution: use block ciphers

- Block cipher:
  1 *block* of chars from P → 1 *block* of chars for C
  - Example of block cipher: columnar transposition
  - Block size = "o(message length)" (informally)

Block Ciphers (2)

- Why block size = "o(message length)" ?
  - Because R must wait for "almost" the entire C before R can decode some characters near beginning of P
  - E.g., for P = '**HELLO WORLD**', block size is "o(10)"
  - Suppose that Key = 3 (3 columns):

```
HEL
LOW
ORL
DXX
```

  - C as sent (in the right-to-left order):

Sender S → **xlwlxroedolh** → Receiver R

Block Ciphers (3)

– C as received (in the right-to-left order): **xlwlxroedolh**

– R knows: K = 3, block size = 12 (=> 4 rows)

```
123
456
789
abc
```

a=10
b=11
c=12

=> R knows that characters wil be sent in the order:
1st-4th-7th-10th--2nd-5th-8th-11th--3rd-6th-9th-12th

– R must wait for at least:
  - 1 char of C to decode 1st char of P ('**h**')
  - 5 chars of C to decode 2nd char of P ('**he**')
  - 9 chars of C to decode 3rd, 4th, and 5th chars of P ('**hello**')
  - 10 chars of C to decode 6th, 7th, and 8th chars of P ('**hello wor**')
  - etc.

Block Ciphers (4)

- *Informally*, we might call ciphers like the above example columnar transposition cipher "weak-block" ciphers
  - R can get some (even most) but not all chars of P before entire C is received
    - R can get one char of P immediately
      - » the 1st-after 1 of C (delay of 1 - 1 = 0)
    - R can get some chars of P with "small" delay
      - » e.g., 2nd-after 5 of C (delay of 5 - 2 = 3)
    - R can get some chars of P with "large" delay
      - » e.g., 3rd-after 9 of C (delay of 9 – 3 = 6)
- There are block ciphers when R cannot even start decoding C before receiving the entire C
  - *Informally*, we might call them "strong-block" ciphers

Pros / Cons for Stream and Block Ciphers (1)

- Pros / cons for stream ciphers
  - + Low delay for decoding individual symbols
    - Can decode as soon as received
  - + Low error propagation
    - Error in $E(c_1)$ does not affect $E(c_2)$
  - - Low diffusion
    - Each char separately encoded => carries over its frequency info
  - - Susceptibility to malicious insertion / modification
    - Adversary can fabricate a new msg from pieces of broken msgs, even if he doesn't know E (just broke a few msgs)

Pros / Cons for Stream and Block Ciphers (2)

- Pros / cons for block ciphers
  - \+ High diffusion
    - Frequency of a *char* from P diffused over (a few chars of) a *block* of C
  - \+ Immune to insertion
    - Impossible to insert a char into a block without easy detection (block size would change)
    - Impossible to modify a char in a block without easy detection (if checksums are used)

Pros / Cons for Stream and Block Ciphers (3)

- Pros / cons for block ciphers — Part 2
  - \- High delay for decoding individual chars
    - See example for '`hello worldxx`' above
      - For some E can't decode even the 1st char before whole k chars of a block are received
  - \- High error propagation
    - It affects the block, not just a single char

Cryptanalysis (1)

- What cryptanalysts do when confronted with unknown?

  Four possible situations w.r.t. available info:

  1) C available
  2) Full P available
  3) Partial P available
  4) E available (or D available)

- (1) – (4) suggest 5 different approaches

Cryptanalysis (2)

- Cryptanalyst approaches

  1) Ciphertext-only attack
     - We have shown examples for such attacks
       - E.g., for Caesar’s cipher, columnar transposition cipher

  2) Known plaintext attack
     - Analyst have C and P
       - Needs to deduce E such that C=E(P), then finds D

  3) Probable plaintext attack
     - Partial decryption provides partial match to C
       - This provides more clues

Cryptanalysis (3)

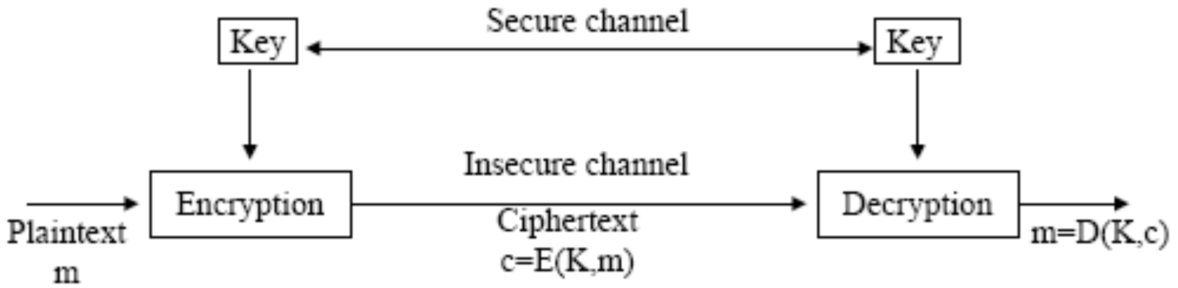
- Cryptanalyst approaches – cont.

4) Chosen plaintext attack
    - Analyst able to fabricate encrypted msgs
        - Then observe effects of msgs on adversary's actions
            - » This provides further hints

5) Chosen ciphertext attack
    - Analyst has both E and C
    - Run E for many candidate plaintexts to find P for which E(P) = C
        - Purpose: to find K_E

Symmetric and Asymmetric Cryptosystems (1)

- Symmetric encryption = secret key encryption
  - $K_E = K_D$ — called a secret key or a private key
  - Only sender S and receiver R know the key



[cf. J. Leiwo]

  - As long as the key remains secret, it also provides authentication (= proof of sender's identity)

Symmetric and Asymmetric Cryptosystems (3)

- Asymmetric encryption = public key encryption (PKE)
  - $K_E \neq K_D$ — public and private keys
- PKE systems eliminate symmetric encryption problems
  - Need no secure key distribution channel
    - => easy key distribution

Symmetric and Asymmetric Cryptosystems (4)

- One PKE approach:
  - R keeps her private key K_D
  - R can distribute the correspoding public key K_E to anybody who wants to send encrypted msgs to her
    - No need for secure channel to send K_E
    - Can even post the key on an open Web site — it is public!
  - Only private K_D can decode msgs encoded with public K_E!
    - Anybody (K_E is public) can encode
    - Only owner of K_D can decode

DES (Data Encryption Standard)

Background and History of DES (1)

- Early 1970's - NBS (Nat'l Bureau of Standards) recognized general public's need for a secure crypto system

  NBS – part of US gov't / Now: NIST – Nat'l Inst. of Stand's & Technology

  - "Encryption for the masses" [A. Striegel]
  - Existing US gov't crypto systems were not meant to be made public
    - E.g. DoD, State Dept.
  - Problems with proliferation of commercial encryption devices
    - Incompatible
    - Not extensively tested by independent body

Background and History of DES (2)

- 1972 - NBS calls for proposals for a *public* crypto system
  - Criteria:
    - Highly secure / easy to understand / publishable / available to all / adaptable to diverse app's / economical / efficient to use / able to be validated / exportable
    - In truth: Not *too* strong (for NSA, etc.)
- 1974 – IBM proposed its Lucifer
  - DES *based* on it
  - Tested by NSA (Nat'l Security Agency) and the general public
- Nov. 1976 – DES adopted as US standard for *sensitive but unclassified* data / communication
  - Later adopted by ISO (Int'l Standards Organization)
  - Official name: DEA - Data Encryption Algorithm / DEA-1 abroad

Overview of DES

@ Andrew: port DES verilog

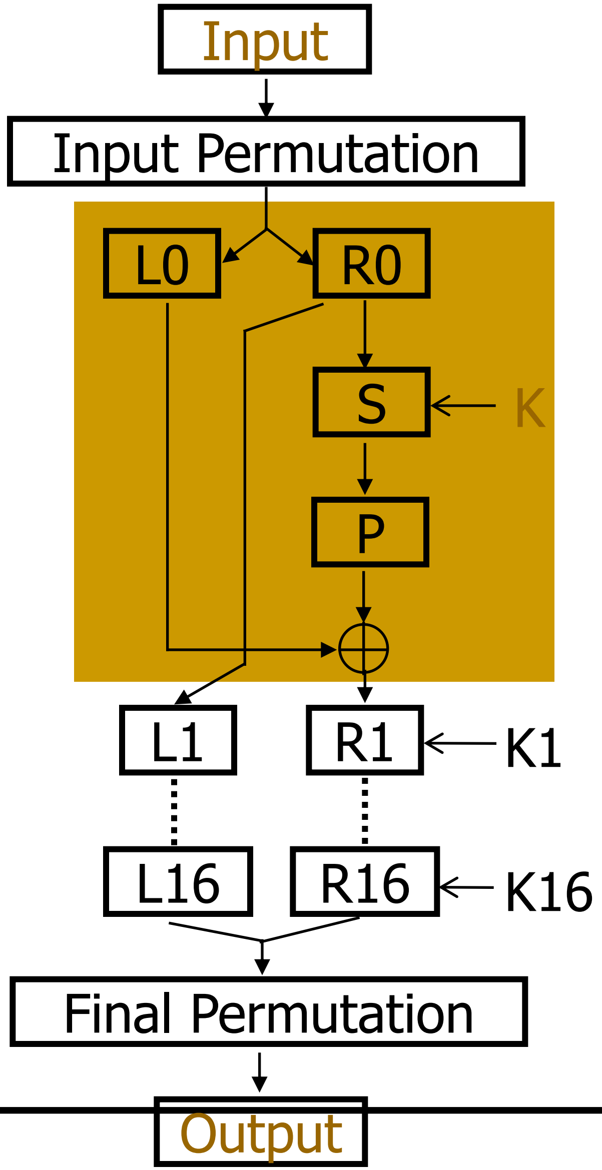
- DES - a block cipher
  - a product cipher
  - 16 rounds (iterations) on the input bits (of P)
    - substitutions (for confusion) and permutations (for diffusion)
  - Each round with a *round key*
    - Generated from the user-supplied key
- Easy to implement in S/W or H/W

- There are 72,000,000,000,000,000 (72 quadrillion) or more possible encryption keys that can be used.
- For each given message, the key can be chosen at random from among this enormous number of keys.

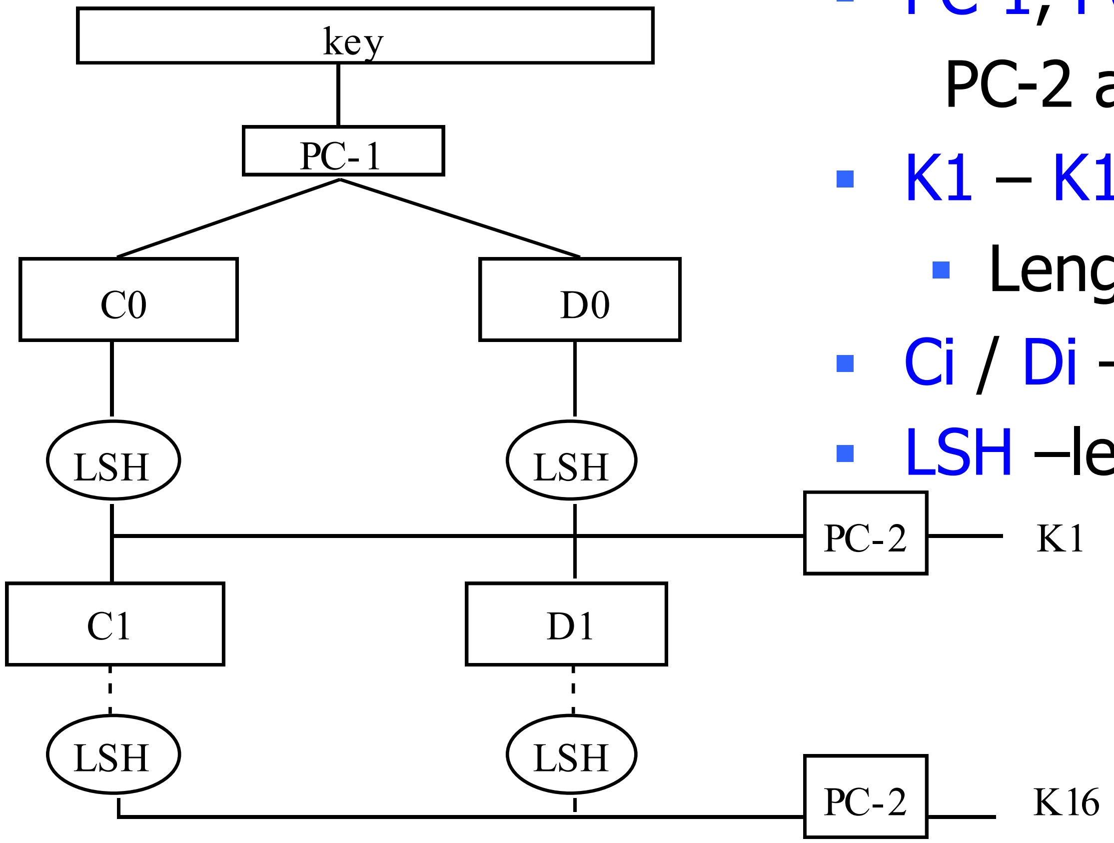
Basic Structure

[Fig. – cf. J. Leiwo]

- Input: 64 bits (a block)
- Li/Ri– left/right half of the input block for iteration i (32 bits) – subject to substitution S and permutation P
- K - user-supplied key
- Ki - round key:
  - 56 bits used +8 unused
    (unused for E but often used for error checking)
- Output: 64 bits (a block)
- Note: Ri becomes L(i+1)
- All basic op's are simple logical ops
  - Left shift / XOR



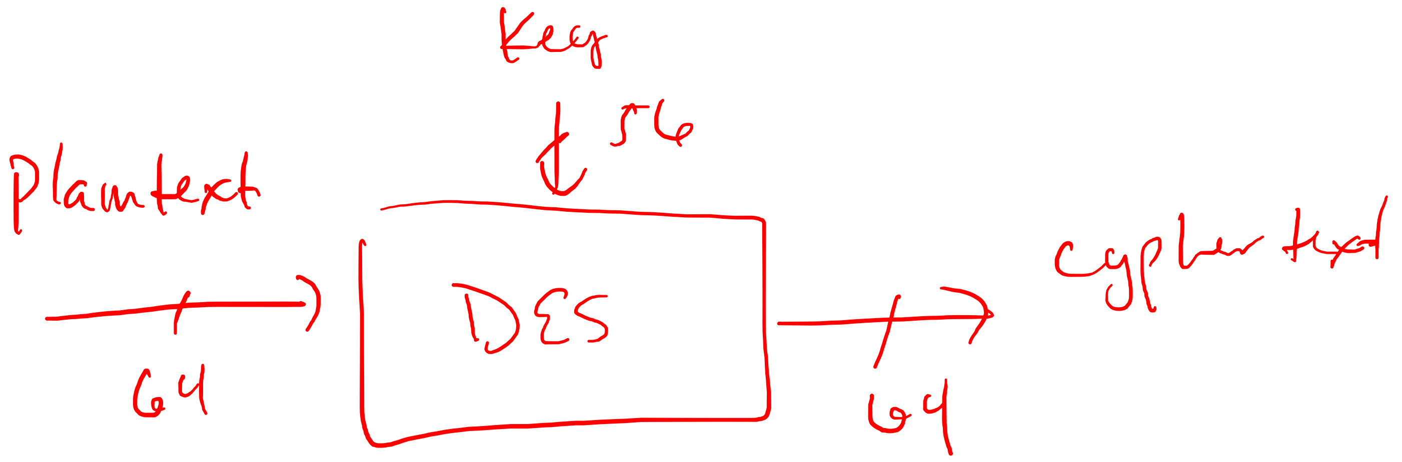
Generation of Round Keys

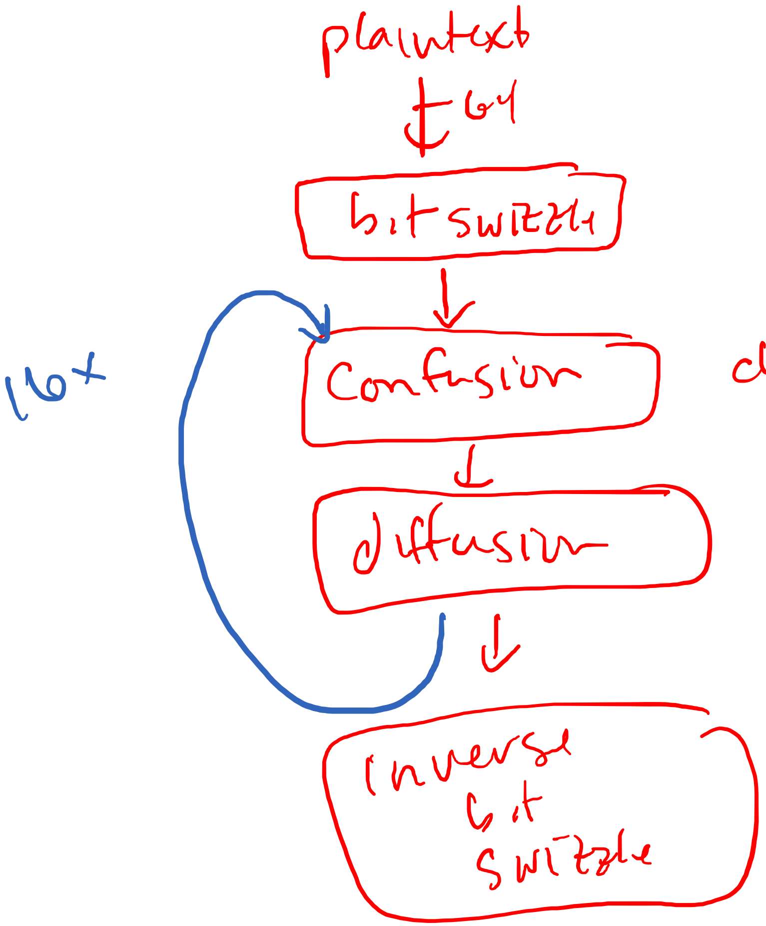


- key – user-supplied key (input)
- PC-1, PC-2 – permutation tables

  PC-2 also extracts 48 of 56 bits
- K1 – K16 – round keys (outputs)
  - Length(Ki) = 48
- Ci / Di – confusion / diffusion (?)
- LSH –left shift (rotation) tables

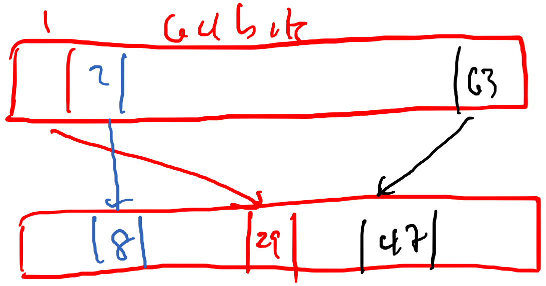
[Fig: cf. Barbara Endicott-Popovsky, U. Washington]


Key
56
Plaintext
64
DES
cypher text
64



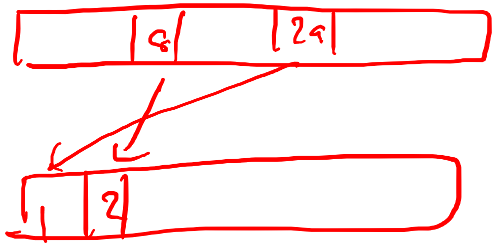
char switch table

(XOR)

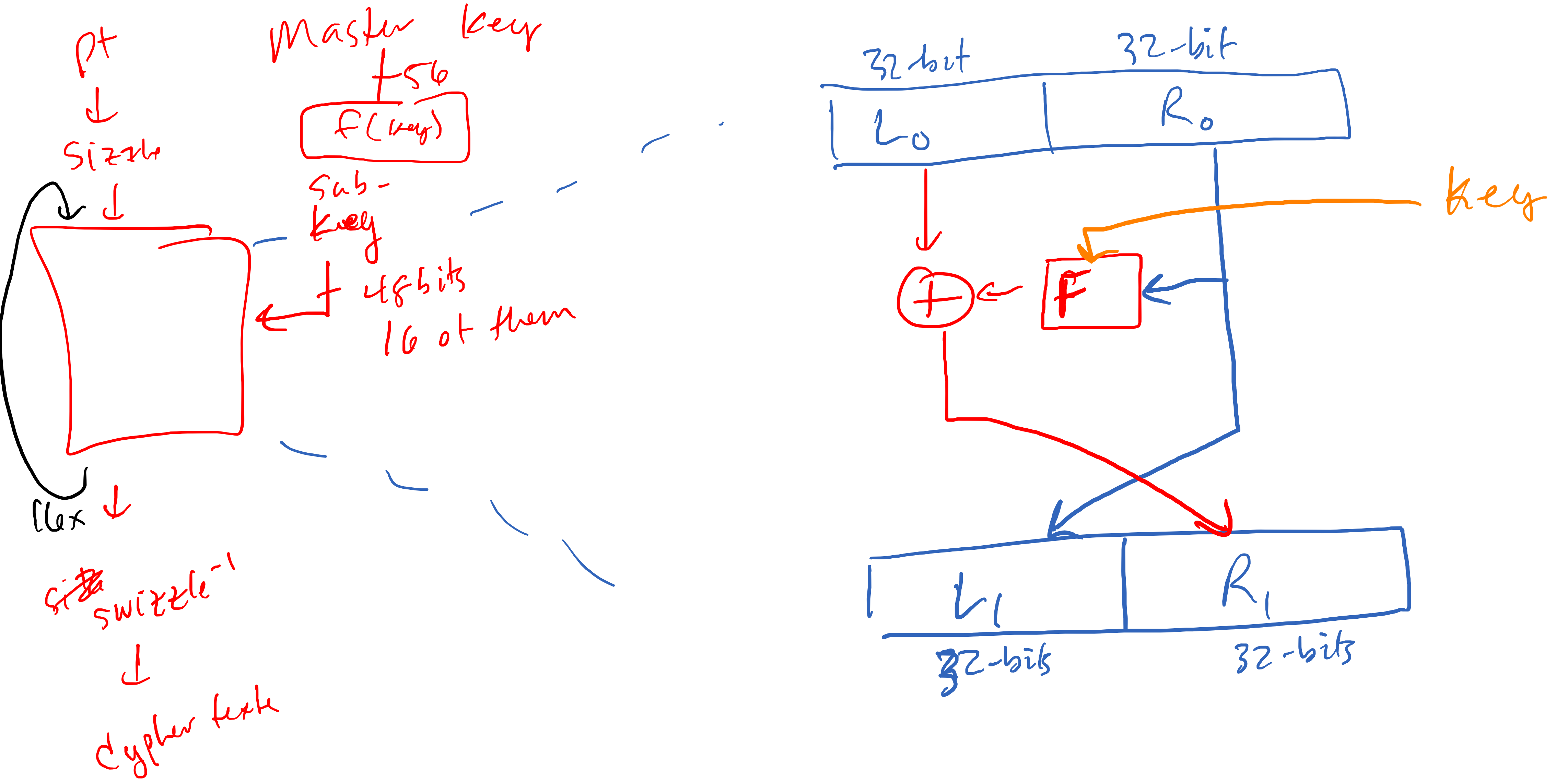


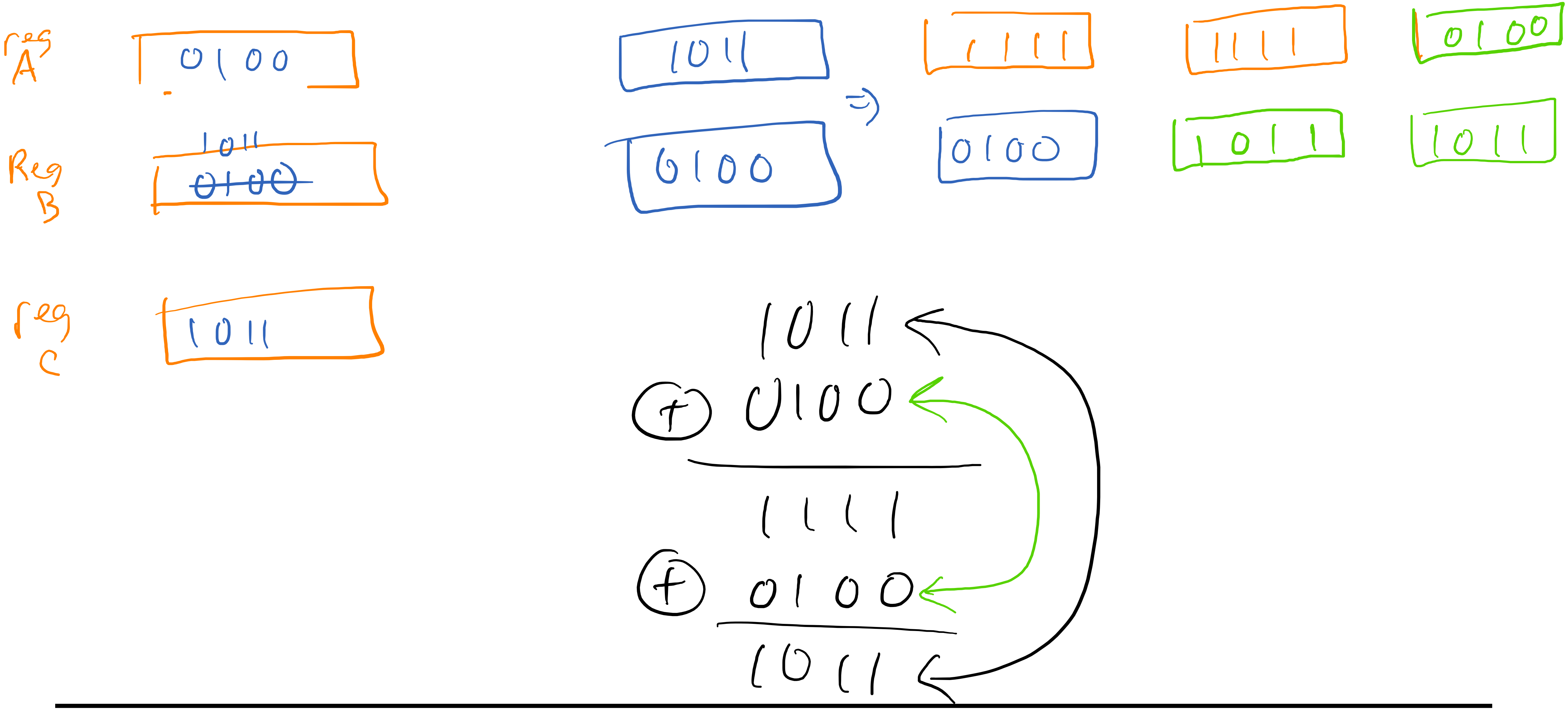
10010001 → 1010 1010

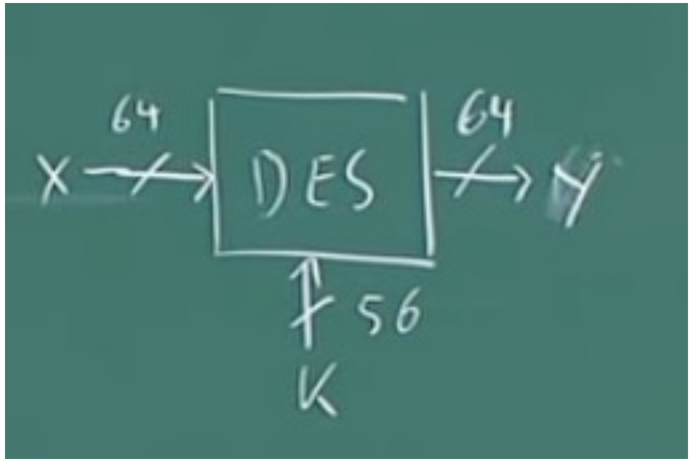
10011001 → 1100 1100



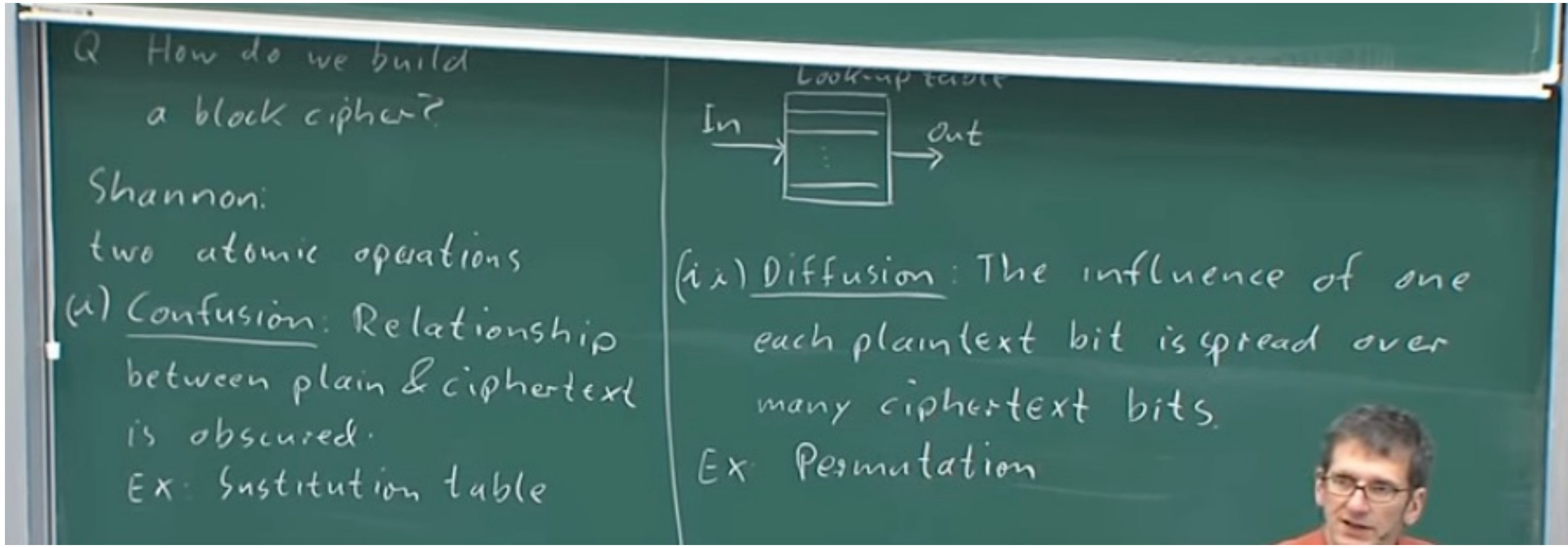
$$A \oplus B \oplus B = A$$



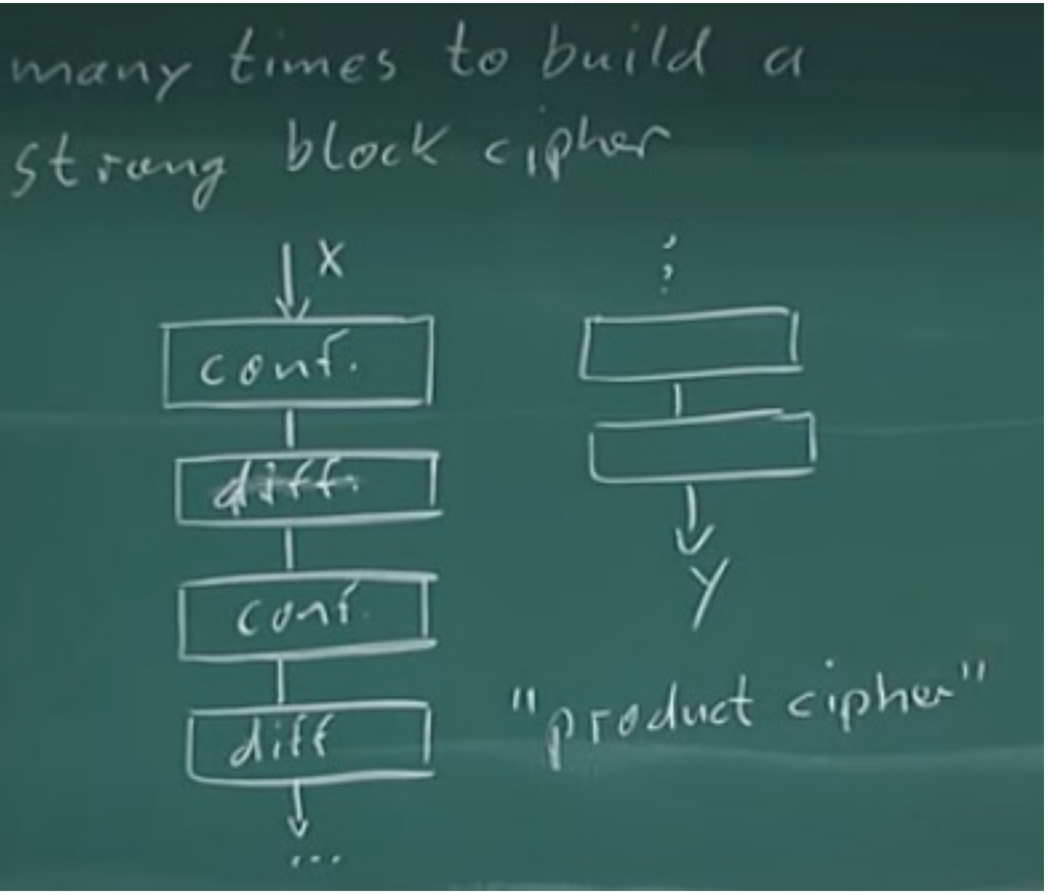

reg A
0100
Reg B
1011
0100
reg C
1011
1011
0100
1111
0100
1111
1111
0100
1011
0100
1011
1011
+ 0100
1111
+ 0100
1011

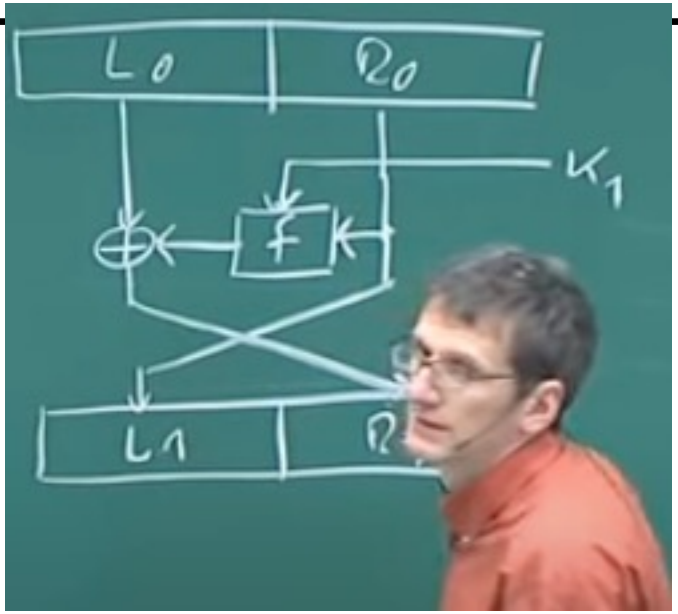


64
X
DES
64
Y
56
K



Q How do we build a block cipher?
Shannon:
two atomic operations
(i) Confusion: Relationship between plain & ciphertext is obscured.
Ex: Sustitution table
In
out
(ii) Diffusion: The influence of one each plaintext bit is spread over many ciphertext bits.
Ex Permutation


many times to build a
strong block cipher
x
conf.
diff.
conf.
diff
y
"product cipher"


L0
R0
K1
f
L1

Problems with DES

- Diffie, Hellman 1977 prediction: "In a few years, technology would allow DES to be broken in days."
- Key length is fixed (= 56)
  - 2^{56} keys ~ 10^{15} keys
  - "Becoming" too short for faster computers
    - 1997: 3,500 machines – 4 months
    - 1998: special "DES cracker" h/w – 4 days
- Design decisions not public
  - Suspected of having backdoors
    - Speculation: To facilitate government access?

Double and Triple DES

- Double DES:
  - Use double DES encryption

    C = E(k2, E(k1, P))

  - Expected to multiply difficulty of breaking the encryption
    - Not true!
      - In general, 2 encryptions are not better than one

        [Merkle, Hellman, 1981]
      - Only doubles the attacker's work

Double and Triple DES (2)

- Triple DES:
  - Is it C = E(k3, E(k2, E(k1, P)) ?
  - Not soooo simple!

Double and Triple DES (3)

- Triple DES: *Is it C=E(k3, E(k2, E(k1, P))?*
  - Tricks used:

    D not E in the 2nd step, k1 used twice (in steps 1 & 3)
  - It is:

    C = E(k1, D(k2, E(k1, P))

    and

    P = D(k1, E(k2, D(k1, C))
  - Doubles the effective key length
    - 112-bit key is quite strong
      - Even for today's computers
      - For all feasible known attacks

Security of DES

- So, is DES insecure?
- No, not yet
  - 1997 attack required a lot of cooperation
  - The 1998 special-purpose machine is still very expensive
  - Triple DES still beyond the reach of these 2 attacks
- But ...
  - In 1995, NIST (formerly NBS) began search for new strong encryption standard

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Project 1 Overview / Demo