Name ..... ID ..... Section ..... Seat No .....

# Sirindhorn International Institute of Technology
# Thammasat University

**Midterm Exam Answers: Semester 2, 2014**

**Course Title:** CSS322 Security and Cryptography

**Instructor:** Steven Gordon

**Date/Time:** Monday 2 March 2015; 13:30–16:30

---

**Instructions:**

- This examination paper has 20 pages (including this page).
- Conditions of Examination: Closed book; No dictionary; Non-programmable calculator is allowed
- Students are not allowed to be out of the exam room during examination. Going to the restroom may result in score deduction.
- Turn off all communication devices (mobile phone etc.) and leave them at the front of the examination room.
- The examination paper is not allowed to be taken out of the examination room. A violation may result in score deduction.
- Write your name, student ID, section, and seat number clearly on the front page of the exam, and on any separate sheets (if they exist).
- Reference material included at the end of the exam may be used.

# Question 1 [12 marks]

For each question fill in the blank space with an appropriate word, acronym, name or phrase. For each blank space you must give only one answer. However, there may be more than one correct answer. Each question is worth 1 mark.

(a) DES (and its variants, such as 3DES) is one example symmetric, block cipher. Another is *AES or IDEA or Blowfish or* ....

(b) *Non-repudiation* is a security service that protects against a sender of a message denying that they ever sent that message.

(c) Any attack that alters the system resources is called *an active* attack.

(d) A *traffic analysis* attack involves a malicious user intercepting ciphertext and learning about communication patterns without obtaining the plaintext.

(e) A modification attack is an attack against the *data integrity* service.

(f) A *denial of service* attack includes the case of a malicious user sending many packets to a server to overload that server.

(g) A challenge with *symmetric* key cryptography is the efficient and secure distribution of keys.

(h) Decryption with a stream cipher involves applying the *XOR* operation on the input stream of *ciphertext* and a keystream.

(i) The *one-time pad* is considered unconditionally secure.

(j) If a cryptanalyst knows only the encryption algorithm being used, ciphertext, and plaintext chosen by the cryptanalyst together with its corresponding encrypted ciphertext, then an attack can be classified as *chosen plaintext*.

(k) A brute force attack against a block cipher takes $x$ seconds. A meet-in-the-middle attack against a double-version of the same block cipher would take approximately $2x$ seconds.

# Question 2 [8 marks]

(a) Encrypt the plaintext *security* using the Playfair cipher and keyword *cryptography* using the letter $x$ as special padding if necessary. What is the ciphertext? [4 marks]

C = _____

**Answer.** *mkocpecp*

(b) The ciphertext *snosdunhoniisxanfofixncunfox* was obtained by encrypting using a rail fence cipher with key *4*. What was the plaintext? [4 marks]

P = _____

**Answer.** *shannon confusion diffusion*

# Question 3 [12 marks]

Consider an RSA public key $PU = \{11, 203\}$.

(a) Encrypt the message $M = 2$ using the public key. [2 marks]

C = _____

**Answer.** *The RSA encryption algorithm is:*

$$C = M^e \bmod n$$

*which is:*

$$C = 2^{11} \bmod 203 = 18$$

(b) Find the corresponding RSA private key. [4 marks]

PR = _____ , _____

**Answer.** *Factor $n$ into its two primes: $p = 7, q = 29$. Find $\phi(n)$ as $(p-1)(q-1) = 168$. We know $e = 11$, so find $d$ such that $11d \bmod 168 = 1$. You will find $d = 107$. Therefore $PR = \{107, 203\}$.*

(c) Consider the approach you used to find the RSA private key above. Assume instead of the small values used in this question, that large values are used (as recommended in practice). Explain two reasons an attacker would not be able to find the private key. [3 marks]

**Answer.** *The attacker must either factor $n$ into the two primes or directly find $\phi(n)$: both are considered computationally infeasible for large values of $n$.*

(d) Assume the attacker does not have the private key (and has no way to find it), explain two approaches that the attacker could try to find $M$ if they intercepted $C$. Also explain why these two approaches are not realistic when using the recommended (large) values. [3 marks]

**Answer.** *The attacker must either try every value of $M$ (too many to try) or calculate the discrete log to find $M$ (computationally infeasible for large values of $n$).*

# Question 4 [10 marks]

(a) If the "avalanche effect" is present in a cipher, is that an indicator of a strong cipher or a weak cipher? [1 mark]

**Answer.** *Strong.*

(b) Explain one method to test for the avalanche effect in a cipher. [2 marks]

**Answer.** *Encrypt two different plaintexts with the same key, but the plaintexts differ by just one bit. Count the number of bits that differ in the ciphertext (they should be about half).*

(c) On average, how many days would it take a computer that can decrypt at a speed of $10^{12}$ operations per second to be successful in a brute force attack on a 64-bit key? [2 marks]

**Answer.** *A 64-bit key requires on average* $2^{63}$ *operations. The computer would take* $2^{63}/10^{12}$ *seconds or 107 days.*

(d) If the cipher that is being attacked in part (c) is using CBC mode of operation, can the attack duration be shortened by using multiple computers at the same time? Explain your answer. [2 marks]

**Answer.** *Yes. Each computer tries different set of keys, all in parallel. Whether or not using CBC doesn't matter.*

(e) Attacks on ciphers are usually measured in terms of: time, memory and known data. For each of these three metrics, compare a brute force attack on DES with a MITM attack on Double-DES, indicating approximately how much time/memory/known data is needed for one attack (relative to the other attack). [3 marks]

**Answer.** *Dobule-DES MITM requires approximately 2 times the amount of time as DES. Double-DES MITM requires 1 or 2 known plaintext-ciphertext pairs. Double-DES MITM requires a significant amount of memory (*$2^{56}$*).*

# Question 5 [10 marks]

Consider a block cipher, *ABC*, which is defined by Table 1. The table gives the ciphertext $C$ (columns 2 to 9) produced when encrypting the plaintext $P$ (column 1) with one of the eight keys.

Table 1: ABC Block Cipher

| P | K=000 | K=001 | K=010 | K=011 | K=100 | K=101 | K=110 | K=111 |
|---|---|---|---|---|---|---|---|---|
| 0000 | 0001 | 1001 | 1010 | 1010 | 1100 | 0111 | 0011 | 0001 |
| 0001 | 1011 | 1100 | 1001 | 0011 | 0000 | 1000 | 0001 | 1100 |
| 0010 | 1111 | 0000 | 0010 | 1011 | 1101 | 1111 | 1101 | 1011 |
| 0011 | 1000 | 1000 | 1110 | 1000 | 0101 | 0010 | 0000 | 0100 |
| 0100 | 0000 | 1101 | 1111 | 0111 | 0001 | 0011 | 1011 | 1000 |
| 0101 | 0111 | 0010 | 0011 | 1001 | 1111 | 0101 | 1100 | 0101 |
| 0110 | 0010 | 1110 | 1000 | 0000 | 1110 | 0000 | 1010 | 1010 |
| 0111 | 0011 | 0101 | 0000 | 1100 | 1010 | 0110 | 0111 | 0011 |
| 1000 | 0100 | 1011 | 0111 | 1101 | 1011 | 1110 | 1110 | 0110 |
| 1001 | 0101 | 1111 | 1101 | 0100 | 0100 | 0100 | 0100 | 1110 |
| 1010 | 1010 | 0110 | 0100 | 0110 | 0011 | 1101 | 0101 | 0000 |
| 1011 | 0110 | 0100 | 0110 | 0101 | 0111 | 1010 | 1111 | 1001 |
| 1100 | 1110 | 0011 | 0101 | 1111 | 0110 | 1001 | 1000 | 1111 |
| 1101 | 1101 | 0111 | 0001 | 0010 | 0010 | 1011 | 0110 | 0111 |
| 1110 | 1100 | 1010 | 1011 | 0001 | 1001 | 1100 | 0010 | 0010 |
| 1111 | 1001 | 0001 | 1100 | 1110 | 1000 | 0001 | 1001 | 1101 |

(a) Assuming CBC was used with *ABC*, decrypt the ciphertext `11110110` using the key `001` and initialisation vector `1110`. Show your calculations in the space below, and write your final answer on the line below. [3 marks]

Plaintext: _____

**Answer.** *C1 = 1111. Decrypt with key 001 gives 1001. XOR with IV gives 0111. So P1 is 0111.*

*C2 = 0110. Decrypt with key 001 gives 1010. XOR with C1 gives 0101. So P2 is 0101.*

*The plaintext is 01110101.*

(b) Consider the cipher *ABC* being used in Counter Mode to act as a pseudorandom number generator. If the initial value of the counter is 0000 and the seed is 101, then what are the first 12 pseudorandom bits? [3 marks]

Bits: _____

**Answer.** *In Counter mode, the counter value is encrypted with the cipher, where the seed is the key. The pseudorandom bits are the output ciphertext. Then the counter is incremented and encrypted with the same seed to produce more bits, and so on.*

$$Seed = 101$$

$$Counter = 0000$$

$$Randombits = 0111$$

$$Counter = 0001$$

$$Randombits = 1000$$

$$Counter = 0010$$

$$Randombits = 1111$$

*So the 12 pseudorandom bits are: 0111 1000 1111.*

(c) What is the maximum period, in bits, of the above PRNG? [2 marks]

**Answer.** *Once the counter reaches 1111 it will then wrap back to 0000. So there are 16 possible input values, then the ciphertext will repeat. So the pseudorandom sequence consists of 64 bits.*

(d) Different tests can be used to check if a sequence of bits does not appear random. One such test is to count the number of 0's and 1's in the entire sequence: if there are not approximately equal number of 0's and 1's then the sequence does not appear to be random. Describe two other tests. [2 marks]

**Answer.** *Count the number of 0's and 1's in subsequences: should be equal number. Count the number of runs of 0's and 1's of length n: should be equal number. Compress: size should be the same as original, i.e. no compression.*

# Question 6 [7 marks]

The table below shows the ASCII table. Note that each character maps to a 7-bit value.

| Last 4 bits \ First 3 bits | 000 | 001 | 010 | 011 | 100 | 101 | 110 | 111 |
|---|---|---|---|---|---|---|---|---|
| 0000 | NUL | DLE | SP | 0 | @ | P | ‘ | p |
| 0001 | SOH | DC1 | ! | 1 | A | Q | a | q |
| 0010 | STX | DC2 | " | 2 | B | R | b | r |
| 0011 | ETX | DC3 | # | 3 | C | S | c | s |
| 0100 | EOT | DC4 | $ | 4 | D | T | d | t |
| 0101 | ENQ | NAK | % | 5 | E | U | e | u |
| 0110 | ACK | SYN | & | 6 | F | V | f | v |
| 0111 | BEL | ETB | ’ | 7 | G | W | g | w |
| 1000 | BS | CAN | ( | 8 | H | X | h | x |
| 1001 | HT | EM | ) | 9 | I | Y | i | y |
| 1010 | LF | SUB | * | : | J | Z | j | z |
| 1011 | VT | ESC | + | ; | K | [ | k | { |
| 1100 | FF | FS | ’ | < | L | \ | l | \| |
| 1101 | CR | GS | – | = | M | ] | m | } |
| 1110 | SO | RS | · | > | N | ^ | n | ~ |
| 1111 | SI | US | / | ? | O | – | o | DEL |

Figure 1: ASCII Table

(a) If a binary one-time pad is used with key `10110001100010110010` to obtain the ciphertext `kPP`, then what is the plaintext (in ASCII characters, not binary)? Show or explain your steps. (Hint: you should recognise the plaintext) [3 marks]

Answer: _____

**Answer.** *Convert the ciphertext letters to binary: 1101011, 1010000, 1010000. XOR the ciphertext with the key to obtain: 0110011, 0110010, 0110010. Convert the plaintext to letters to ASCII: 322.*

(b) In general, the OTP has two requirements on the key that the Vigenere cipher does not. What are the two requirements? [2 marks]

**Answer.** *The key should be random and equal length to the plaintext.*

(c) Explain a problem with the key in part (a). [2 marks]

**Answer.** *There is repetition: the last 7 bits is also is the middle 7 bits. As a result, the ciphertext characters repeat with the plaintext characters.*

# Question 7 [9 marks]

(a) If the input of `E/P` in the first round of S-DES is `1101` and $K_1$ is `01011000`, then what is the input of `P4` in the first round? [3 marks]

Answer: _____

**Answer.** *Input of E/P is 1101. Output of E/P is 11101011. XOR with $K_1$: 11101011 XOR 01011000 = 10110011. Left half, 1011, is input to S-Box S0. Row 11 and column 01 gives: 01. Right half, 0011, is input to S-Box S1. Row 01 and column 01 gives: 00. The input to P4 is 0100.*

(b) If the input of the 2nd round of S-DES is `10010110`, and the output of `P4` in the 2nd round is `1011`, then what is the ciphertext? (Note: the input of the 2nd round is the same as the output of the SWap operation). [3 marks]

Answer: _____

**Answer.** *The left half of the 8 bit round input, 1001, is XORed with the output of P4, 1011, to produce 0010. That is joined with the right half of the round input to get 00100110. These 8 bits are then used as input to $IP^{-1}$. $IP^{-1}$ must return the inverse of IP (i.e. 41357286), hence the output is: 00101001*

(c) If you know the ciphertext as well as the input of the 2nd round of S-DES, then which step(s) make it difficult to find $K_2$? Explain your answer. [3 marks]

**Answer.** *The S-Boxes S0 and S1. Given the ciphertext it is easy to reverse $IP^{-1}$, the XOR and P4 to find the outputs of S0 and S1. And it is easy to apply E/P to get the input to the XOR with the key. Therefore to find the key, you must know the inputs to the S-Boxes. But applying the S-Boxes in reverse leads to multiple possible inputs: there is no way to know which is the correct input (without some other statistical analysis).*

# Question 8 [6 marks]

Consider a public-key crytposystem with three users: $A$, $B$, and $C$. Assume all necessary keys have been created and distributed to the relevant users.

(a) List the set of keys that user $A$ knows (or can easily discover). [1 mark]

**Answer.** $PU_a, PR_a, PU_b, PU_c$

(b) List the set of keys that user $A$ knows, but users $B$ and $C$ do not. [1 mark]

**Answer.** $PR_a$

(c) If user $A$ wants to send a confidential message $M$ to user $B$, then explain what user $A$ does. [1 mark]

**Answer.** *User A encrypts $M$ using key $PU_b$, and then sends the ciphertext to $B$*

(d) Explain why the message $M$ is confidential, i.e. user $C$ cannot read it. [1 mark]

**Answer.** *User $C$ receives the ciphertext but cannot decrypt because they do not know the key $PR_b$.*

(e) If user $C$ wants to send an authenticated message $M$ to user $B$, then explain what user $C$ does. [1 mark]

**Answer.** *User $C$ encrypts $M$ using key $PR_c$, and then sends the ciphertext to $B$*

(f) Explain how $C$ is certain the message comes from $B$, and not $A$ pretending to be $B$. [1 mark]

**Answer.** ***This question is confusing in that it is a different case than the previous part. It was marked correct for everyone.*** *The message only successfully decrypts with the corresponding key that it was encrypted with. If it decrypts with $PU_b$ then it means it must have been encrypted with $PR_b$, which $C$ knows only $B$ has ($A$ does not know $PR_b$).*

# Question 9 [6 marks]

**Note: this question may take a large amount of time if you don't follow a good approach. It is only worth 6 marks. Therefore I suggest attempting it only after you have attempted all other questions.**

A plaintext message was encrypted using a rows/columns transposition cipher (using a key length of less than 10 characters), followed by a Caesar cipher, to produce the ciphertext:

`zbtkxhnabgtxbbggfzbmfmmm`

You've discovered that no padding was used (or was necessary) in any of the ciphers. You also know the most frequent character in the plaintext is *i*, the first letter in the plaintext is *t*, the first word in the plaintext is 6 characters long, and the plaintext contains the word *the*. What is the full plaintext message?

Answer: _____

**Answer.** *The most frequent character in the ciphertext is b, occuring 5 times. Therefore, since the rows/columns cipher only permutates characters, the output of the rows/columns must have i as the the most frequent character (since i is the most frequent plaintext character). So the Caesar cipher must encrypt i (8) to b (1), meaning a key of 19. Decrypting the ciphertext with a Caesar cipher of key 19 gives:*

*giareouhinaeiinnmgitmttt*

*This is the output of the rows/columns. As there is no padding and 24 characters, the number of columns is either: 2, 3, 4, 6, 8 or 12. But it cannot be 12 because the key is less than 10 characters. Since the first letter is t, the first row must include a t. The first row for different columns will be:*

- *8 columns:* *gruninit*
- *6 columns:* *geiimm*
- *4 columns:* *guii*
- *3 columns:* *gin*
- *2 columns:* *gi*

*There must be 8 columns, that is the key length is 8. The last column must move to the first position.*

*T g r u n i n i*
*T i e h a i m t*
*T a o i e n g m*

*Since there is the word "the" on the second row:*

*T U R g n i n i*
*T H E i a i m t*
*T I O a e n g m*

*Now you need to try to form 6 letter words. After several attempts you should find TURING (you can also look at expected word segments in rows 2 and 3), and then finally "Turing in the Imitation Game". (The rows/column key was 83256174).*

(continue answer if necessary)

# Reference Material

### S-DES operations

```
P8: 6 3 7 4 8 5 10 9  P10: 3 5 2 7 4 10 1 9 8 6
IP: 2 6 3 1 4 8 5 7  E/P: 4 1 2 3 2 3 4 1  P4: 2 4 3 1
```

$$S0 = \begin{bmatrix} 01 & 00 & 11 & 10 \\ 11 & 10 & 01 & 00 \\ 00 & 10 & 01 & 11 \\ 11 & 01 & 11 & 10 \end{bmatrix} \quad S1 = \begin{bmatrix} 00 & 01 & 10 & 11 \\ 10 & 00 & 01 & 11 \\ 11 & 00 & 01 & 00 \\ 10 & 01 & 00 & 11 \end{bmatrix}$$

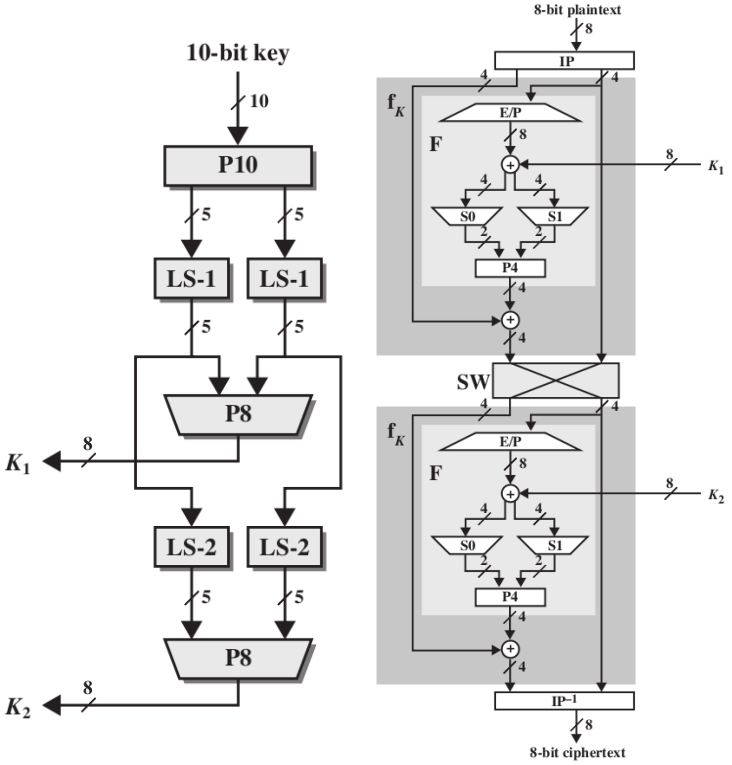



Figure 2: S-DES Key Generation and Encryption

### Mapping of English characters to numbers

```
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 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
```

**Fermat's theorem** if $p$ is prime and $a$ is a positive integer, then $a^p \equiv a \pmod{p}$

**Euler's theorem** For positive integers $a$ and $n$, $a^{\phi(n)+1} \equiv a \pmod{n}$

**First 20 prime numbers** 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71.

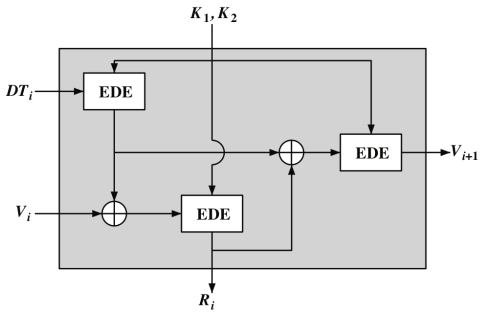
### Linear Congruential Generator

$$X_{n+1} = (aX_n + c) \bmod m$$

**Blum Blum Shub** $p$, $q$ are large prime numbers such that $p \equiv q \equiv 3 \pmod 4$; $n = p \times q$; $s$, random number relatively prime to $n$. Generate sequence of bits, $B_i$:

$$\begin{aligned} X_0 &= s^2 \bmod n \\ \text{for } i &= 1 \to \infty \\ X_i &= (X_{i-1})^2 \bmod n \\ B_i &= X_i \bmod 2 \end{aligned}$$

**ANSI X9.17** See figure below:




### Modes of operation

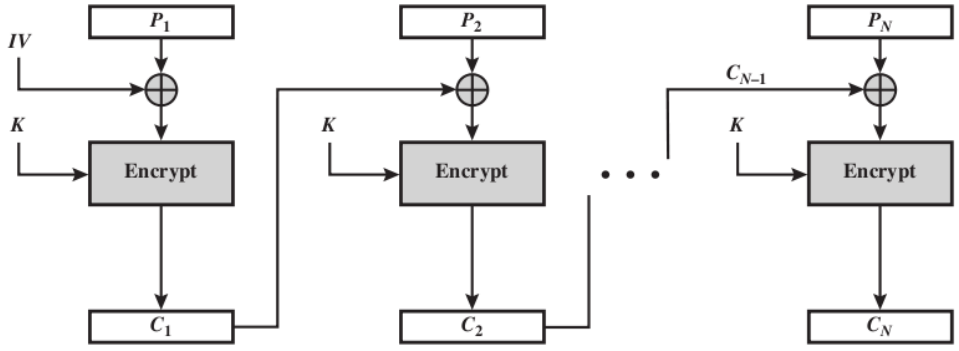



Figure 3: CBC mode of operation

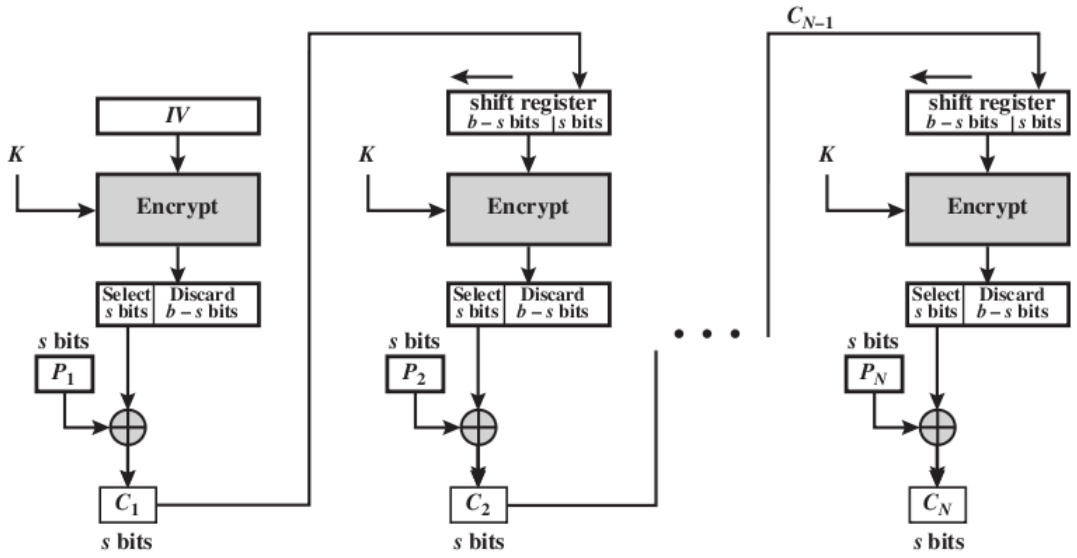



Figure 4: CFB mode of operation

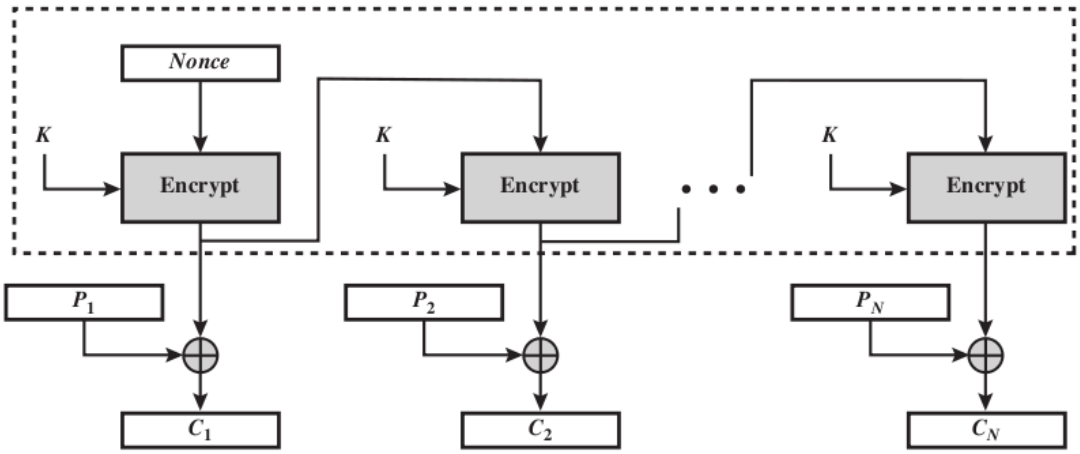



Figure 5: OFB mode of operation

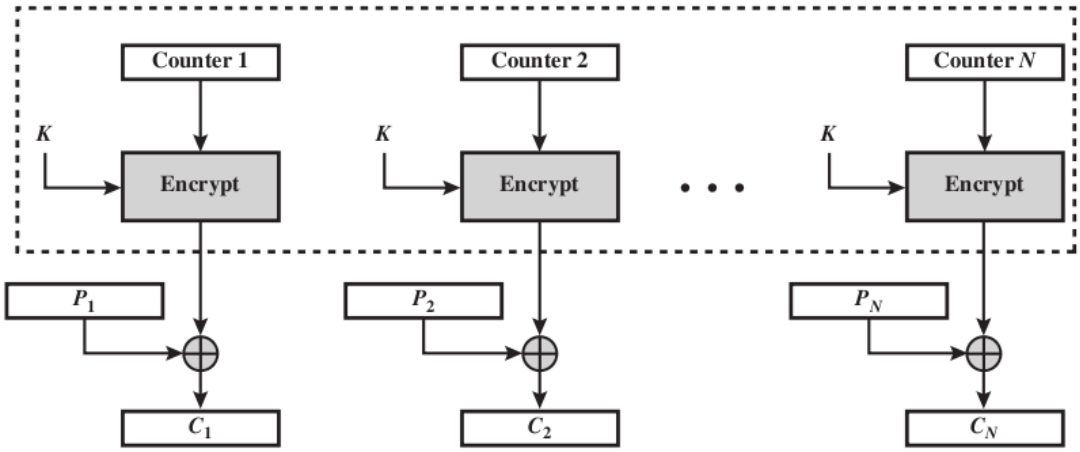



Figure 6: CTR mode of operation