Introduction into Cyber Security

Chapter 2: Symmetric Encryption

WiSe 18/19

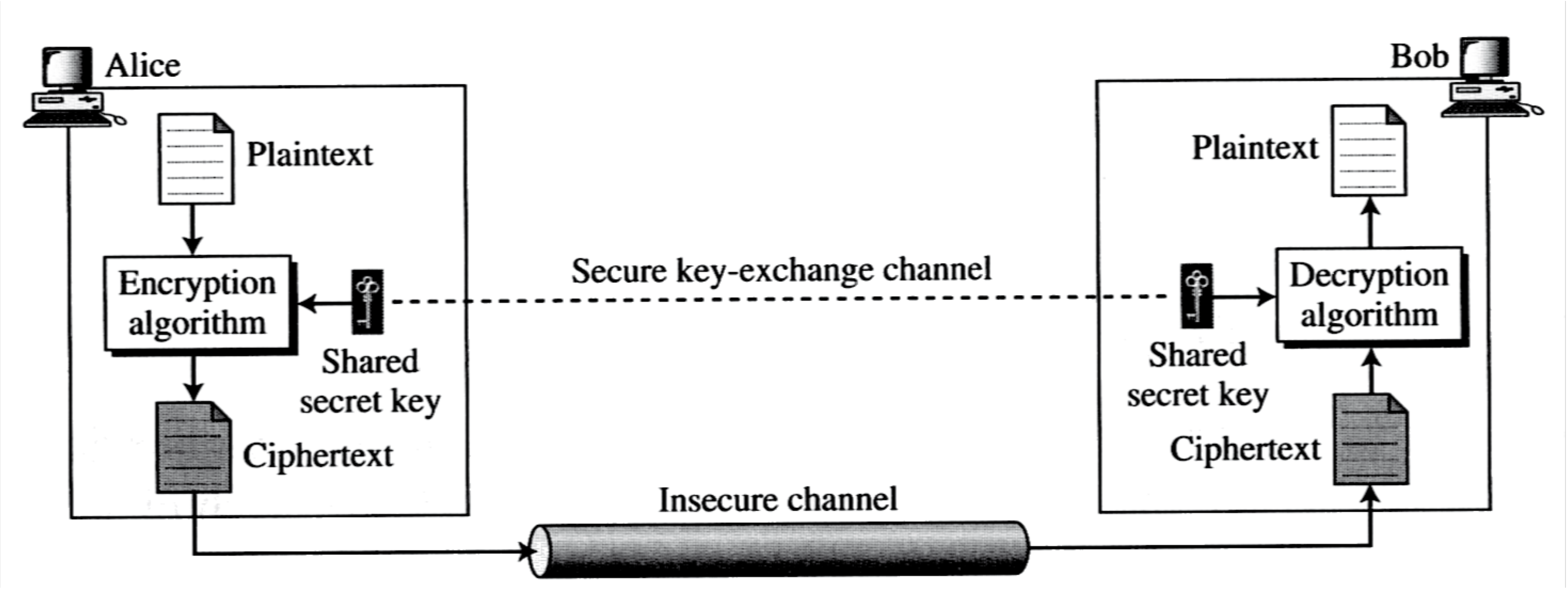
Chair of IT Security

Chapter Overview

- General Idea of Symmetric Encryption
- Block ciphers
- Modes to use block ciphers
- Stream ciphers
- (Pseudo) Random Number Generators

General Idea of Symmetric Encryption

- The two communication endpoints share a secret key
- The secret key is used for both encryption and decryption



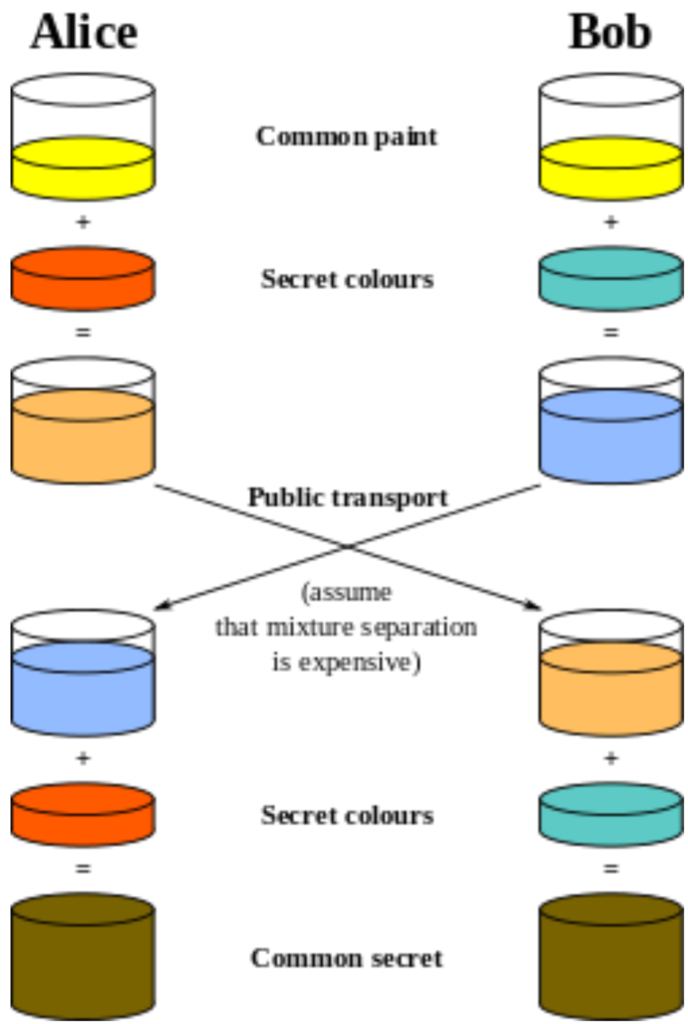
Encryption

- A symmetric encryption scheme consists of
  - A key generation algorithm
  - An encryption algorithm
  - A decryption algorithm
- An encryption algorithm E is an algorithm that
  - Takes a plaintext message M of arbitrary length $M \in \{0,1\}^*$
  - and a key $K \in \{0,1\}^n$ as input
  - and outputs a ciphertext $C = E_K(M) \in \{0,1\}^*$
- A decryption algorithm D is an algorithm that
  - Takes a ciphertext C and a key K as input
  - And outputs a plaintext $M = D_K(C)$
- For every K and every M, $D_K(E_K(M)) = M$

Kirckhoff Principle & Avalanche Effect

- A cryptosystem should be secure even if everything about the system, except the key, is public knowledge
- In contrast, keeping the design of a cryptosystem secret is often referred to "security through obscurity"
- Avalanche effect: small change in either plaintext or the key should produce a significant change in the ciphertext

Preview: Diffie-Hellman Key Exchange (src: Wikipedia)



Diffie-Hellman Key Exchange: Idea

- Prime numbers **p** and primitive root **g** to p are publicly known
- Alice picks a secret number **a** and computes $\mathbf{g}^a$ *mod* **p** (let's call it **A**) and sends the result to Bob.
- Bob does the same thing, but with its own secret number **b**. So $\mathbf{g}^b$ *mod* **p** (called **B**) is sent to Alice
- Now, Alice can compute $\mathbf{B}^a$ *mod* **p**.
- Bob can do the same with the input he got from Alice: $\mathbf{A}^b$ *mod* **p**.

Caesar Cipher

- Caesar cipher is a shift cypher. It shifts letters by a fixed value, e.g.,

A B C D E F G H I J K L M ...

F G H I J K L M N O P Q R...

HELLO => MQQT

Encryption $E_K(x) = x + k \bmod 26$

Decryption $D_K(y) = y – k \bmod 26$

- Another example: Column transposition
- Problems: brute force attack and frequency analysis

Column Transposition

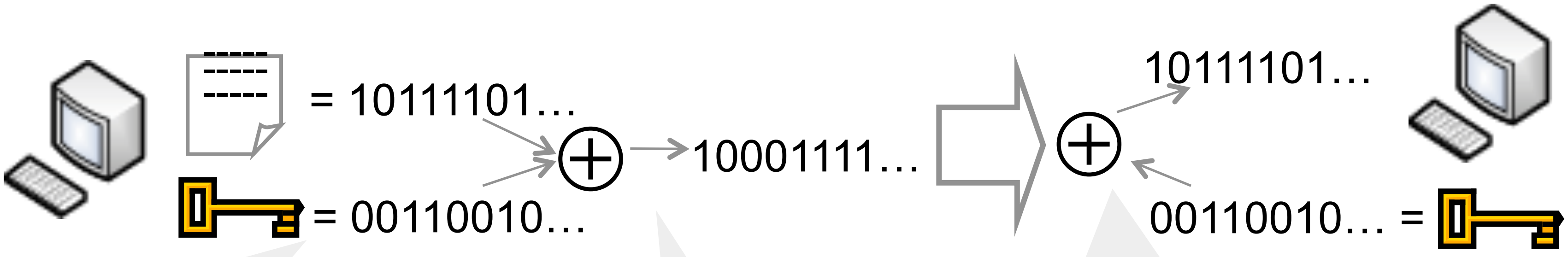
- Plaintext is written down in a rectangle, row by row, and read column by column. The order of columns is the key.

- Key: 4 3 1 2 5 6 7
- Plaintext:

a	t	t	a	c	k	p
o	s	t	p	o	n	e
d	u	n	t	i	l	t
w	o	a	m	x	y	z

- Ciphertext: ttnaaptm…

One-Time Pad



Key is a random bit sequence as long as the plaintext

Encrypt by bitwise XOR of plaintext and key:
ciphertext = plaintext ⊕ key

Decrypt by bitwise XOR of ciphertext and key:
ciphertext ⊕ key =
(plaintext ⊕ key) ⊕ key =
plaintext ⊕ (key ⊕ key) =
plaintext

- A cipher achieves perfect secrecy if and only if there are as many possible keys as possible plaintexts, and every key is equally likely (Claude Shannon)

Advantages of One-Time Pad

- Easy to compute
  - Encryption and decryption are the same operation
  - Bitwise XOR is very cheap to compute
- As secure as theoretically possible
  - Given a ciphertext, all plaintexts are equally likely, regardless of attacker's computational resources
  - …as long as the key sequence is truly random
    - True randomness is expensive to obtain in large quantities
  - …as long as each key is same length as plaintext
    - But how does the sender communicate the key to receiver?

Problems with One-Time Pad

- Key must be as long as plaintext
  - Impractical in most realistic scenarios
  - Still used for diplomatic and intelligence traffic
- Does not guarantee integrity
  - One-time pad only guarantees confidentiality
  - Attacker cannot recover plaintext, but can easily change it to something else
- Insecure if keys are reused
  - Attacker can obtain XOR of plaintexts

- Obviously not practical

Brute Force Attacks

- Try every possible key
  - Successful on average after trying half of the keys
- Difficulty of brute force attack is proportional to key size

Key Size (bits)	Number of Alternative Keys	Time required at 1 decryption/µs	Time required at 10^6 decryptions/µs
32	$2^{32} = 4.3 \times 10^9$	2^{31} µs = 35.8 minutes	2.15 milliseconds
56	$2^{56} = 7.2 \times 10^{16}$	2^{55} µs = 1142 years	10.01 hours
128	$2^{128} = 3.4 \times 10^{38}$	2^{127} µs = 5.4×10^{24} years	5.4×10^{18} years
168	$2^{168} = 3.7 \times 10^{50}$	2^{167} µs = 5.9×10^{36} years	5.9×10^{30} years
26 characters (permutation)	$26! = 4 \times 10^{26}$	2×10^{26} µs = 6.4×10^{12} years	6.4×10^6 years

Block and Stream Ciphers

- Block ciphers encrypt blocks of plaintext of the same length with the same key
- Stream ciphers produce a pseudo-random stream of key bits
  - Plaintext is XORed bitwise with the key stream to produce ciphertext
- Block ciphers can, however, be turned into stream ciphers as we will see
- Stream ciphers are also block ciphers with a block size of “1”
- I. e. this distinction is somewhat blurred, particularly at the edges

Block Ciphers

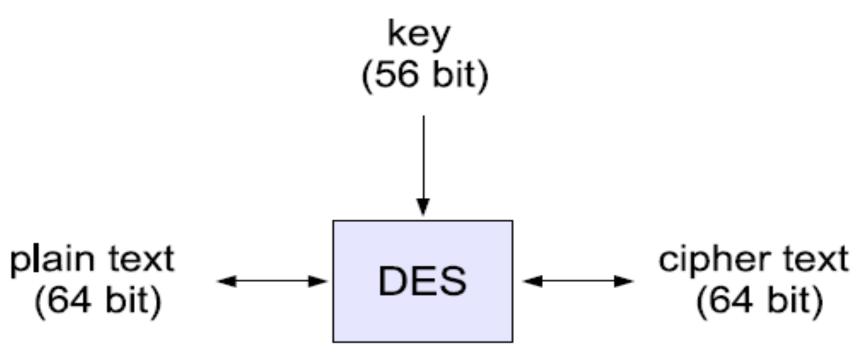
- Operate on a single chunk (“block”) of plaintext
  - For example, 64 bits for DES, 128 bits for AES
  - Same key is reused for each block (can use short keys)
- Result should look like a random permutation
  - “As if” plaintext bits were randomly shuffled
- Only computational guarantee of secrecy
  - Not impossible to break, just very expensive
    - If there is no efficient algorithm (unproven assumption!), then can only break by brute-force, try-every-possible-key search
  - Time and cost of breaking the cipher exceed the value and/or useful lifetime of protected information

Commonly known Block Ciphers

- DES
- 3DES
- AES
- Twofish
- …

DES

- Published in 1977 by the National Bureau of Standards*
  - Designed by IBM and the NSA
- Uses a 64-bit key and a block length of 64 bit
- Main operations: substitutions and permutations
- 8 bits of the key are used as parity bits
  - Effective key size is 56 bits



* called the National Institute of Standards and Technology (NIST) since 1988

Principles of DES

- First, each input block is subjected to a fixed input permutation
- Over the two resulting 32-bit blocks *L* and *R*, 16 similar encryption steps are executed, each depending on a 48-bit sub-key of the external (56-bit) key *k*.
  - Sub-keys are generated by a key selection procedure
- Finally, execution of an output permutation inverse to the input permutation
- Decryption analogous to encryption
  - 16 sub-keys are required in reverse order

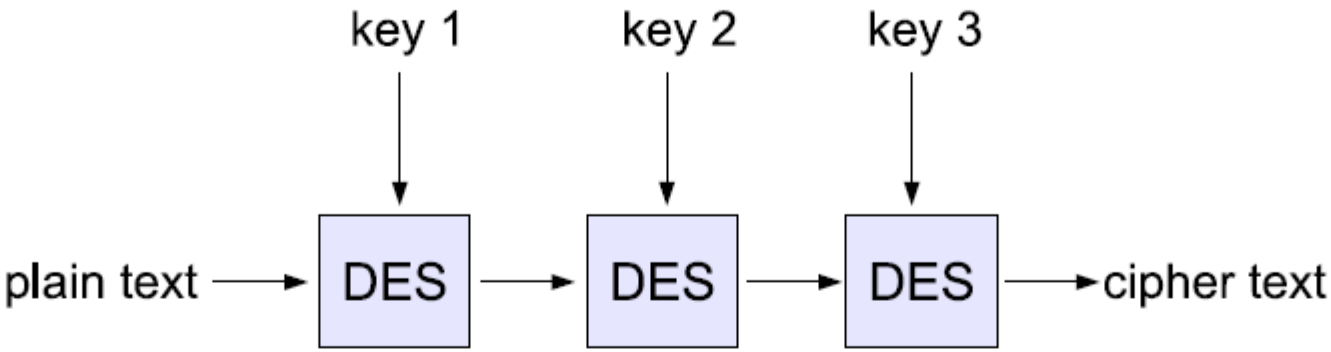
Security of DES

- January 13th, 1999: DES key broken within 22 hours and 15 minutes
  - In a contest sponsored by RSA Labs using
  - EFF's Deep Crack custom DES cracker ...
  - … and the idle CPU time of around 100,000 computers
- It is no longer advisable to use DES
  - Especially not for new applications
- Biggest weakness still is the key length of 56 bits only!

Problems with 2DES

- First idea to increase the key size of DES
  - Use DES twice in a row with two independent keys k1, k2
- Problem: this does not double the effective key size
- “Meet-in-the-middle-attack”
  - Assume attacker has a plaintext/ciphertext pair (M,C) with DES(k2,DES(k1,M)) = C but no knowledge of the keys k1, k2
  - Attacker can compute a list of intermediate ciphertexts Z by encrypting M with each possibile key k1: 2^{56} DES operations
  - Attacker can decrypt C with all possible k2 until he finds one that matches one of the Z's: again at most 2^{56} DES operations
  - Overall: at most $2*2^{56}$ DES operations to find the keys k1, k2
  - This is a known-plaintext attack against 2DES with a complexity of 2^{57}

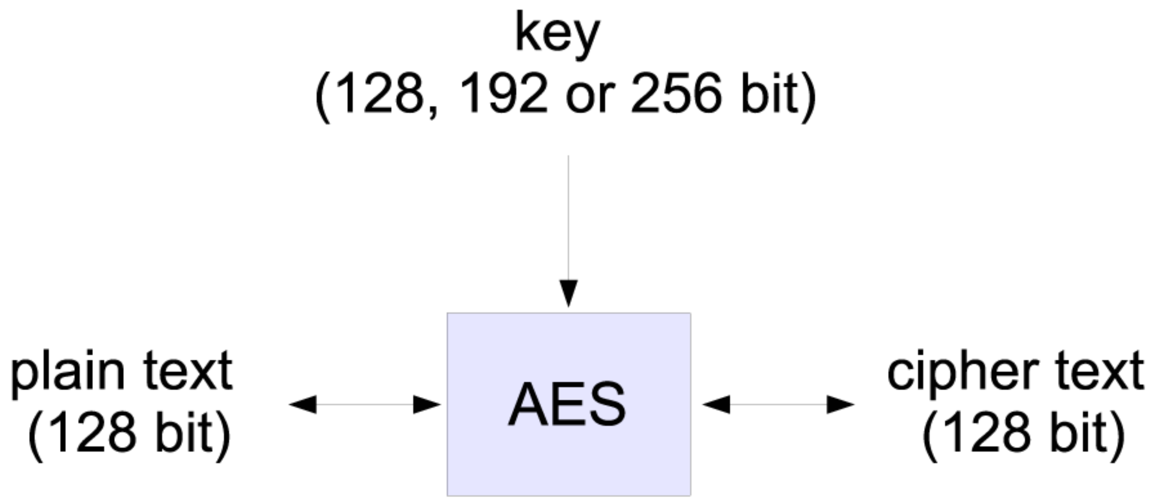
3DES = "Triple DES"



- Use DES three times in a row
  - Two variants in use: 3-key 3DES and 2-key 3DES
  - Both variants first use encryption with key1, decryption with key2, encryption with key3
  - 3-key 3DES: k1, k2, k3 pairwise different
  - 2-key 3DES: k1 = k3

AES

- Goals
  - More secure than 3DES
  - More efficient than 3DES
  - Support different key lengths



AES Selection

- January 1997: National Institute of Standardization
  - “[...] the AES would specify an unclassified, publicly disclosed encryption algorithm, available royalty-free, worldwide.“
- August 1998: presentation of 15 candidates
  - Cast-256, Crypton, DEAL, DFC, E2, Frog, HPC, Loki97, Magenta, MARS, RC6, Rijndael, SAFER+, Serpent, Twofish
  - Broken under public scrutiny: DEAL, Frog, HPC, Loki97, Magenta
- August 1999: selection of 5 candidates for the next round
- October 2000: Rijndael is selected as AES
- November 2001: AES is standardized in FIPS 197

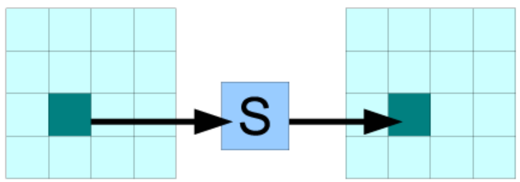
Structure of AES

- AES is round based
- AES uses a State Matrix with byte entries to represent the input and output of each round

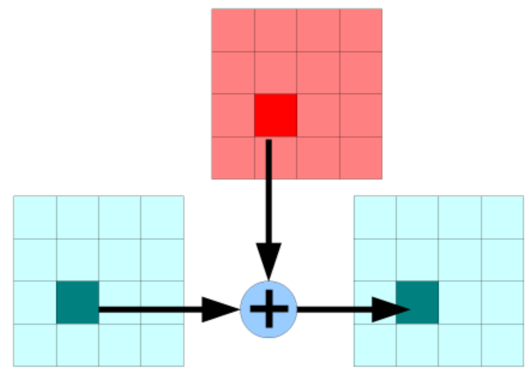
$$\begin{array}{|c|c|c|c|}\hline i_0 & i_4 & i_8 & i_{12} \\ \hline i_1 & i_5 & i_9 & i_{13} \\ \hline i_2 & i_6 & i_{10} & i_{14} \\ \hline i_3 & i_7 & i_{11} & i_{15} \\ \hline \end{array} \dashrightarrow \begin{array}{|c|c|c|c|}\hline s_{00} & s_{01} & s_{02} & s_{03} \\ \hline s_{10} & s_{11} & s_{12} & s_{13} \\ \hline s_{20} & s_{21} & s_{22} & s_{23} \\ \hline s_{30} & s_{31} & s_{32} & s_{33} \\ \hline \end{array} \dashrightarrow \begin{array}{|c|c|c|c|}\hline o_0 & o_4 & o_8 & o_{12} \\ \hline o_1 & o_5 & o_9 & o_{13} \\ \hline o_2 & o_6 & o_{10} & o_{14} \\ \hline o_3 & o_7 & o_{11} & o_{15} \\ \hline \end{array}$$

Operations used in each round

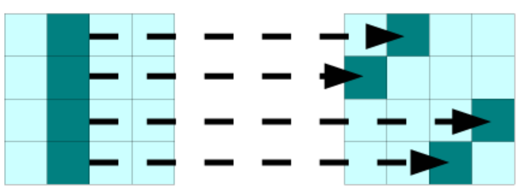
Byte Substitution (SB)



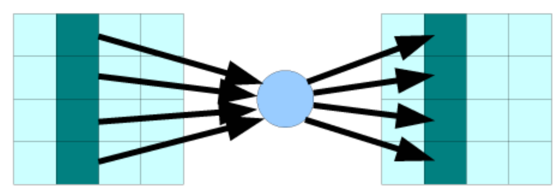
Key Addition (KA)



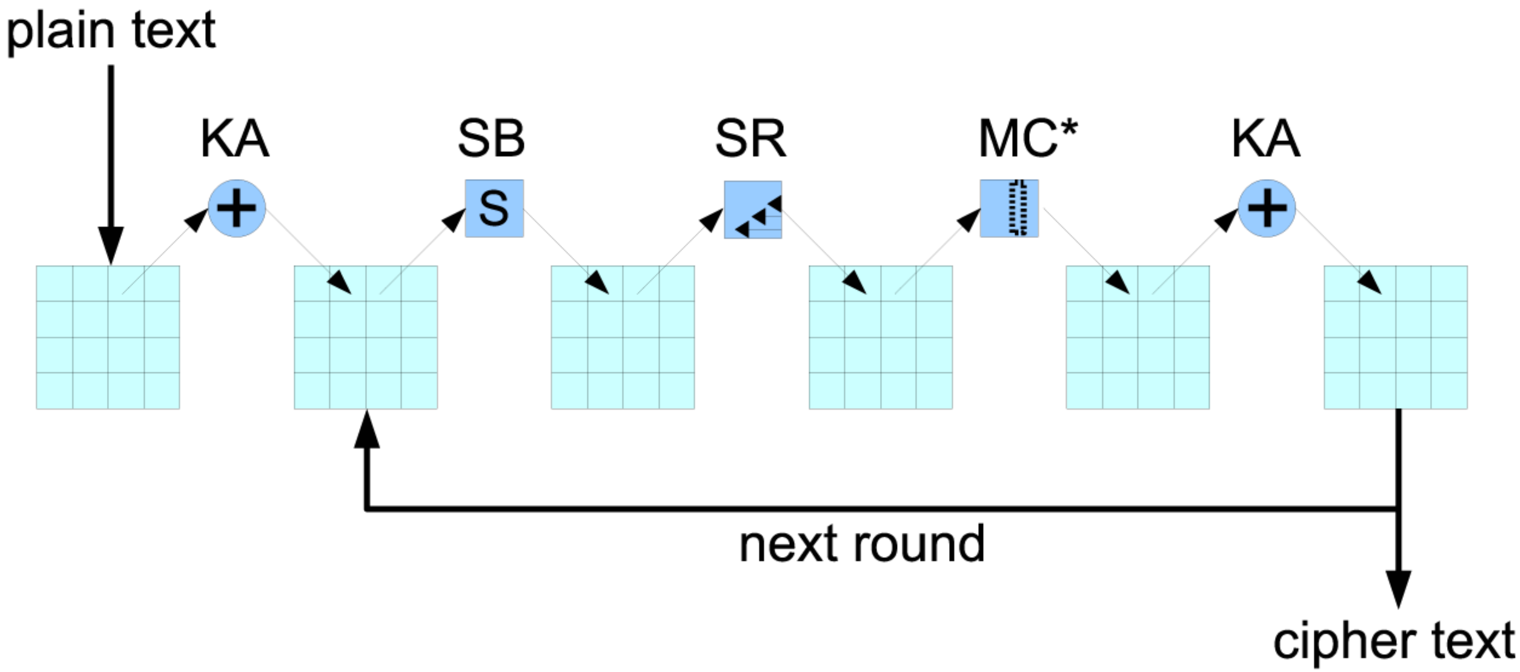
Mix Column (MC)



Shift Row (SR)



Rounds



- The round key is different for each round and generated from the secret key
- * No Mix Column takes place in the last round

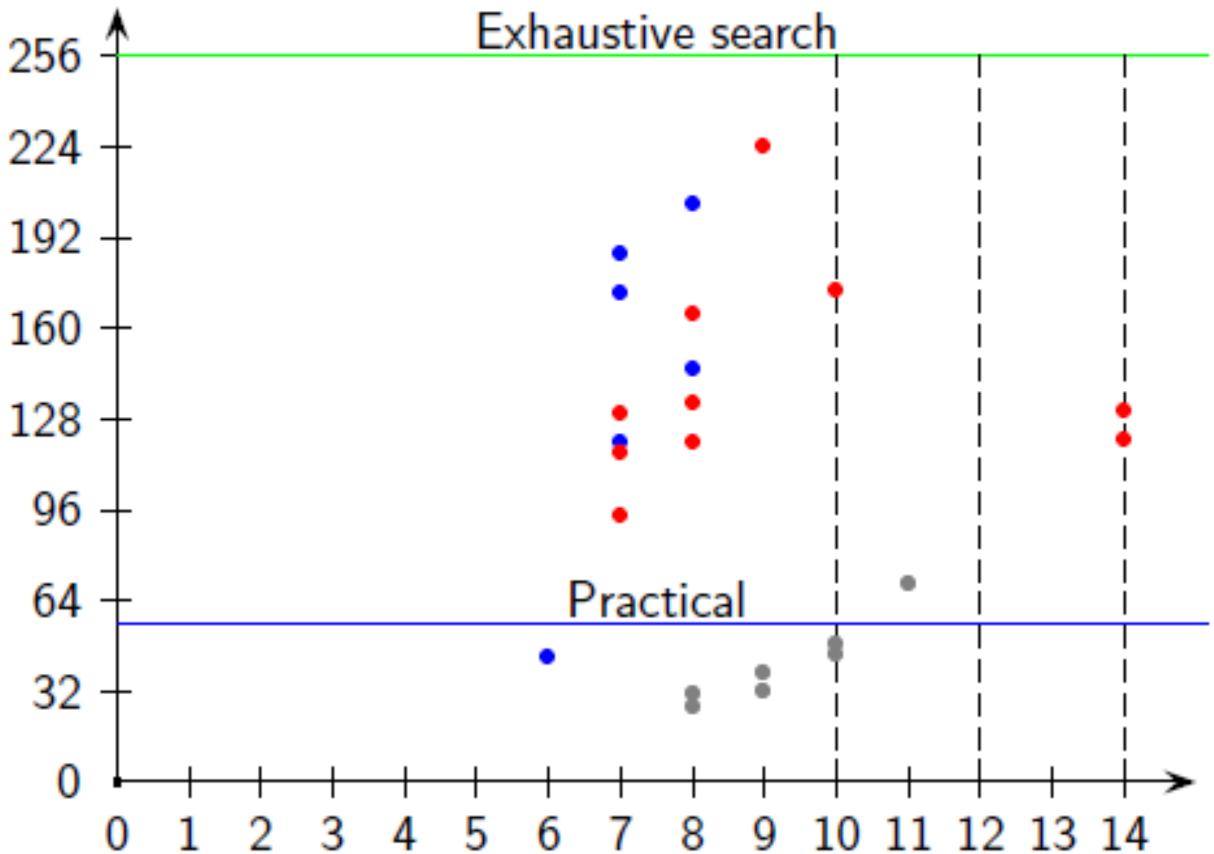
Number of Rounds

- Depends on the key length
  - 128 bit key – 10 rounds
  - 192 bit key – 12 rounds
  - 256 bit key – 14 rounds

Recent Attacks Against AES

- May and August 2009, Biryukov et al. University of Luxembourg
  - Related-key attacks on AES-256 and AES-192
    - Currently best attack against AES-256: key recovery attack with time complexity of 2^{119}
    - Attack against AES-192: key recovery within 2^{176}
  - Related-key attacks
    - Requires access to plaintexts encrypted with multiple keys that are related in a specific way
- No reason to worry yet
  - No attacks against full round AES-128 known that are better than brute force
  - No practical attacks against full round AES-256, AES-192

Overview on time-complexity of Attacks Against AES-256

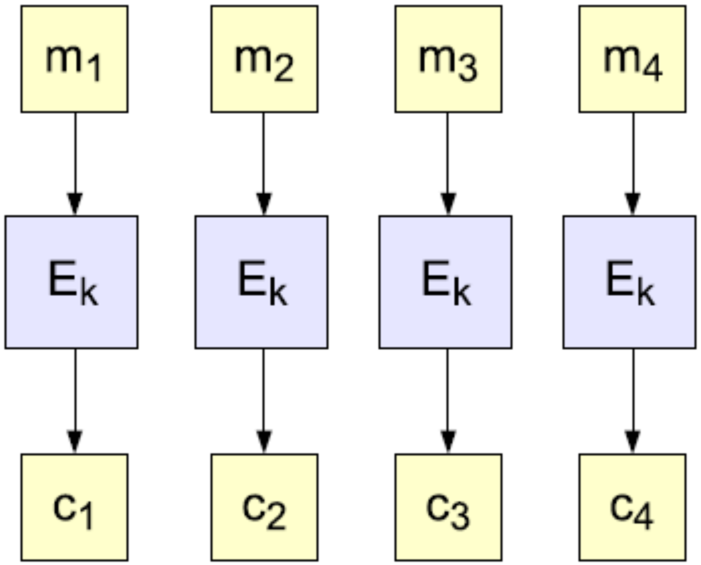


Alex Biryukov, Orr Dunkelman, Nathan Keller,
Dmitry Khovratovich, Adi Shamir

Encrypting a Large Message

- So, we’ve got a good block cipher, but our plaintext is larger than 128-bit block size
- Electronic Code Book (ECB) mode
  - Split plaintext into blocks, encrypt each one separately using the block cipher
- Cipher Block Chaining (CBC) mode
  - Split plaintext into blocks, XOR each block with the result of encrypting previous blocks
- Also various counter modes, feedback modes, etc.

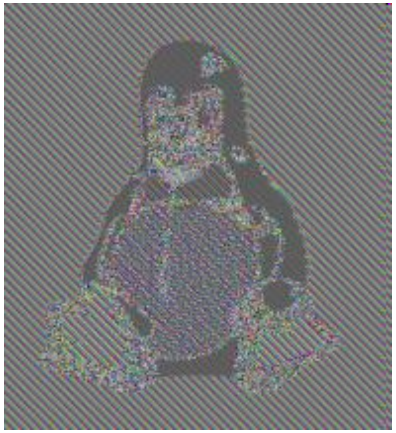
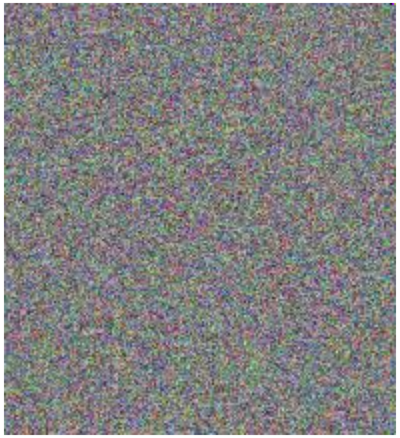
ECB Mode



- Encryption: $c_i = E_K(m_i)$
- Decryption: $m_i = D_K(c_i)$

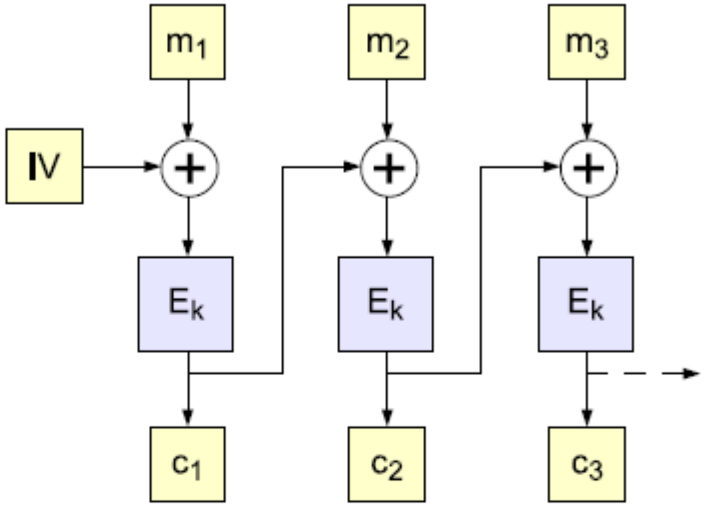
- Disadvantages
  - Same plaintext block always leads to the same output block
  - Patterns in the plaintext block still show in the ciphertext
  - Re-ordering or deletion of ciphertexts cannot be detected

Why ECB is Not Enough

- Ciphertext as a whole in ECB Mode reveals information about the original plaintext as a whole
  - Even if an individual block does not reveal anything

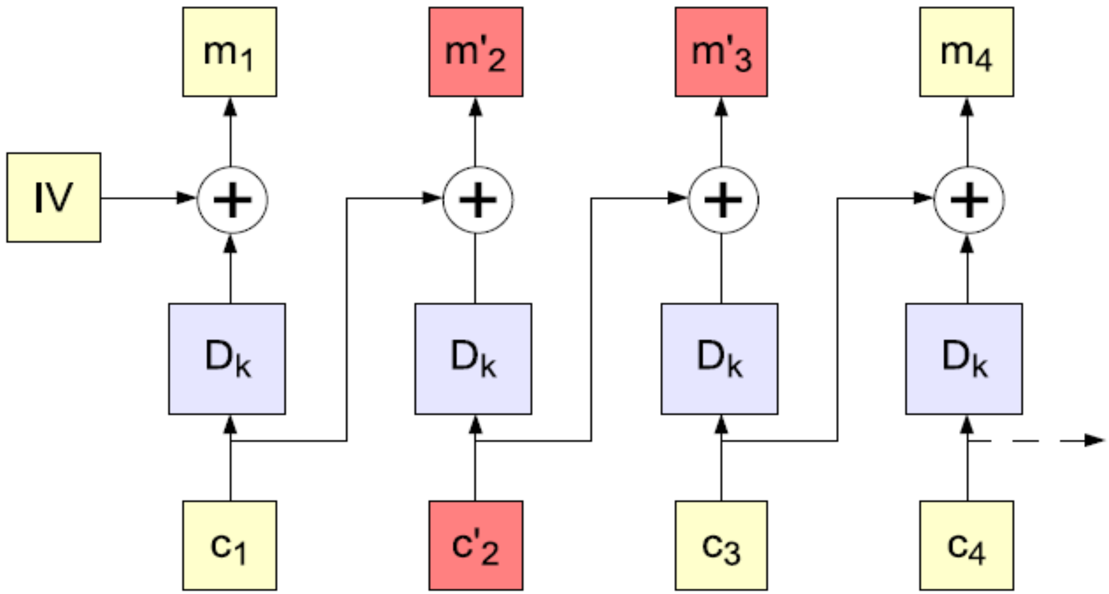
Cipher Block Chaining Mode



- IV : = c_0
- Encryption: $c_i = E_k(m_i \text{ xor } c_{i-1})$
- Decryption: $m_i = D_k(c_i) \text{ xor } c_{i-1}$

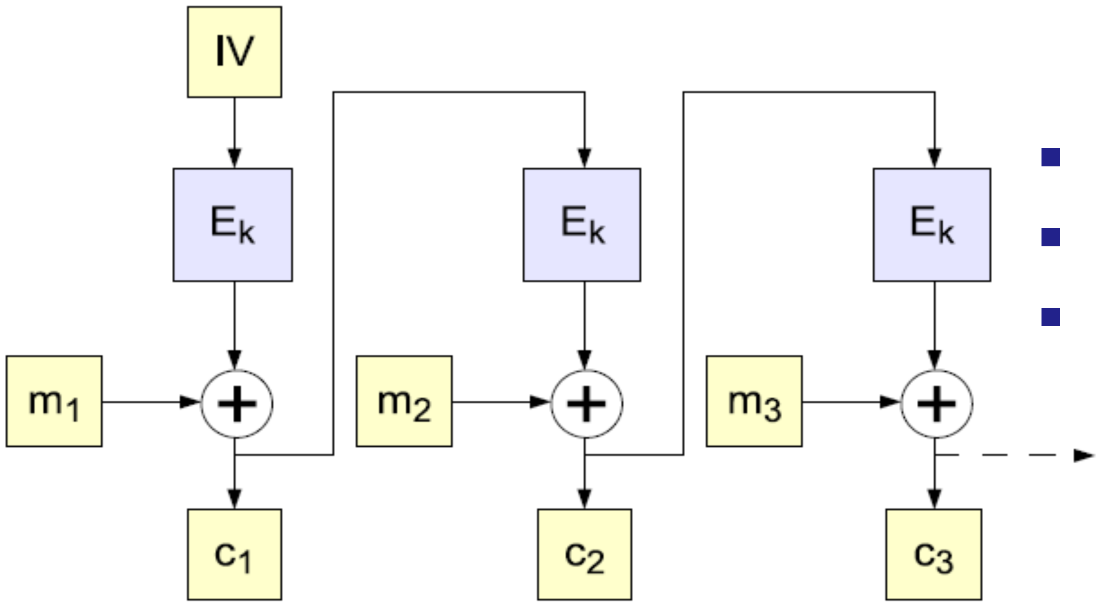
- Uses the xor of plaintext block and the ciphertext block corresponding to the previous plaintext as input to the block cipher
- Advantages
  - Deletion of a ciphertext block can be detected
  - Re-ordering of ciphertext blocks can be detected
  - Self-synchronizing on transmission errors

Self-Synchronization



- Transmission error in c_2 will only influence m_2 and m_3
- Subsequent plaintext will be correctly recovered

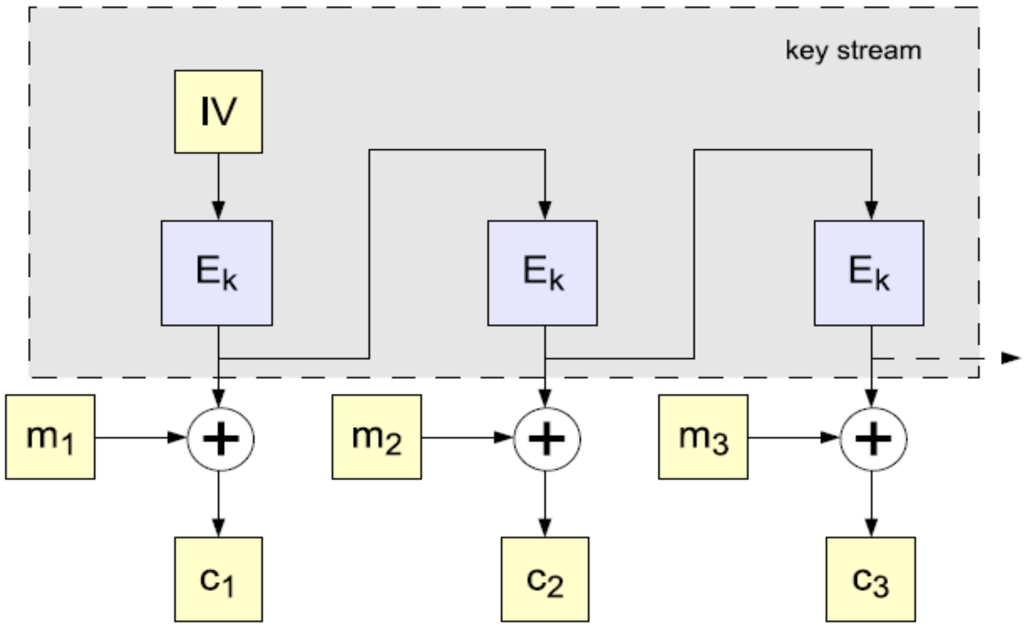
Cipher Feedback Mode (CFB) - Simplified



- IV public, IV : = c_0
- Encryption: $c_i = E_k(c_{i-1})$ xor m_i
- Decryption: $m_i = c_i$ xor $E_k(c_{i-1})$

- Generates a key stream that depends on the ciphertext
- In the non-simplified version
  - block length of the encryption function is longer than plaintext block
  - part of the output of the encryption function is discarded
  - Non-discarded part is used to shuffle the bits of IV to the left

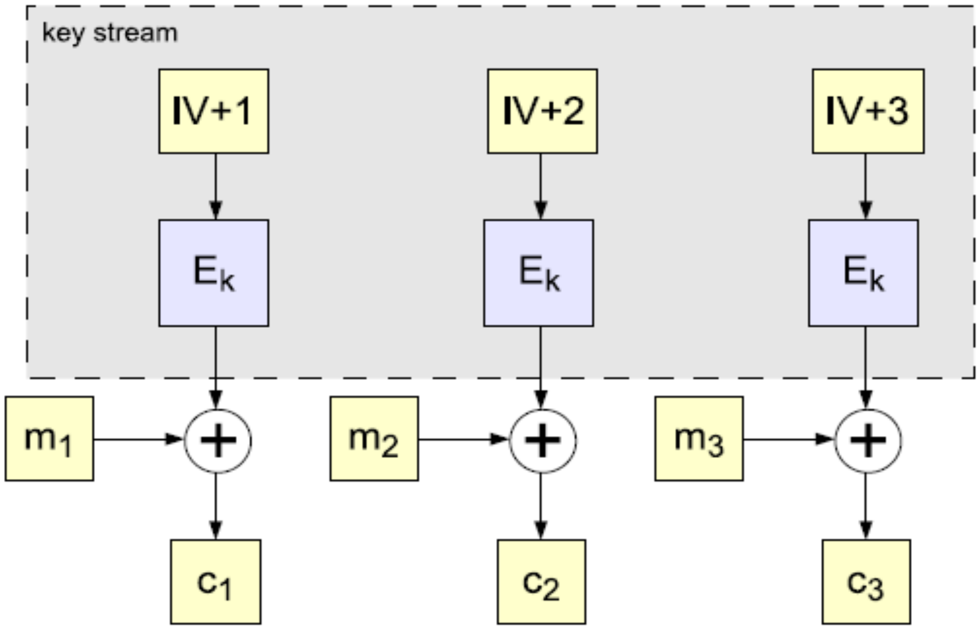
Output Feedback Mode (OFB) - Simplified



- IV public
- Encryption: $c_i = E_k^i(IV)$ xor m_i
  - IV encrypted i-times
- Decryption: $m_i = c_i$ xor $E_k^i(IV)$

- Generates a key stream that does not depend on the ciphertext
- Key stream can be pre-computed as soon as IV is known
- Non simplified version as cipher feedback mode

Counter Mode (CTR)



- IV public
- Encryption: $c_i = E_k{}^i(IV+i)$ xor m_i
- Decryption: $m_i = c_i$ xor $E_k{}^i(IV+i)$

- Like OFB turns a block cipher into a stream cipher
- Can additionally be parallelized as there is no feedback

Important Properties of the Modes

- OFB, CFB and CTR
  - Not restricted to complete blocks
  - Turn a block cipher into a stream cipher (to some extent)
    - Plaintext is xored with key stream bits, key stream depends on IV, Counter, and/or the last ciphertext block
- ECB, CBC
  - Require padding to complete blocks
  - Padding has to be easy to strip-off

When Is a Cipher “Secure”?

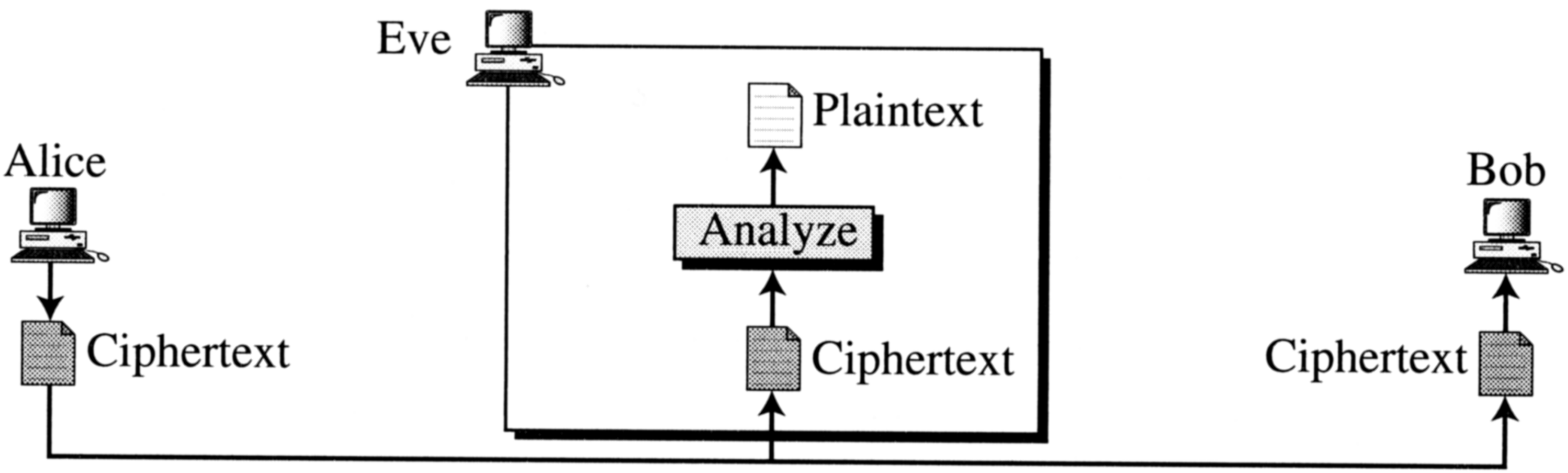
- Hard to recover the key?
  - What if attacker can learn plaintext without learning the key?
- Hard to recover plaintext from ciphertext?
  - What if attacker learns some bits or some function of bits?
- Fixed mapping from plaintexts to ciphertexts?
  - What if attacker sees two identical ciphertexts and infers that the corresponding plaintexts are identical?
  - Implication: encryption must be randomized or stateful

How Can a Cipher Be Attacked?

- Attackers knows ciphertext and encryption algorithm
  - Main question: what else does the attacker know?
  - Depends on the application in which the cipher is used!
- Brute-force attack: try out all possible keys
- Ciphertext-only attack
- Known-plaintext attack (stronger)
  - Knows some plaintext/ciphertext pairs
- Chosen-plaintext attack (even stronger)
  - Can obtain ciphertext for any plaintext of his choice
- Chosen-ciphertext attack (very strong)
  - Can decrypt any ciphertext except the target before target is known
- Adaptive chosen-ciphertext attack
  - Can decrypt any ciphertext chosen adaptively, i.e. depending on the target and the result of the previous ciphertexts

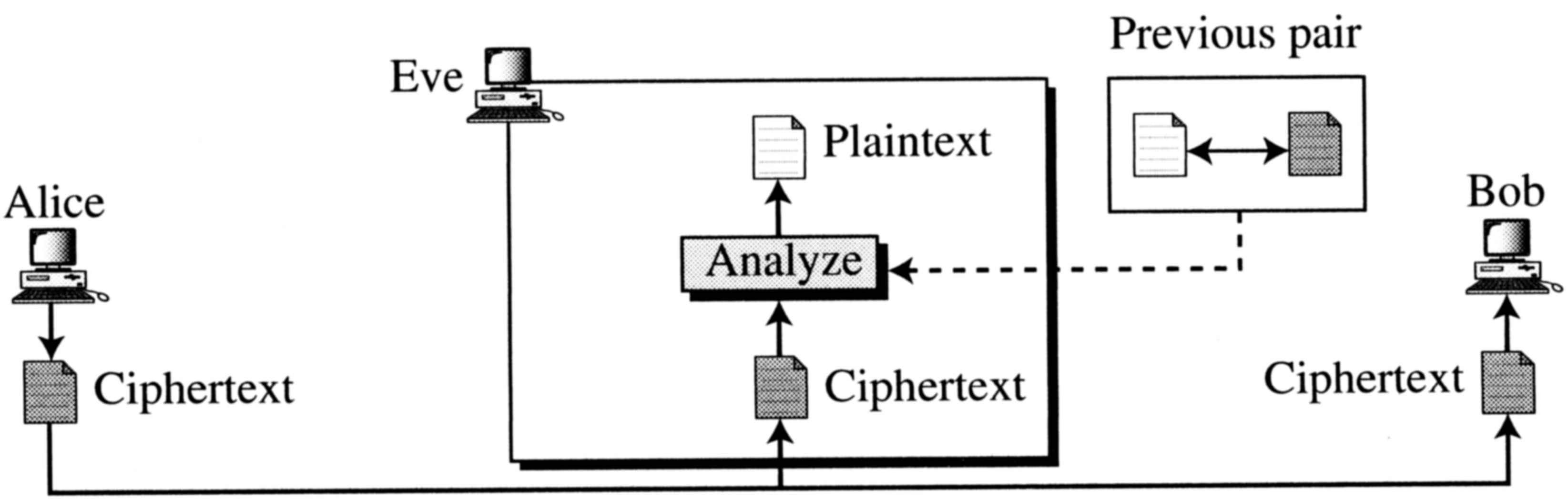
Ciphertext-only Attack

- An attacker tries to recover the plaintext but has access only to the ciphertext



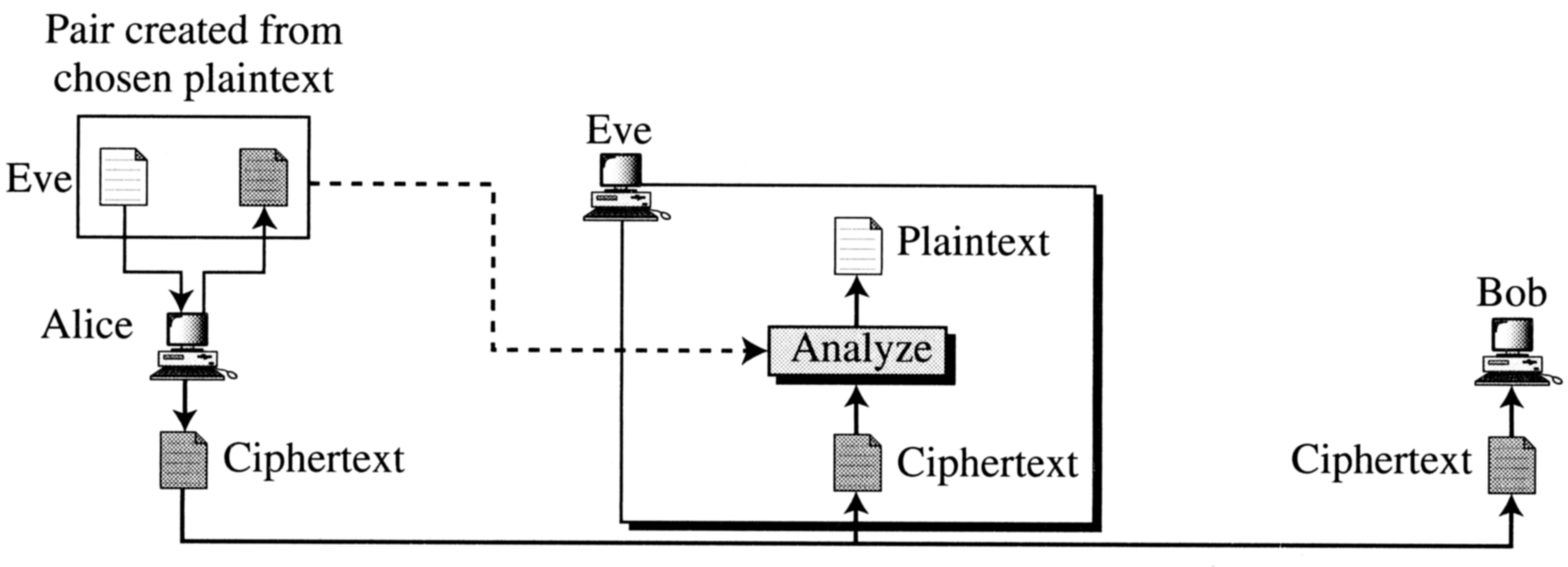
Known-plaintext Attack

- The attacker tries to recover the plaintext from the ciphertext ...
- … and has access to some pairs of plaintext and ciphertext



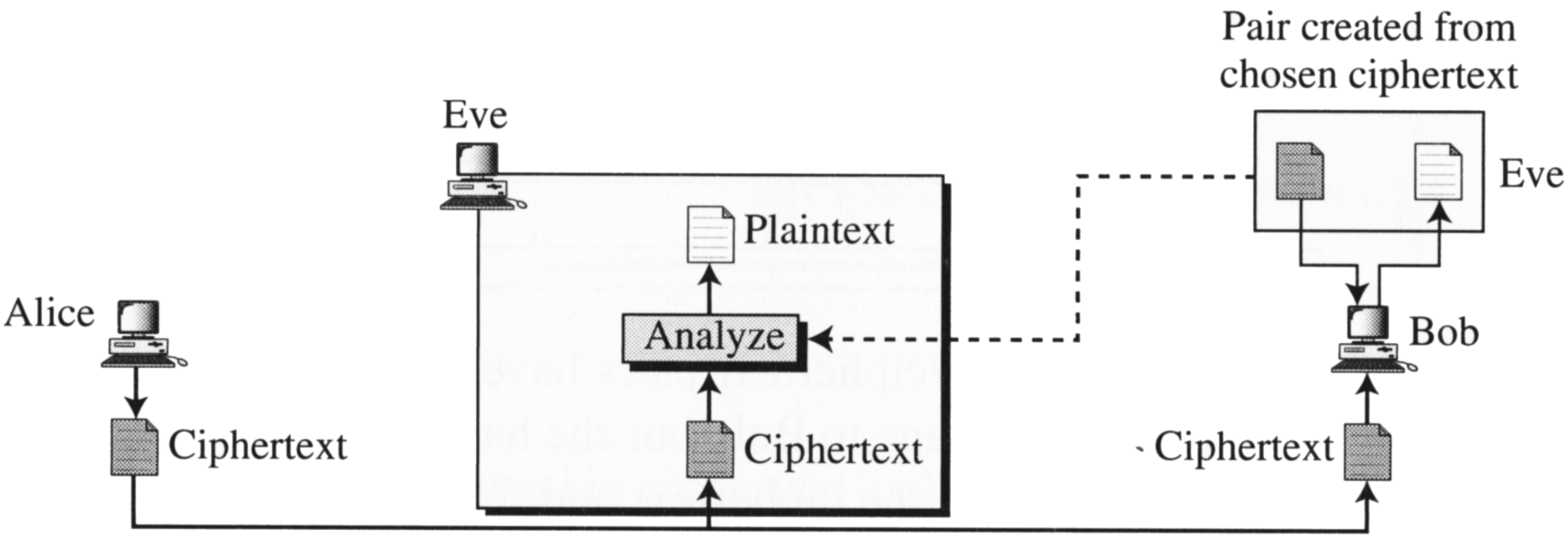
Chosen-plaintext Attack

- The attacker tries to recover the plaintext from the ciphertext ...
- … and can obtain ciphertexts for plaintexts of his choice



Chosen-ciphertext Attack

- The attacker tries to recover the plaintext from the ciphertext ...
- … and can select ciphertexts (other than the target) for which he can obtain plaintexts



Stream Ciphers

- Remember the one-time pad?
  - $E_K(M)$ = M xor Key
  - Key must be a random bit sequence as long as message
- Idea: replace “random” with “pseudo-random”
  - Encrypt with pseudo-random number generator (PRNG)
  - PRNG takes a short, truly random secret seed and expands it into a long “random-looking” sequence
    - E.g., 128-bit seed into a 1600-bit pseudo-random sequence
- $E_K(M)$ = IV, M xor PRNG(IV,K)
  - Message processed bit by bit, not in blocks

Properties of Stream Ciphers

- Usually very fast (faster than block ciphers)
  - Used where speed is important: WiFi, DVD, speech
- Unlike one-time pad, stream ciphers do not provide perfect secrecy
  - Only as secure as the underlying PRNG
  - If used properly, can be as secure as block ciphers
- PRNG is, by definition, unpredictable
  - Given the stream of PRNG output (but not the seed!), it's hard to predict what the next bit will be
    - If PRNG(unknown random seed)=b1…bi, then bi+1 is "0" with probability ½, "1" with probability ½

Weaknesses of Stream Ciphers

- No integrity
  - Associativity & commutativity: (X xor Y) xor Z=(X xor Z) xor Y
  - (M1 xor PRNG(seed)) xor M2 = (M1 xor M2) xor PRNG(seed)
- Known-plaintext attack is very dangerous if keystream is ever repeated
  - Self-cancellation property of XOR: X xor X=0
  - (M1 xor PRNG(seed)) xor (M2 xor PRNG(seed)) = M1 xor M2
  - If attacker knows M1, then easily recovers M2
    - Most plaintexts contain enough redundancy that knowledge of M1 or M2 is not even necessary to recover both from M1 xor M2

Stream Cipher Terminology

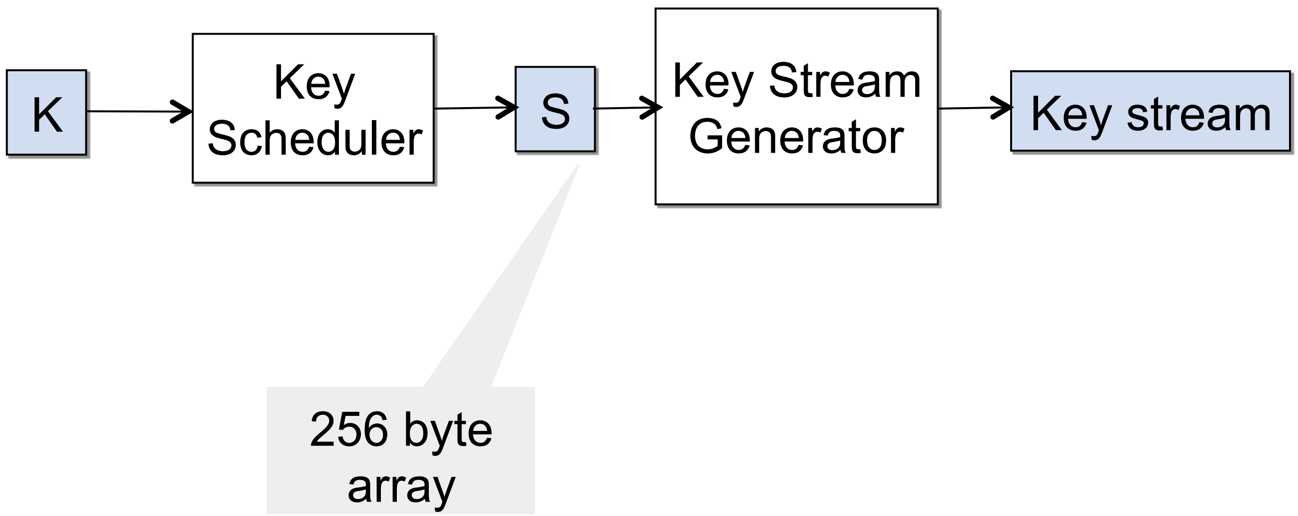
- Seed of pseudo-random generator often consists of initialization vector (IV) and key
  - IV is usually sent with the ciphertext
  - The key is a secret known only to the sender and the recipient, not sent with the ciphertext
- The pseudo-random bit stream produced by PRNG(IV,key) is referred to as keystream
  - PRNG must be cryptographically secure
- Encrypt message by XORing with keystream
  - ciphertext = message xor keystream

Examples for Stream Ciphers

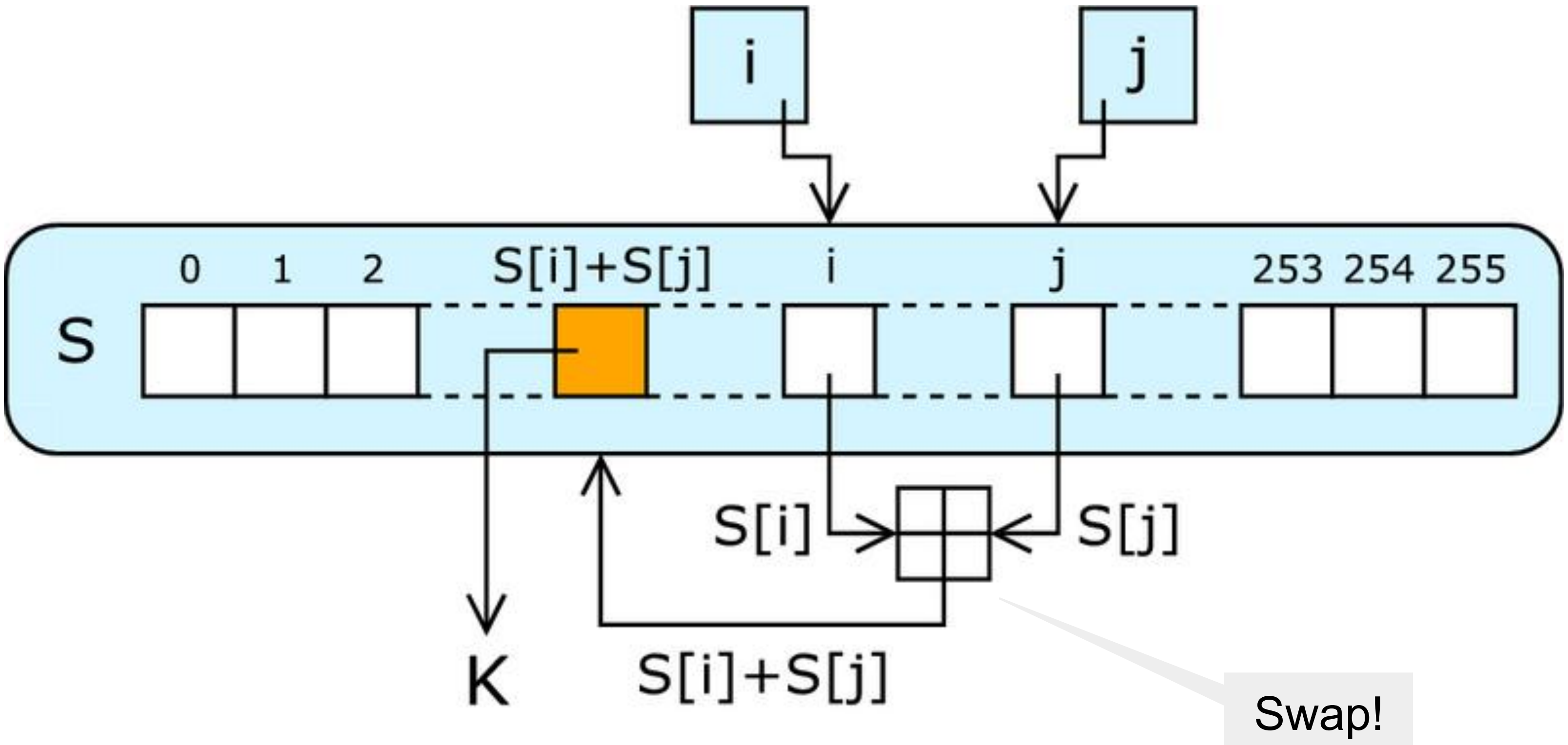
- RC4
  - Used, e.g. in WLAN, TLS, IPsec
- A5/1, A5/2
  - Used in GSM/GPRS
- SEAL
- ...

RC4

- Designed by Ron Rivest for RSA in 1987
- Simple, fast, widely used
  - SSL/TLS for Web security, WLAN
- Structure:



RC4 Key Stream Generation



- Key scheduler fills 256 byte array S
- Key stream byte K generated as illustrated above

Key Stream Generator

- In each round of the loop a key stream byte is generate

```
i = j := 0
loop
  i := (i+1) mod 256
  j := (j+S[i]) mod 256
  swap(S[i],S[j])
  output S[(S[i]+S[j]) mod 256]
end loop
```

RC4 Key scheduler – How S is filled

```
Divide key K into 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])
```

Key can be any length up to 2048 bits

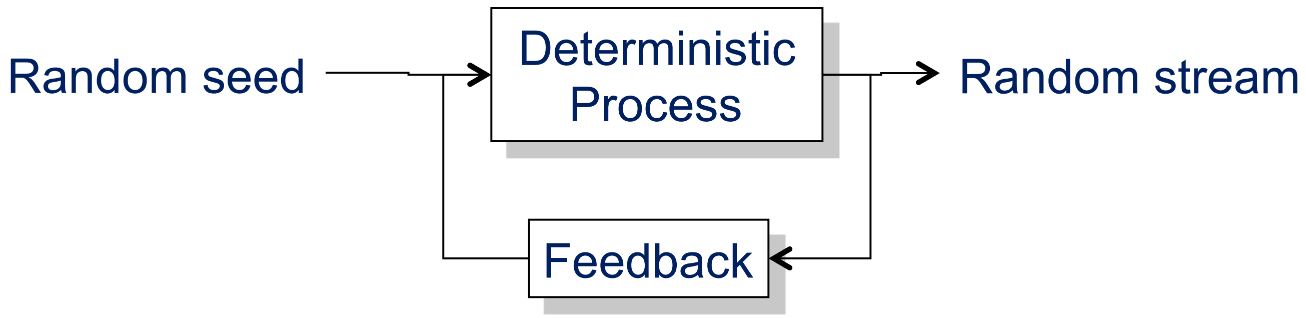
Generate initial permutation from key K

- To use RC4, usually pre-pend initialization vector (IV) to the key
  - IV can be random or a counter
- RC4 is not random enough! 1st byte of generated sequence depends only on 3 cells of state array S. This can be used to extract the key.
  - To use RC4 securely, RSA suggests discarding first 256 bytes

Fluhrer-Mantin-Shamir attack

(Pseudo) Random Number Generators

- Random Numbers can be generated by repeating an experiment with a random result
  - E.g. throwing a coin
- Pseudo Random Numbers just “look random” but are generated by a deterministic process with feed back using a (smaller) random “seed” as input



PRNGs

- Pseudo Random Number Generators (PRNGs) are used in cryptography for many different purposes
  - Generation of symmetric keys
  - Generation of asymmetric keys or parameters used in key generation
  - Generation of random challenges in authentication mechanisms
- PRNGs are typically based on PR Bit Gs that generate one pseudo random output bit
- Some standards also use the term Pseudo Random Function (PRF) instead of PRNG

PRBGs

- A PRBG is said to pass the next bit test if there is no polynomial-time algorithm, which on input of the first k bits of the output of PRBG can predict the next bit with probability greater than ½
- A PRNG that is based on a PRBG that passes the next bit test is called cryptographically secure
- Cryptographically secure PRBGs can be constructed from
  - (Keyed) Hash functions (see next chapter)
  - Block ciphers
  - Number theoretic problems

Cryptographically Secure PRNG

- Next-bit test
  - Given N bits of the pseudo-random sequence, predict (N +1)st bit
    - Probability of correct prediction should be very close to 1/2 for any efficient adversarial algorithm
- PRNG state compromise
  - Even if attacker learns complete or partial state of the PRNG, he should not be able to reproduce the previously generated sequence
    - … or future sequence, if there'll be future random input(s)
- Common PRNGs are not cryptographically secure

Reading and Figure Credits

- Basics
  - Stallings: Chapter on Symmetric Encryption
  - Kaufman: Chapters 3 and 4
- Further Reading
  - Random Numbers: RFC 1750
  - Really nice comic on AES
    - http://www.moserware.com/2009/09/stick-figure-guide-to-advanced.html
- Figure Credits: Forouzan "Introduction to Cryptography and Network Security"