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UCL
Université catholique de Louvain

Cryptography 1

INGI2347: COMPUTER SYSTEM SECURITY (Spring 2016)

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Lecture slides adapted from UCL INGI2347 by Gildas Avoine, Upenn CSE331 by Steve Zdancewic, and Dan Boneh, Stanford Cryptography I@Coursera. Reproduced with permission

Plan for today

Lecture 4

- What's crypto? NEXT
- Symmetric key encryption
- Trusted 3rd parties
- Public key encryption
- Crypto hash functions

κρμπτο γραφη (Cryptography)

- Greek for "secret writing"
- Confidentiality
  - Obscure a message from eaves-droppers
- Integrity
  - Assure recipient that the message was not altered
- Authentication
  - Verify the identity of the source of a message
- Non-repudiation
  - Convince a 3rd party that what was said is accurate

Cryptography is everywhere

Secure communication:

- web traffic: HTTPS
- wireless traffic: 802.11i WPA2 (and WEP), GSM, Bluetooth

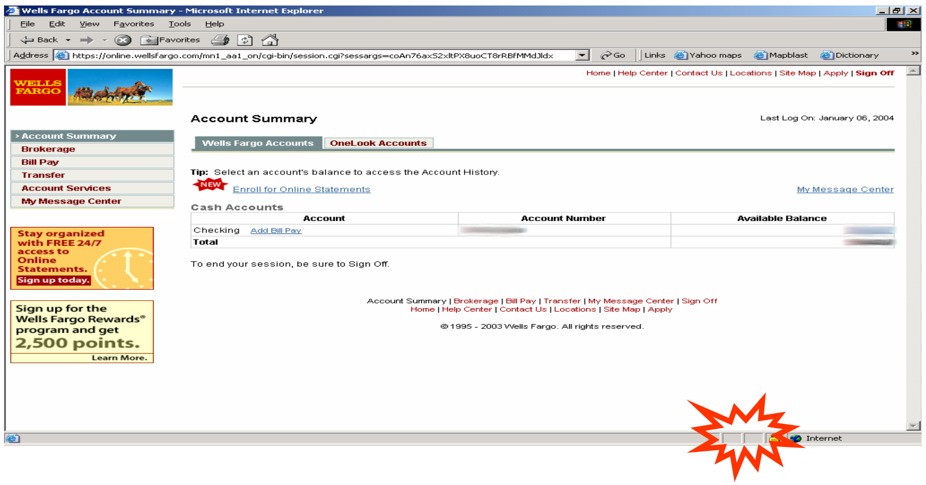
Encrypting files on disk: EFS, TrueCrypt

Content protection (e.g. DVD, Blu-ray): CSS, AACS

User authentication

… and much much more

Secure communication



Alice

HTTPS

SSL / TLS

Bob

no eavesdropping
no tampering

Secure Sockets Layer / TLS

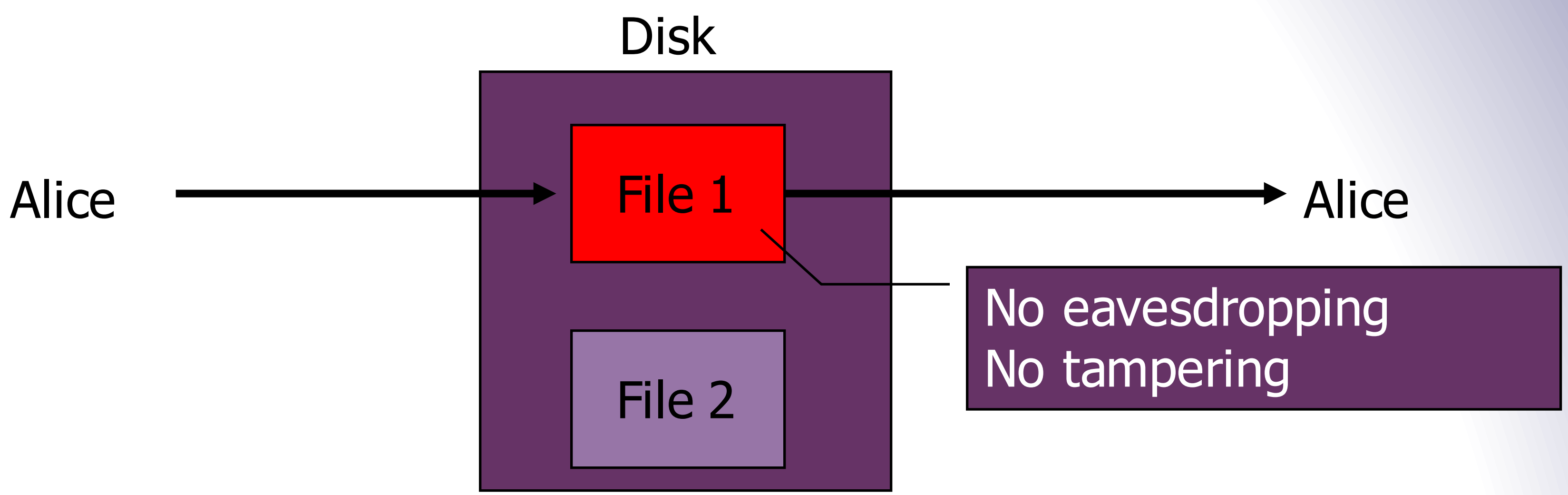
Two main parts

1. Handshake Protocol: **Establish shared secret key using public-key cryptography**

2. Record Layer: **Transmit data using shared secret key**

   Ensure confidentiality and integrity

Protected files on disk



Analogous to secure communication:

Alice today sends a message to Alice tomorrow

Terminology

- Encryption algorithm
  - Transforms a plaintext into a ciphertext that is unintelligible for non-authorized parties
  - Usually parametrized with a cryptographic key
- Asymmetric (Public) key cryptography
  - Crypto system: encryption + decryption algorithms + key generation
- Symmetric (Shared) key cryptography
  - Cipher/decipher: symmetric-key encryption/decryption algorithms

Build block: sym.-key encryption

E, D: cipher k: secret key (e.g., 128 bits)

m, c: plaintext, cipher text

- Same secret key for both encryption and decryption
- Encryption algorithm is publicly known
  - Never use a proprietary algorithm
- Fast in software or hardware implementations

Use Cases

- **Single use key:** (one time key)
  - Key is only used to encrypt one message
    - encrypted email: new key generated for every email
- **Multi use key:** (many time key)
  - Key used to encrypt multiple messages
    - encrypted files: same key used to encrypt many files
    - SSL: same key used to encrypt many packets
  - Need more machinery than for one-time key

Things To Remember

- Cryptography is:
  - A tremendous tool
  - The basis for many security mechanisms

- Cryptography is **NOT**:
  - The solution to all security problems
  - Reliable unless implemented and used properly
  - Something you should try to invent yourself
    - many many examples of broken ad-hoc designs
  - Privacy | Steganography | (Encoding|Decoding)

Cryptography is NOT

- Privacy
  - Ability to control how personal information spreads in a community
- Steganography
  - Science of information hiding
- Encoding | Decoding
  - Code is a system of symbols which represent information
  - Encoding transforms information into a codeword
  - Decoding recovers information from a codeword

Cryptanalysis: a rigorous science

Proves or disproves the security of a cryptosystem

- The three steps:
  - Precisely specify threat model
  - Propose a construction
  - Prove that breaking construction under threat mode will solve an underlying hard problem
- Definition of break:
  - Decrypting (totally or partially) a given ciphertext
  - Recovering the key of the cryptosystem
  - Proving a cryptosystem is less secure than what is claimed

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Symmetric-key cryptography

Assumes parties already share a secret key

Symmetric Ciphers: definition

Def: a **cipher** defined over (K, M, C)

is a pair of "efficient" algs (E, D) where

$$E : K \times M \to C, \quad D : K \times C \to M$$

$$\text{s.t.} \quad \forall m \in M, k \in K : \quad D(k, E(k, m)) = m$$

E is often randomized | D is always deterministic

Stream vs. Block Ciphers

- Stream ciphers
  - Act on the plaintext one symbol at a time
  - Examples: RC4, GSM A5-1, Bluetooth E0, CSS, …
  - High speed rate, hardware implementations very cheap
  - Security analysis is not well established
- Block ciphers
  - Act on the plaintext in blocks of symbols
  - Examples: DES, 3DES, AES, IDEA, Blowfish, RC5, Kasumi, Safer, …
  - Suited to software implementations on various systems
    - (e.g., 8-bit, 32-bit, 64-bit processors)
  - Security analysis is well established

Stream Ciphers: The One Time Pad (Vernam 1917)

First example of a "secure" cipher

$$M = C = \{0,1\}^n, \quad K = \{0,1\}^n$$

key = (random bit string as long the message)

$$E(k,m) = k \oplus m$$

$$D(k,c) = k \oplus c$$

msg:	0	1	1	0	1	1	1	
key:	1	0	1	1	0	1	0	$\oplus$
CT:	1	1	0	1	1	0	1	

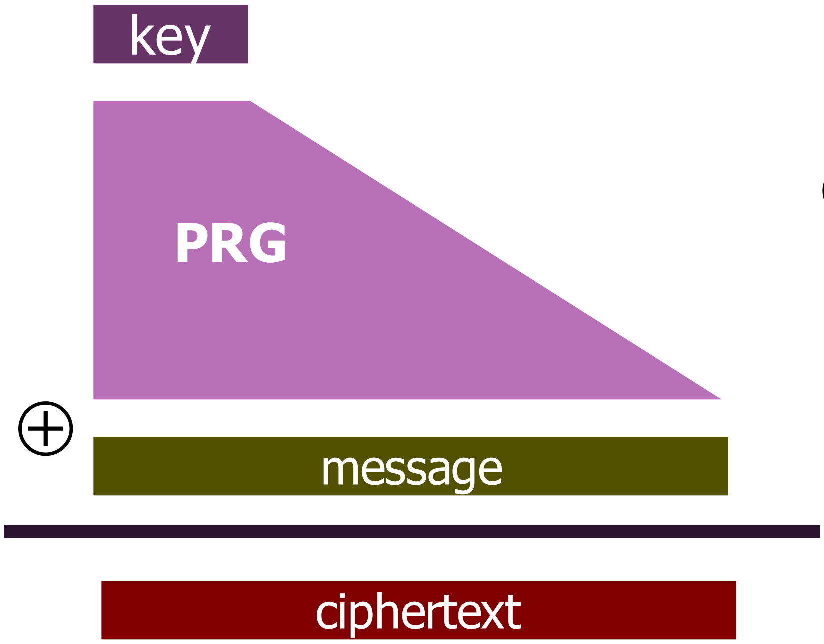
Indeed:

$$D(k,E(k,m)) = D(k,k \oplus m) = k \oplus (k \oplus m) = (k \oplus k) \oplus m = 0 \oplus m = m$$

Stream ciphers (single key use)

Problem: OTP key is as long the message

<u>Solution</u>: Pseudo random key – stream ciphers



$$c \leftarrow \text{PRG}(k) \oplus m$$

Dangers in using stream ciphers

One time key !! "Two time pad" is insecure:

$$\begin{cases} C_1 \leftarrow m_1 \oplus PRG(k) \\ C_2 \leftarrow m_2 \oplus PRG(k) \end{cases}$$

Eavesdropper does:

$$C_1 \oplus C_2 \quad \rightarrow \quad m_1 \oplus m_2$$

Enough redundancy in English and ASCII encoding that:

$$m_1 \oplus m_2 \rightarrow \quad m_1 , m_2$$

What is a secure cipher?

Attacker's abilities: **obtains one ciphertext** (for now)

Possible security requirements:

attempt #1: **attacker cannot recover secret key**

$$E(k,m)=m$$

Insecure: **leaks m**

attempt #2: **attacker cannot recover all of plaintext**

$$E(k,m_0 || m_1) = m_0 || E(k,m_1)$$

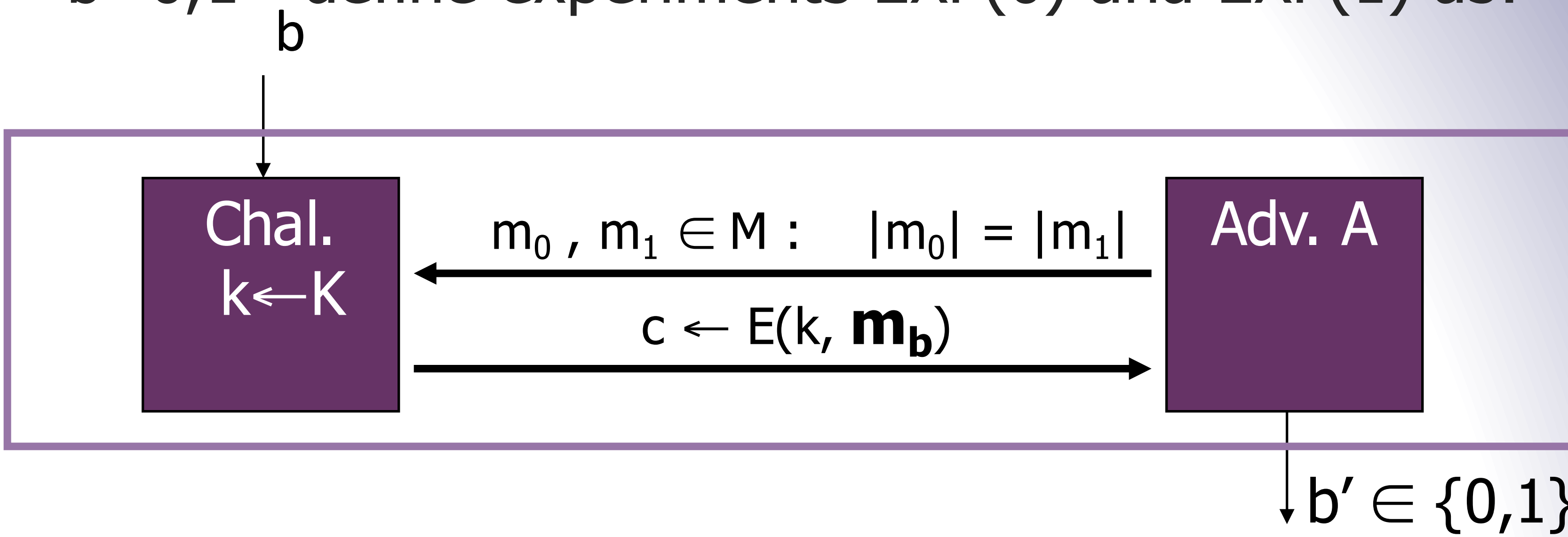
Insecure: **leaks m_0**

Shannon's information-theoretic perfect secrecy:

ciphertext should reveal no "info" about plaintext

Semantic Security (one-time key)

For b=0,1 define experiments EXP(0) and EXP(1) as:



for b=0,1: W_b := [event that EXP(b)=1]

$$\mathrm{Adv}_{SS}[A,E] := \left|\ \Pr[W_0] - \Pr[W_1]\ \right| \quad \in [0,1]$$

Sematic Security Advantage of A against E

Semantic Security (one-time key)

Def: $\mathbb{E}$ is **semantically secure** if for all efficient A

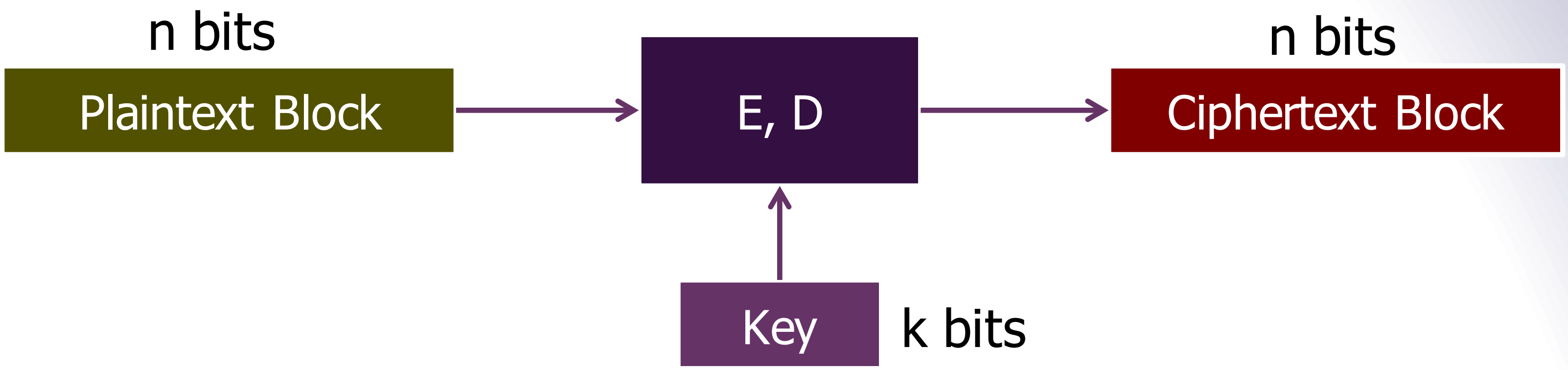
$\mathrm{Adv}_{SS}[A,\mathbb{E}]$ is negligible

Model of the attacker (also for PK)

- Chosen-ciphertext attack (CCA)
  - The attacker has access to a **decryption** oracle: he can choose ciphertexts (other than the ciphertext he is challenged with) and get their corresponding plaintext

- Chosen-plaintext attack (CPA)
  - The adversary has access to an **encryption** oracle: he can choose plaintexts and get their corresponding ciphertexts
  - More powerful than CCA

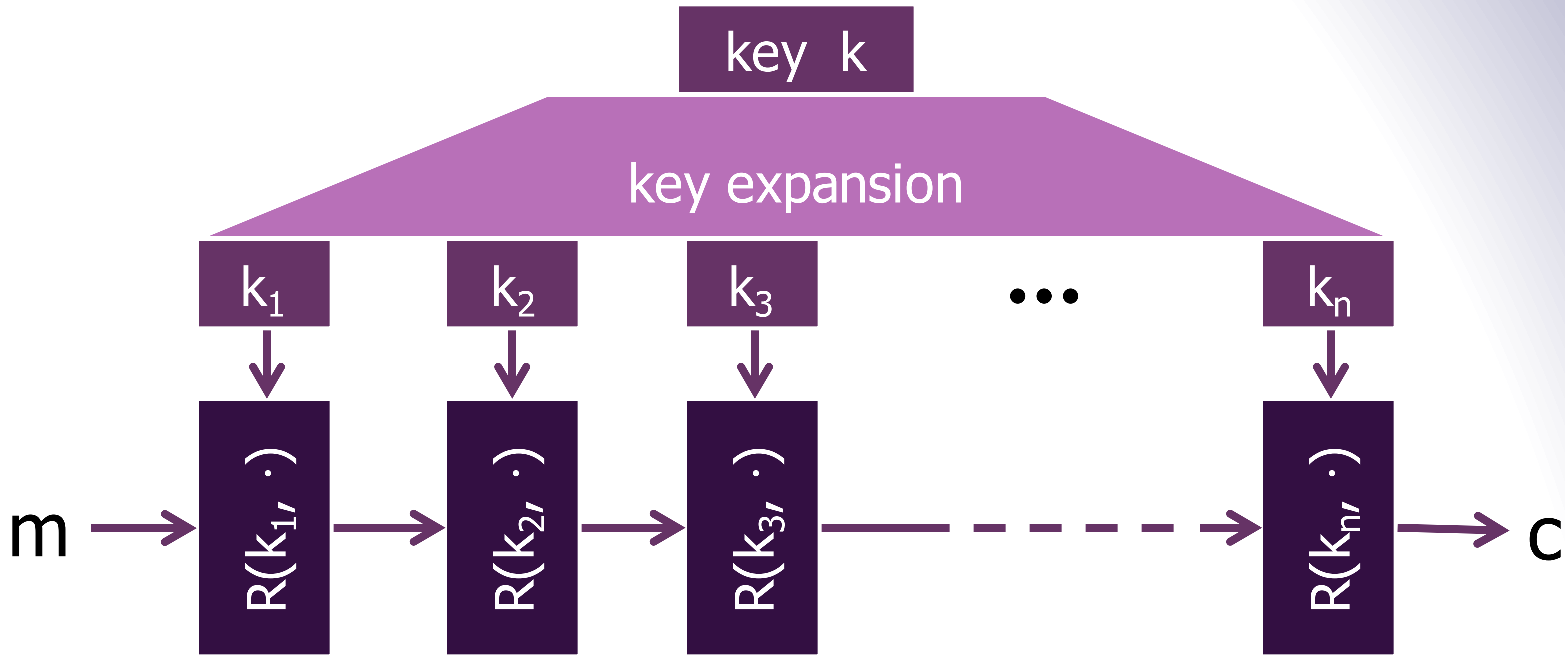
Block Ciphers



- Canonical examples:

1. 3DES: n= 64 bits, k = 168 bits
2. AES: n=128 bits, k = 128, 192, 256 bits

Block Ciphers Built by Iteration



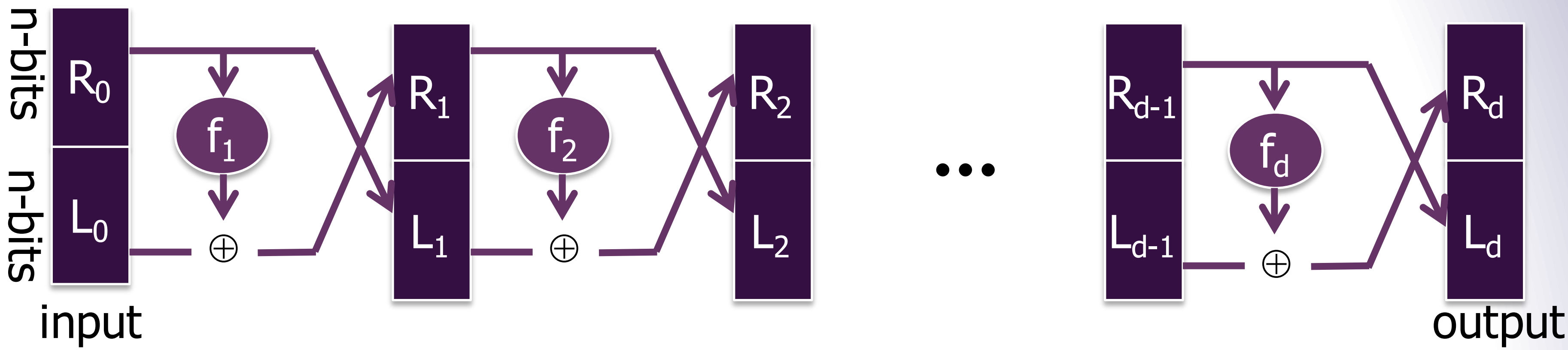
R(k,m) is called a round function

for 3DES (n=48), for AES-128 (n=10)

Block Ciphers: DES
(Feistel Network)

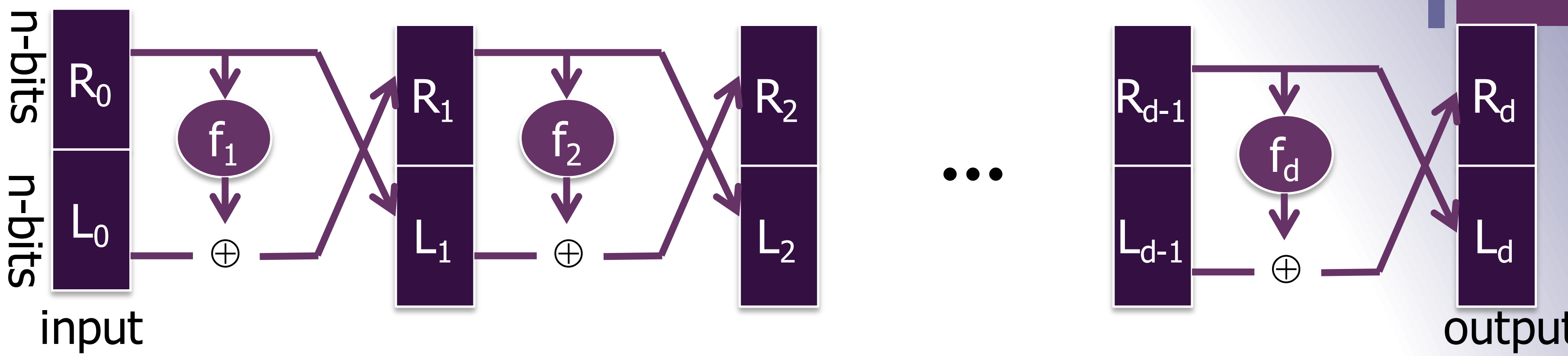
Given functions $f_1, \ldots, f_d$: $\{0,1\}^n \longrightarrow \{0,1\}^n$

Goal: build invertible function F: $\{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$



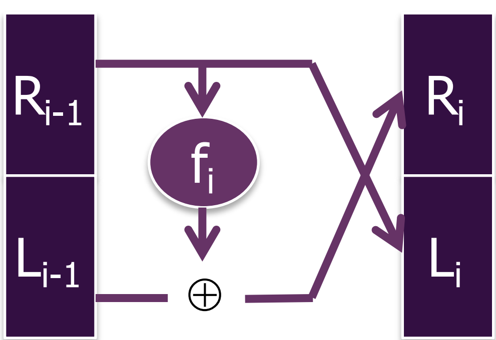
In symbols: $\begin{cases} R_i = f_i(R_{i-1}) \oplus L_{i-1} \\ L_i = R_{i-1} \end{cases}$

Feistel Network



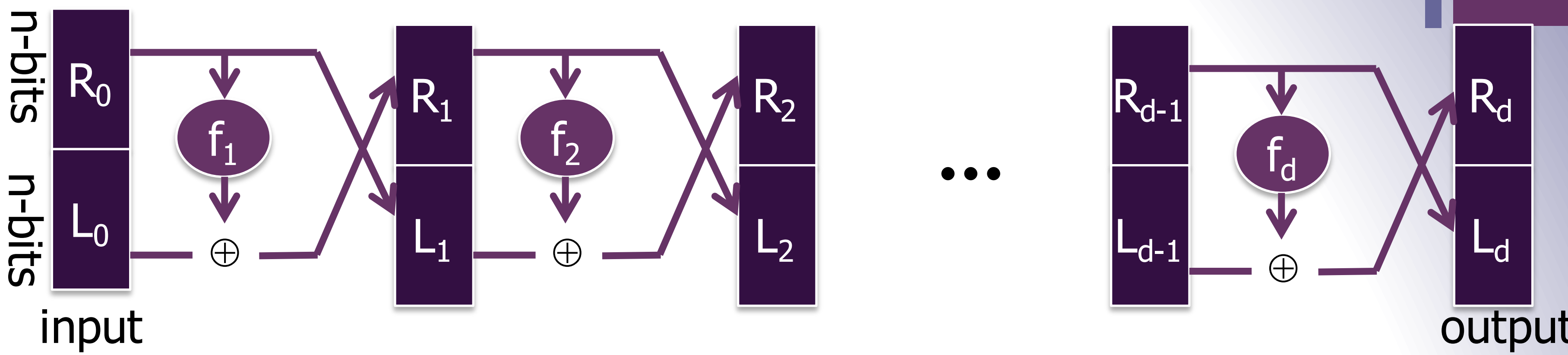
Feistel network F: $\{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$ is invertible

Construct inverse:



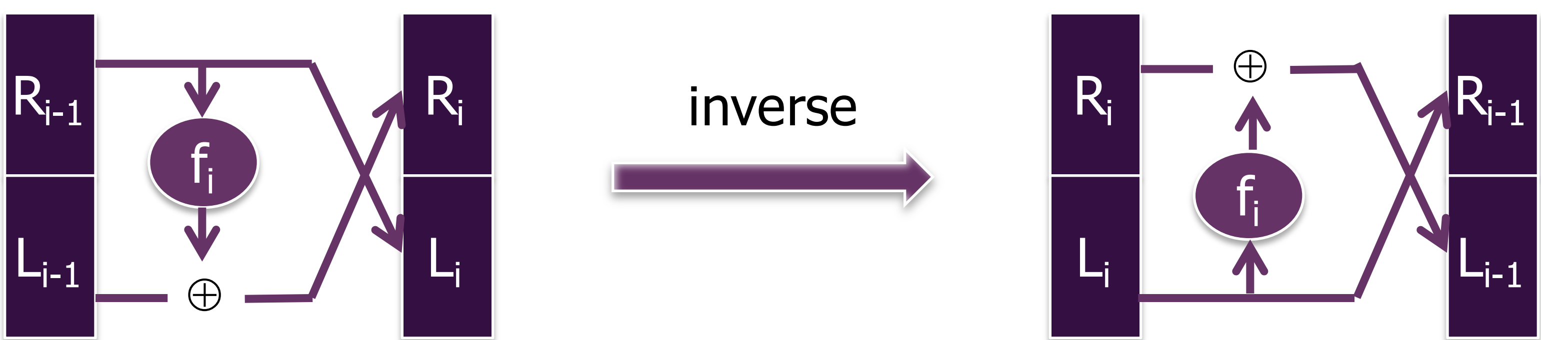
$$\begin{cases} R_{i-1} = L_i \\ L_{i-1} = \end{cases}$$

Feistel Network inverse construction

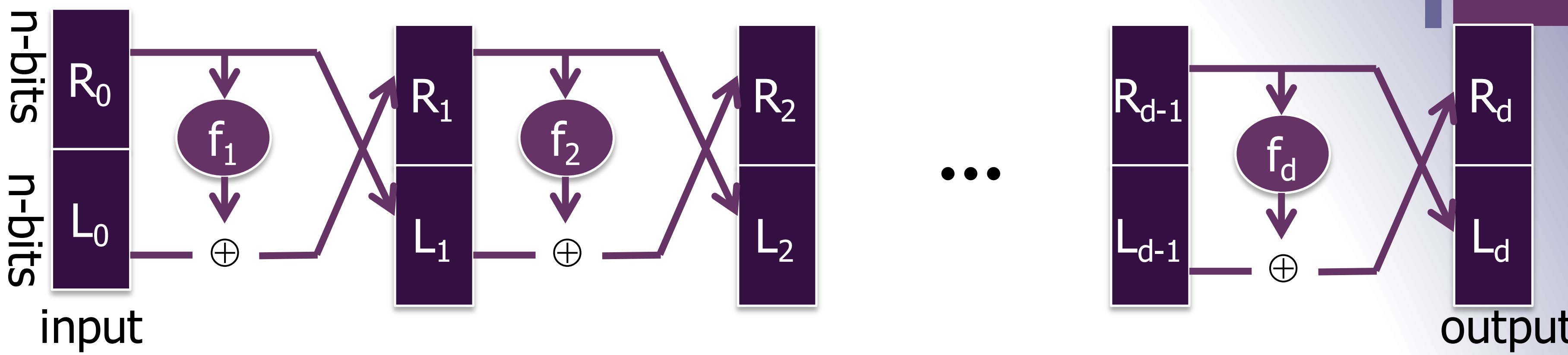


Feistel network F: $\{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$ is invertible

Construct inverse:

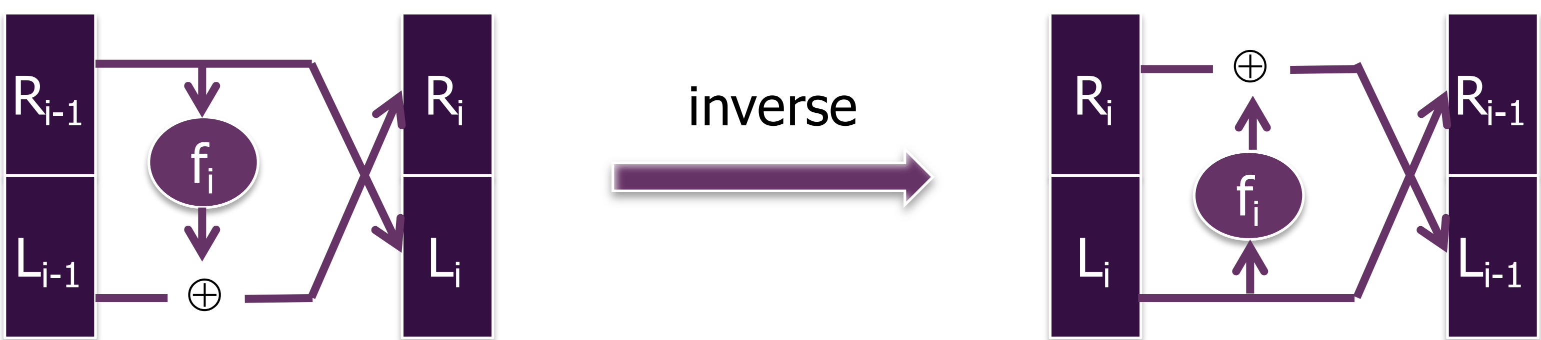


Feistel Network Decryption

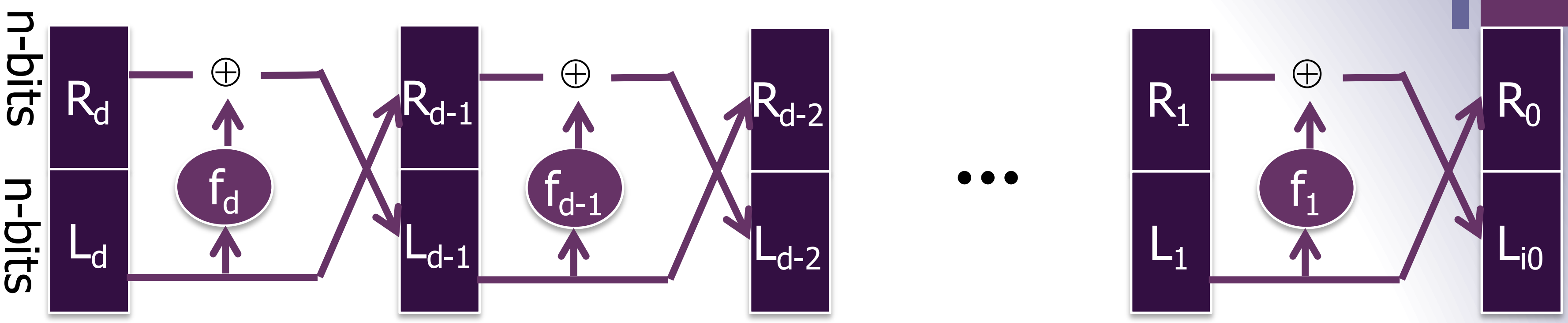


Feistel network F: $\{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$ is invertible

Construct inverse:



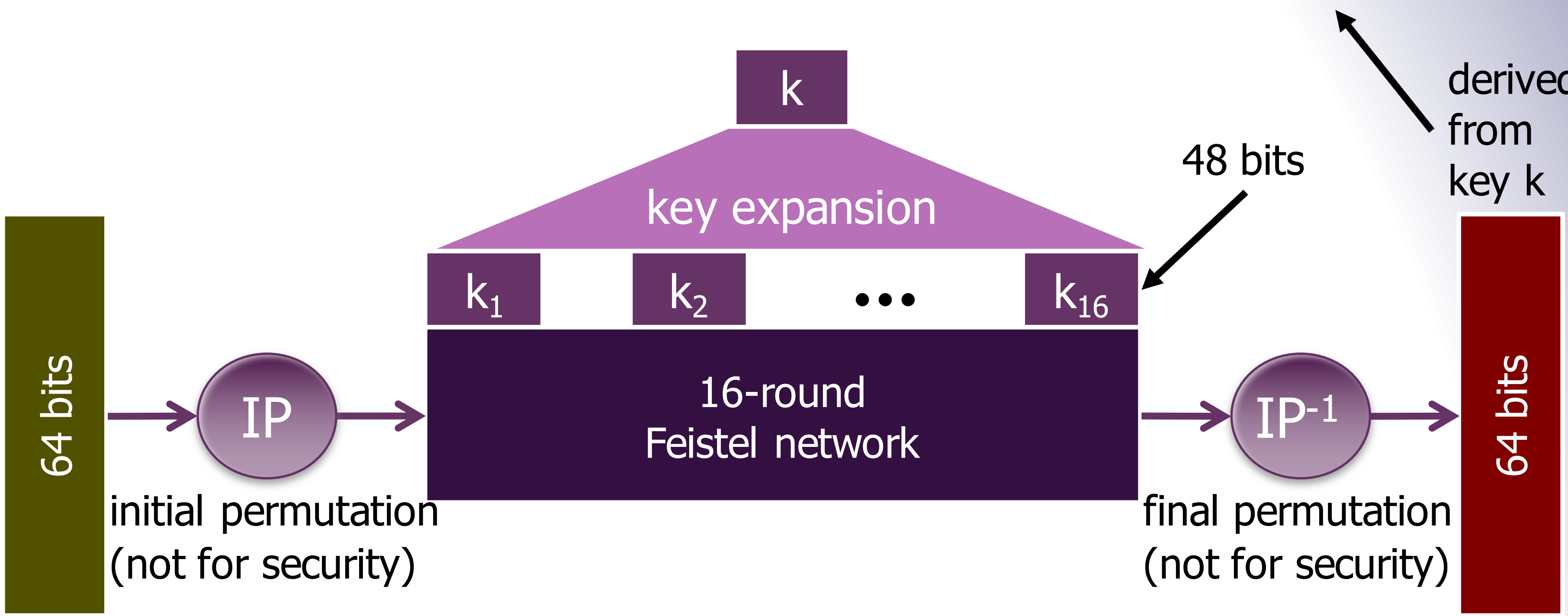
Feistel Network Decryption



- Inversion is basically the same circuit, with $f_1, \ldots, f_d$ applied in reverse order
- General method for building invertible functions (block ciphers) from arbitrary functions
- Used in many block ciphers … but not AES

DES: 16-round Feistel Network

$f_1, \ldots, f_{16}: \{0,1\}^{32} \longrightarrow \{0,1\}^{32}$, $f_i(x) = \mathbf{F}(k_i, x)$



input To invert, use keys in reverse order output

DES challenge

msg = "The unknown messages is: XXXX … "

CT = c_1 c_2 c_3 c_4 …

Goal: find $k \in \{0,1\}^{56}$ s.t. $DES(k, m_i) = c_i$ for $i=1,2,3$

1997: Internet search -- **3 months**

1998: EFF machine (deep crack) -- **3 days** (250K $)

1999: combined search -- **22 hours**

2006: COPACOBANA (120 FPGAs) **-- 7 days** (10K $)

$\Rightarrow$ 56-bit ciphers should not be used !! (128-bit key $\Rightarrow$ 2^{72} days)

Triple-DES

Strengthening DES against exhaustive search

- Let $E : K \times M \longrightarrow M$ be a block cipher
- Define **3E**: $K^3 \times M \longrightarrow M$ as

$$\mathbf{3E}\big(\ (k_1,k_2,k_3),\ m\big) = E(k_1,\ D(k_2,\ E(k_3,\ m)))$$

$k_1 = k_2 = k_3$
=> single DES

For 3DES: key-size = 3×56 = 168 bits.
3×slower than DES.

Advanced Encryption Standard (AES)

- National Institute of Standards & Technology NIST
  - Computer Security Research Center (CSRC)
  - http://csrc.nist.gov/
- Uses the Rijndael algorithm
  - Invented by Belgian researchers
    Dr. Joan Daemen & Dr. Vincent Rijmen
  - http://jda.noekeon.org/JDA_VRI_Rijndael_V2_1999.pdf
  - Adopted May 26, 2002
  - Key length: 128, 192, or 256 bits
  - Block size: 128 bits
    - If DES could be broken in 1 second, then AES would require 149 trillion years to be broken

Performance

Crypto++ 5.6.0 [Wei Dai]

AMD Opteron, 2.2 GHz (Linux)

	Cipher	Block/key size	Speed (MB/sec)
stream	RC4		126
	Salsa20/12		643
	Sosemanuk		727
block	3DES	64/168	13
	AES-128	128/128	109

Problems with Shared Key Crypto

- Compromised key means interceptors can decrypt any ciphertext they've acquired
  - Change keys frequently to limit damage
- Distribution of keys is problematic
  - Keys must be transmitted securely
  - Use couriers?
  - Distribute in pieces over separate channels?

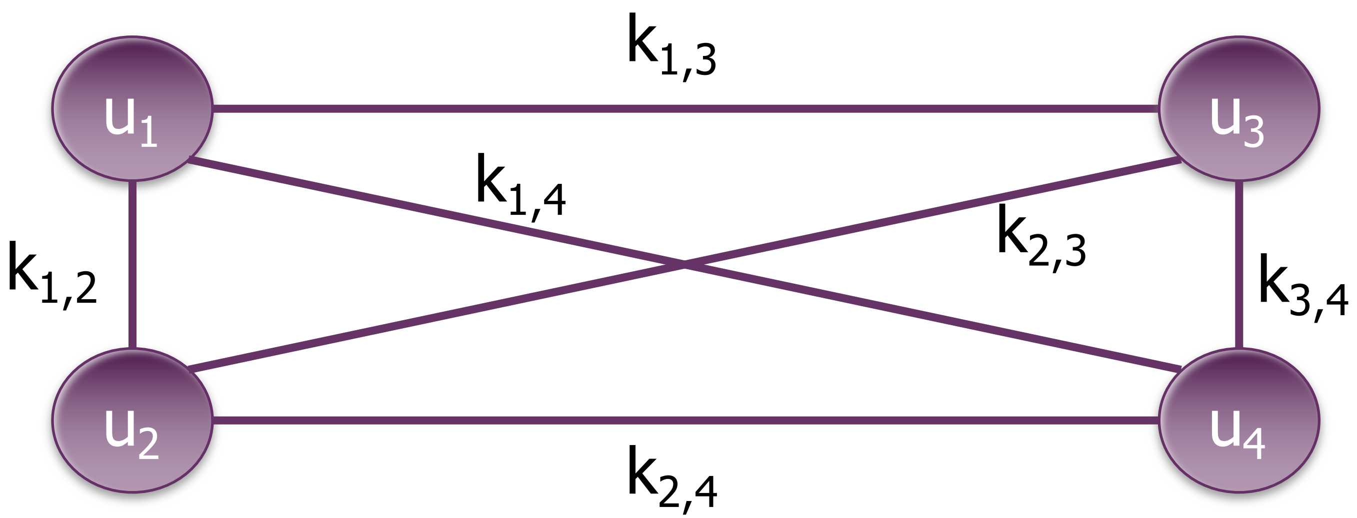
Trusted 3rd Parties

Basic key exchange

Key Management

Problem: n users

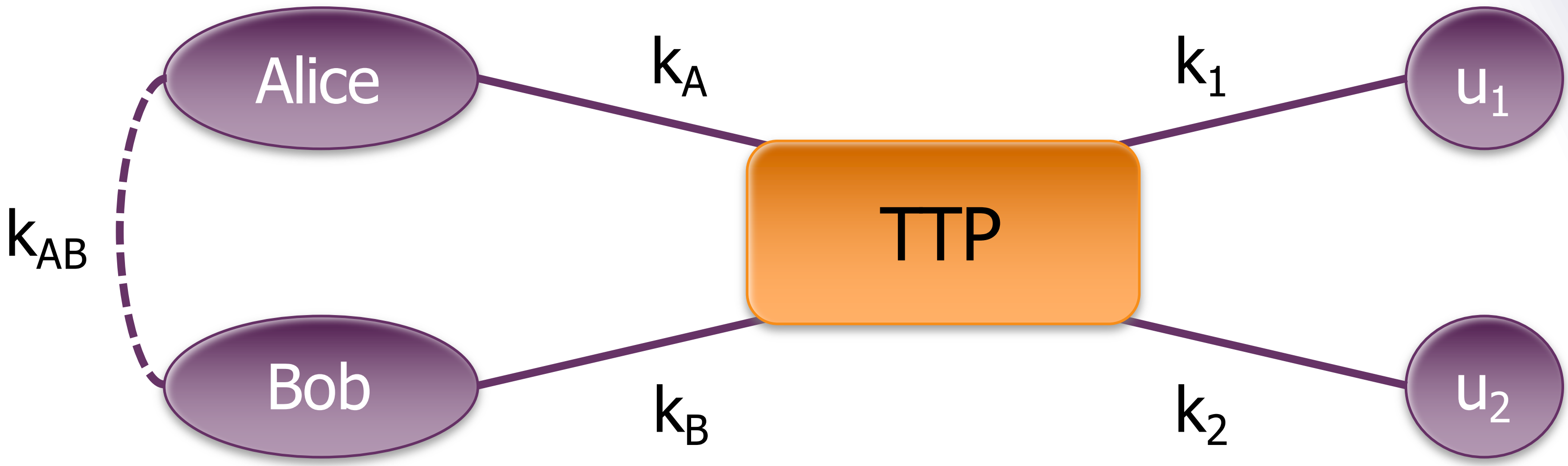
- Storing mutual secret keys is difficult



Total: $O(n)$ keys per user ; $O(n^2)$ keys in the system

A better solution

- Onlined Trusted 3rd Party (TTP)



- Every user only remembers one key

Generating keys: a toy protocol

Alice wants a shared key with Bob

- Eavesdropping security only

Bob (k_B) **Alice (k_A)** **TTP**

"Alice wants key with Bob"

choose random k_{AB}

$E(k_A, \text{"A,B"} \mid\mid K_{AB})$

$\text{ticket} \leftarrow E(k_B, \text{"A,B"} \mid\mid K_{AB})$

ticket

k_{AB} k_{AB}

(E,D) a CPA-secure cipher: attacker cannot distinguish between an encrypted value and a random one

Generating keys: a toy protocol

Alice wants a shared key with Bob

- Eavesdropping security only

Eavesdropper sees:

$E(k_A, \text{"A, B"} \mid\mid k_{AB})$; $E(k_B, \text{"A, B"} \mid\mid k_{AB})$

(E,D) is CPA-secure $\Rightarrow$
eavesdropper learns nothing about k_{AB}

- TTP needed for every key exchange, knows all session keys
- In a corporate environment might make sense
  - Example: Kerberos system

Toy protocol: insecure against active attacks

Example: insecure against replay attacks

Attacker records session between Alice and Bob

- For example a book order

Attacker replays session to Bob

- Bob thinks Alice is ordering another copy of book

Key question

Can we generate shared keys without an **online** TTP?

Answer: yes!

Starting point of public-key cryptography:

- Merkle (1974), Diffie-Hellman (1976), RSA (1977)

- Further references:

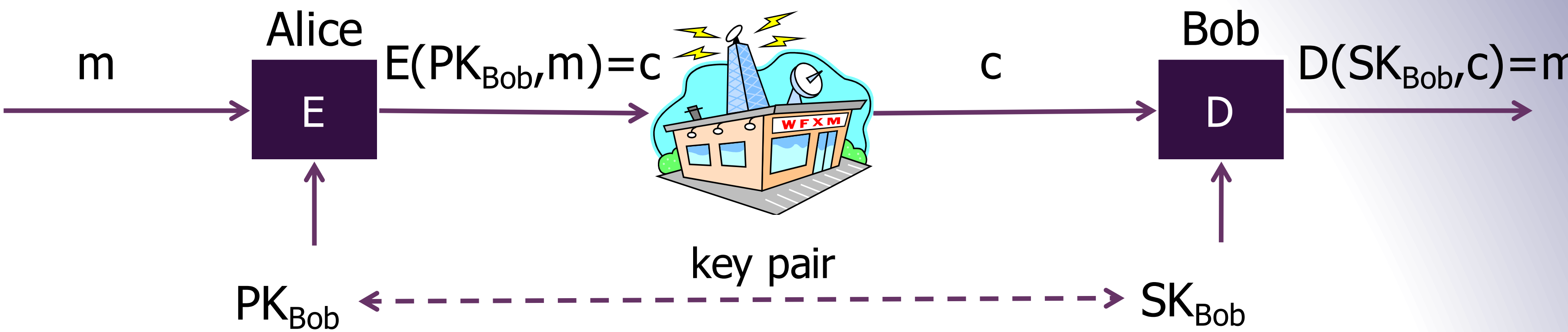
  - More recently: ID-based enc. (BF 2001), Functional enc. (BSW 2011)

Public key cryptography

Asymmetric or Public Key Crypto

- Sender encrypts using a ***public*** key
- Receiver decrypts using a ***private*** key
- Only the private key must be kept secret!
  - Public key can be distributed at will
- Constructions generally rely on hard problems from number theory or algebra (e.g., FACT)
- Can be used for digital signatures
- Examples: RSA, El Gamal, DSA

Public Key Encryption



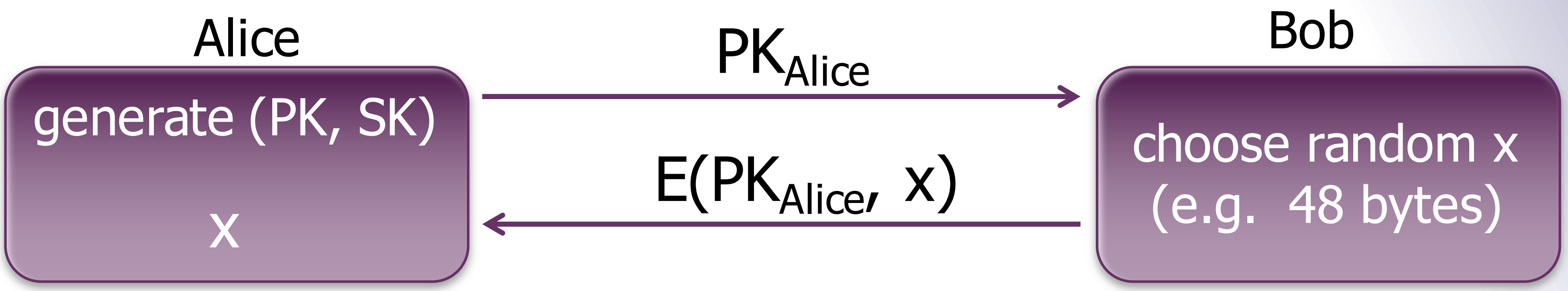
PK: public key , SK: secret key (e.g., 1024 bits)

Example: Bob generates (PK_{Bob}, SK_{Bob}) and gives PK_{Bob} to Alice

- Sometimes E is the same algorithm as D
- Fast in software or hardware implementations

Applications

Session setup (for now, only eavesdropping security)



Non-interactive applications: (e.g., Email)

- Bob sends email to Alice encrypted using PK_{Alice}
- Note: Bob needs PK_{Alice} (public key management)

Public Key Encryption

Def: a public-key cryptosys. is a triple of algs. (G, E, D)

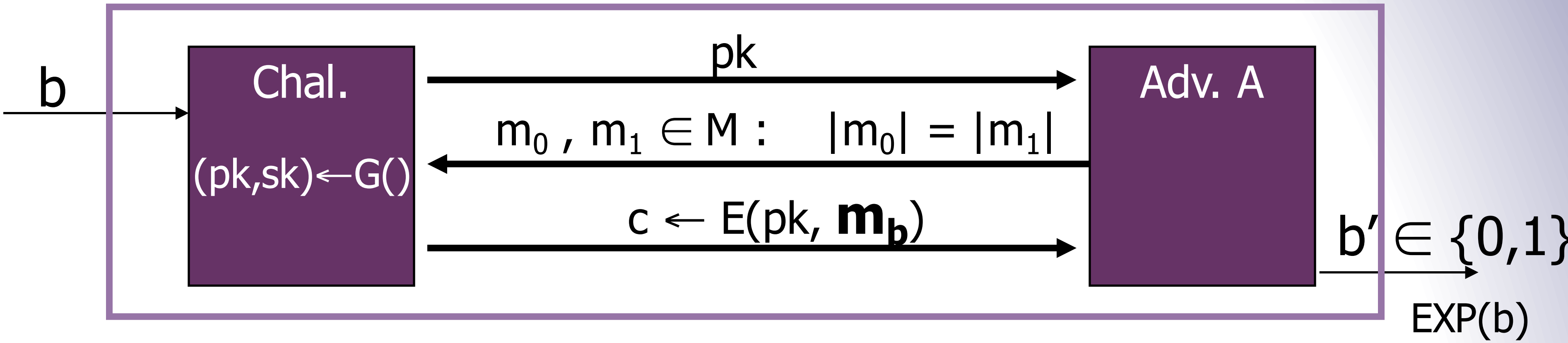
- $G()$: randomized alg. outputs a key pair (PK, SK)
- $E(PK, m)$: randomized alg. that takes $m \in M$ and outputs $c \in C$
- $D(SK, c)$: deterministic alg. that takes $c \in C$ and outputs $m \in M$ or $\perp$

Consistency: $\forall (PK, SK)$ output by G :

$$\forall m \in M: \quad D(SK, \; E(PK, m) \,) = m$$

Semantic Security

For $b=0,1$ define experiments EXP(0) and EXP(1) as:



Def: $\mathbb{E}=(G,E,D)$ is sem. secure if for all efficient A:

$$\mathrm{Adv}_{SS}[A,\mathbb{E}] = \left| \Pr[\mathrm{EXP}(0)=1] - \Pr[\mathrm{EXP}(1)=1] \right| < \text{negligible}$$

Establishing a shared secret

Alice **Bob**

(pk, sk) $\leftarrow$ G()

"Alice", pk $\longrightarrow$

choose random $x \in \{0,1\}^{128}$

$\longleftarrow$ "Bob", c$\leftarrow$E(pk,x)

D(sk,c) $\rightarrow$ x

x shared secret

Security (eavesdropping)

Adversary sees **pk, E(pk, x)** and wants **x** $\in M$

Semantic security $\Rightarrow$

adversary cannot distinguish

$\{$ pk, E(pk, x), x $\}$ from $\{$ pk, E(pk, x), rand $\in M$ $\}$

$\Rightarrow$ can derive session key from x

Note: protocol is vulnerable to man-in-the-middle

Insecure against man in the middle

The protocol is insecure against **active** attacks

Alice | **MiTM** | **Bob**

$(pk, sk) \leftarrow G()$

$(pk', sk') \leftarrow G()$

$\xrightarrow{\text{"Alice", } pk}$ ||

|| $\xrightarrow{\textbf{"Alice", } \boldsymbol{pk'}}$

choose random

$x \in \{0,1\}^{128}$

|| $\xleftarrow{\text{"Bob", } E(pk', x)}$

$x \leftarrow D(sk', E(pk', x))$

$\xleftarrow{\textbf{"Bob", } \boldsymbol{E(pk, x)}}$ ||

Trade-offs for Public Key Crypto

- More computationally expensive than symmetric (shared) key crypto
  - Algorithms are harder to implement
  - Require more complex machinery
- More formal justification of difficulty
  - Hardness based on complexity-theoretic results
- A principal needs 1 private key and 1 public key
  - Number of keys for pair-wise communication is O(n)

RSA Algorithm

- Ron Rivest, Adi Shamir, Leonard Adleman
  - Proposed in 1979
  - They won the 2002 Turing award for this work
- Has withstood years of cryptanalysis
  - Not a guarantee of security!
  - But a strong vote of confidence
    - Further reading: Twenty years of attacks on the RSA cryptosystem, D. Boneh, Notices of the AMS, 1999
- Hardware implementations:
  - 1000 x slower than DES

RSA at a High Level

- Public and private key are derived from secret prime numbers
  - Today at least 1024 bits to ensure security (4096 bits is better)
- Plaintext message (a sequence of bits)
  - Treated as a (large!) binary number
- Encryption is modular exponentiation
- To break the encryption, conjectured that one must be able to factor large numbers
  - Not known to be in P (polynomial time algorithms)

Crypto hash functions

Hash Algorithms

- Take a variable length string
- Produce a fixed length digest

$$h:\{0,1\}^* \xrightarrow{\text{hash}} \{0,1\}^n$$

- (Non-cryptographic) Examples:
  - Parity (or byte-wise XOR)
  - CRC
- Realistic Example:
  - The NIST Secure Hash Algorithm (SHA) takes a message of less than 2^{64} bits and produces a digest of 160 bits

Cryptographic Hashes

- Create a hard-to-invert summary of input data
- Like a check-sum or error detection code
  - Uses a cryptographic algorithm internally
  - More expensive to compute
- Sometimes called a Message Digest
- Examples:
  - Secure Hash Algorithm (SHA)
  - Message Digest (MD4, MD5)

Desired Properties

- One way hash function
  - Given a hash value y, it should be infeasible to find m s.t. $\mathrm{h}(m)=y$
- Collision resistance
  - It should be infeasible to find two different messages m_1 and m_2 s.t. $\mathrm{h}(m_1)=\mathrm{h}(m_2)$
- Random oracle property
  - $\mathrm{h}(m)$ is indistinguishable from a random n-bit value
  - Attacker must spend a lot of effort to be able to modify the message without altering the hash value

Any questions?