Cryptography 1

INGI2347: COMPUTER SYSTEM SECURITY (Spring 2015)

Marco Canini

UCL
Université catholique de Louvain

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

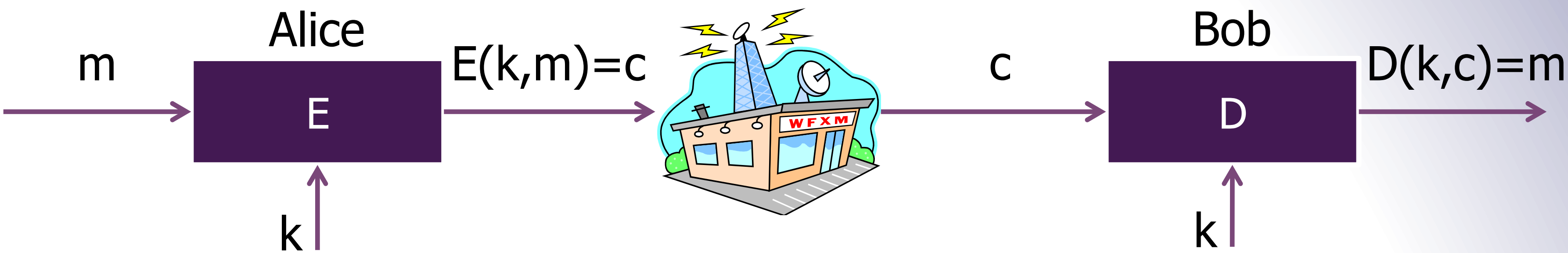
κρυπτο γραφη (Cryptography)

- 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-repudation
  - Convince a 3rd party that what was said is accurate

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

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

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

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

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

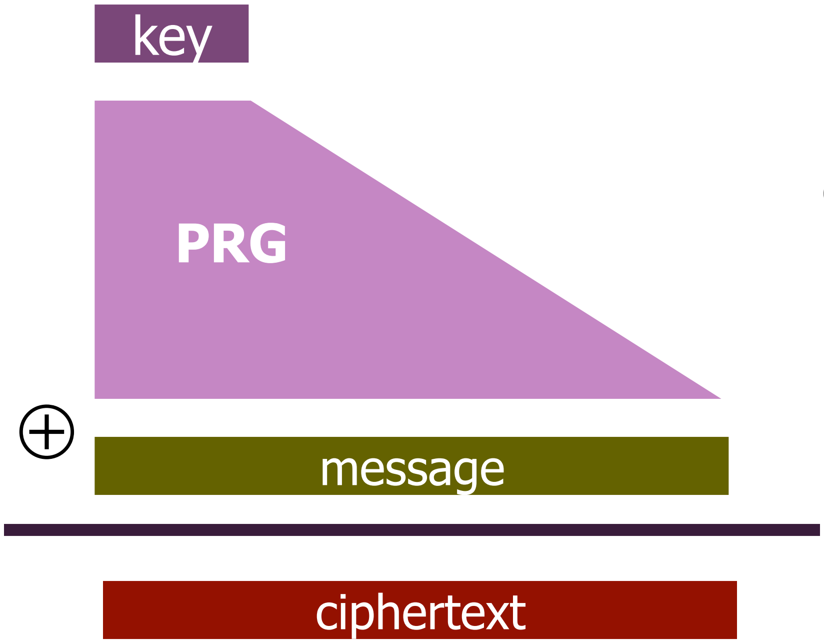
Indeed:

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

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**

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

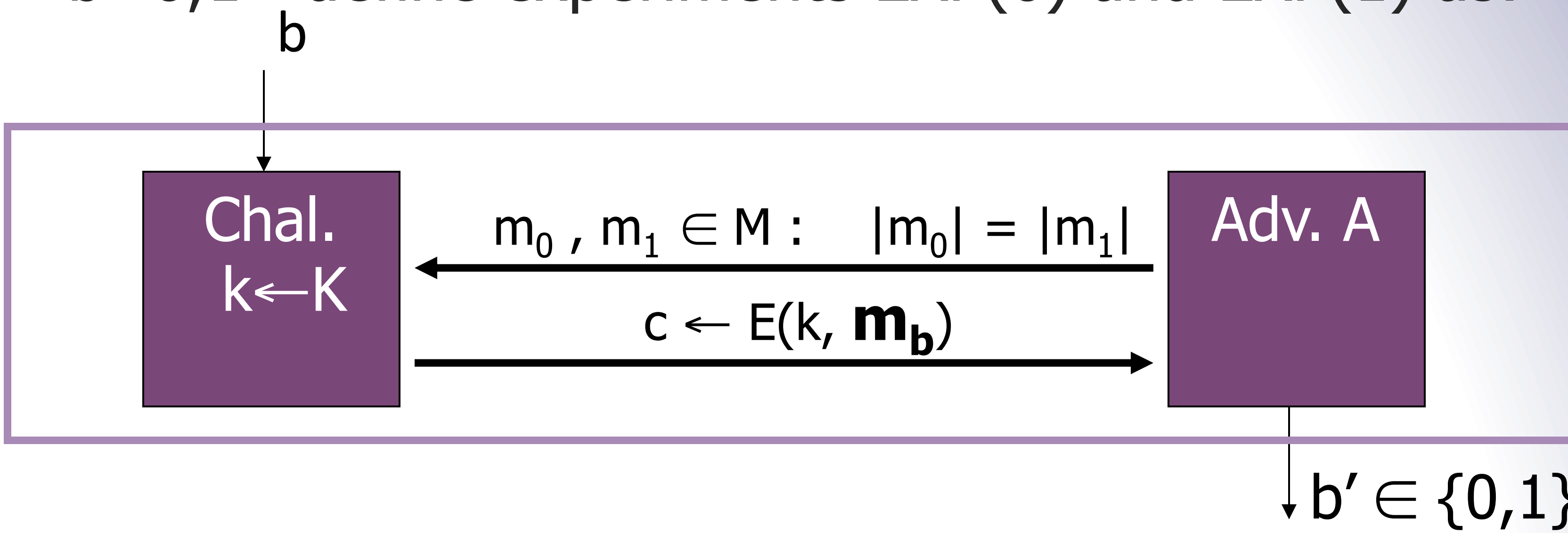
Insecure: **leaks m_0**

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]

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

Sematic Security Advantage of A against E

Semantic Security (one-time key)

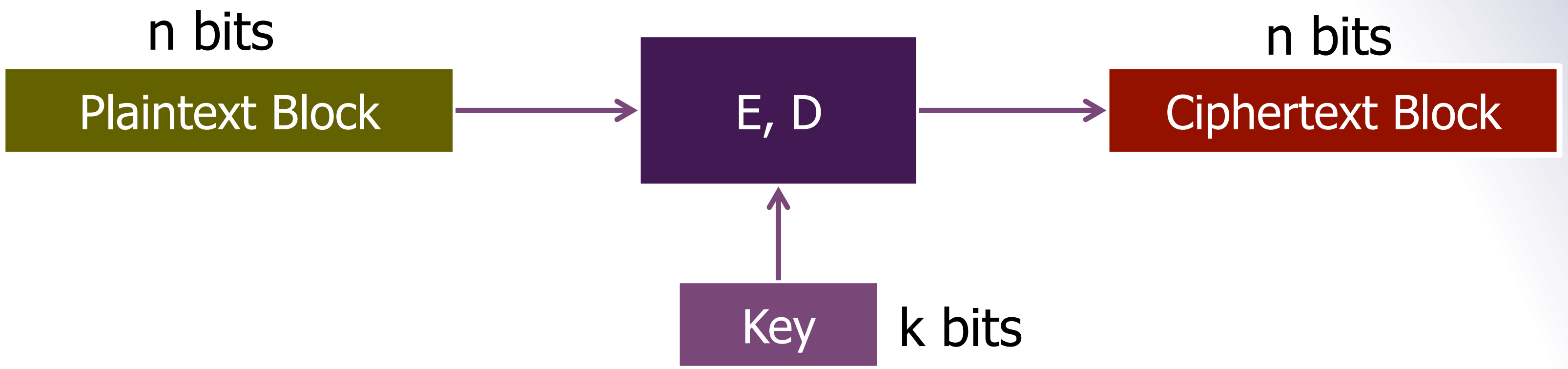
Def: E is **semantically secure** if for all efficient A

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

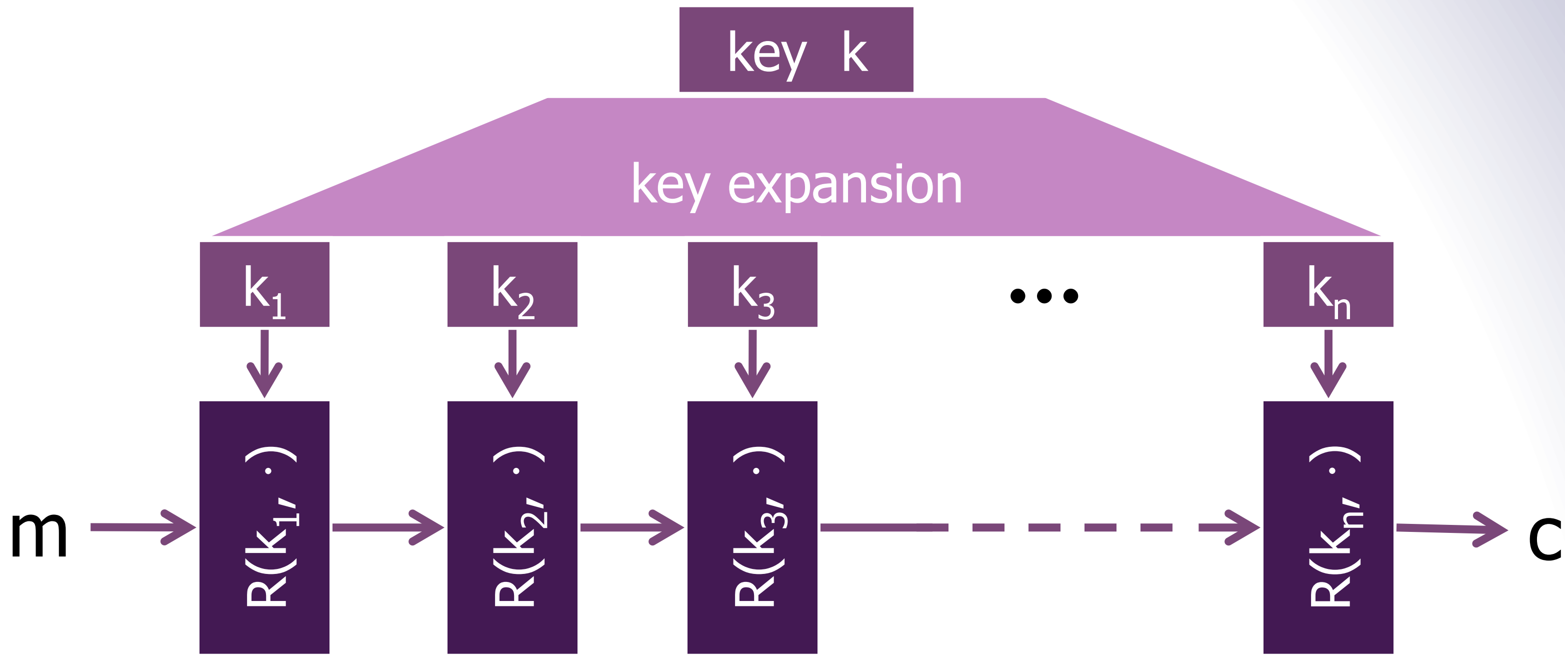
Block Ciphers



- 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



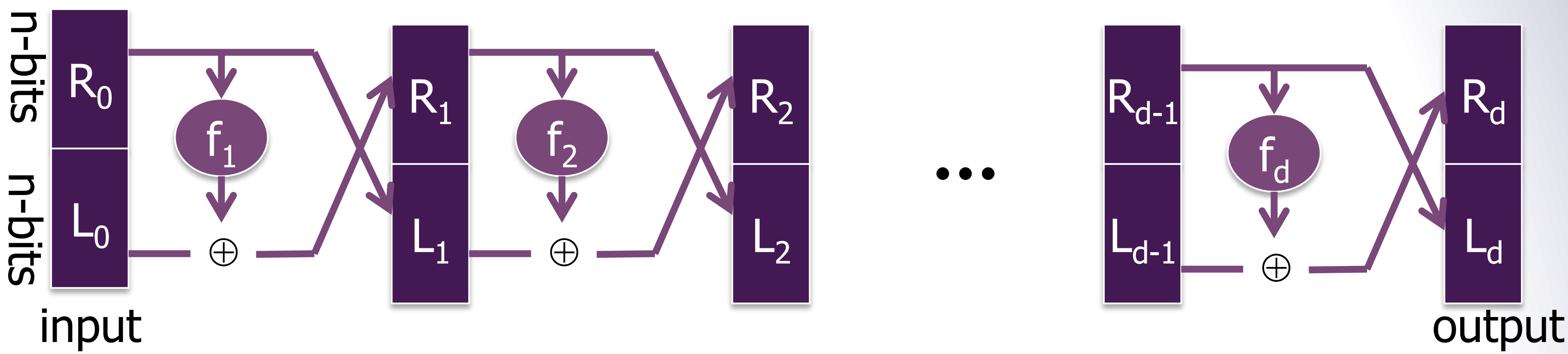
R(k,m) is called a round function

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

Block Ciphers: DES
(Feistel Network)

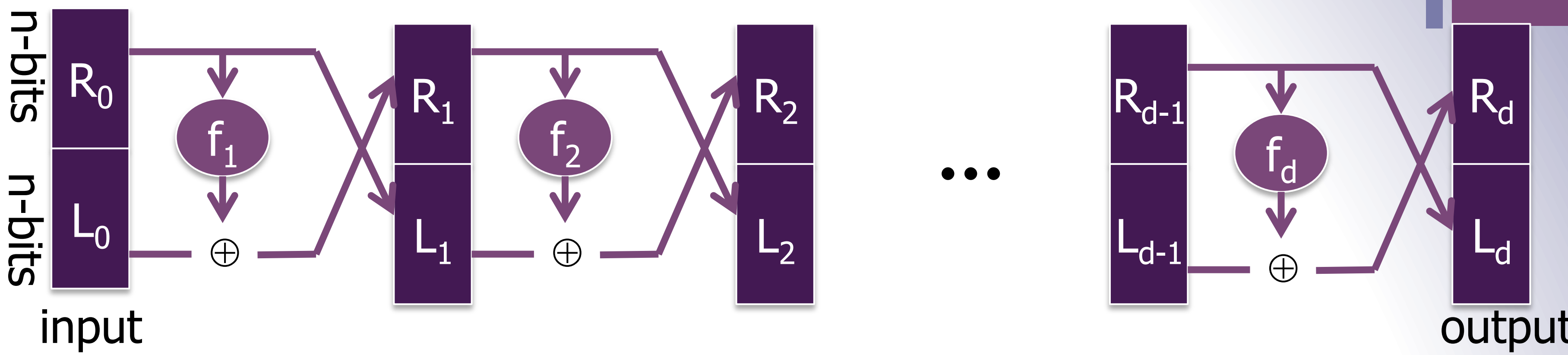
Given functions $f_1, \ldots, f_d$: $\{0,1\}^n \longrightarrow \{0,1\}^n$

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



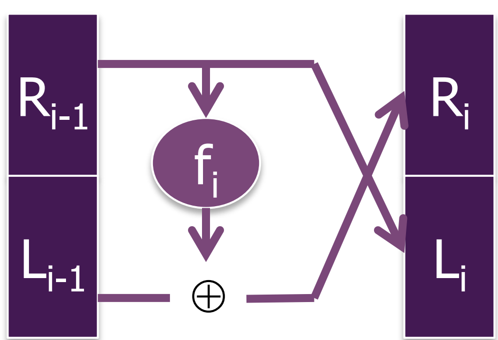
In symbols:
$$\begin{cases} R_i = f_i(R_{i-1}) \oplus L_{i-1} \\ L_i = R_{i-1} \end{cases}$$

Feistel Network



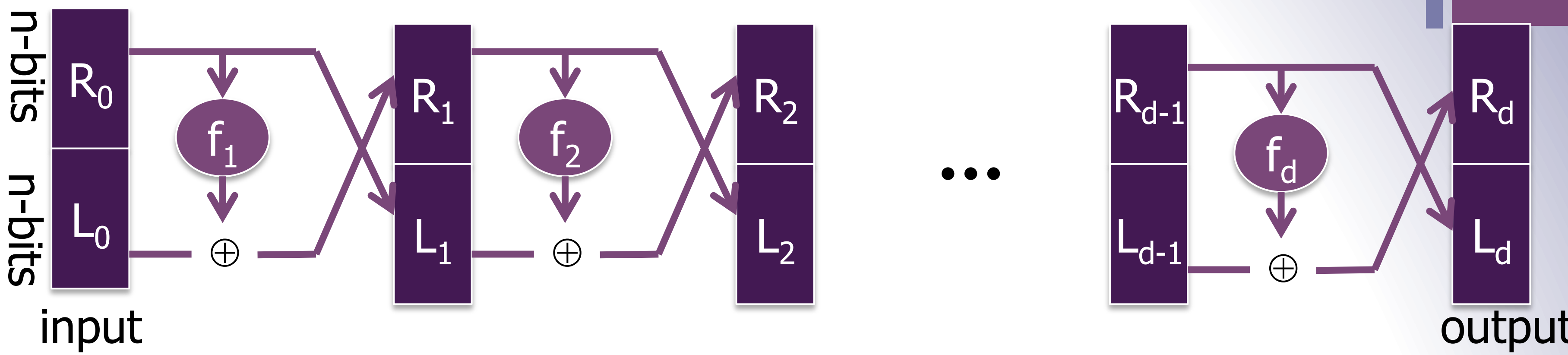
Feistel network $F: \{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$ is invertible

Construct inverse:



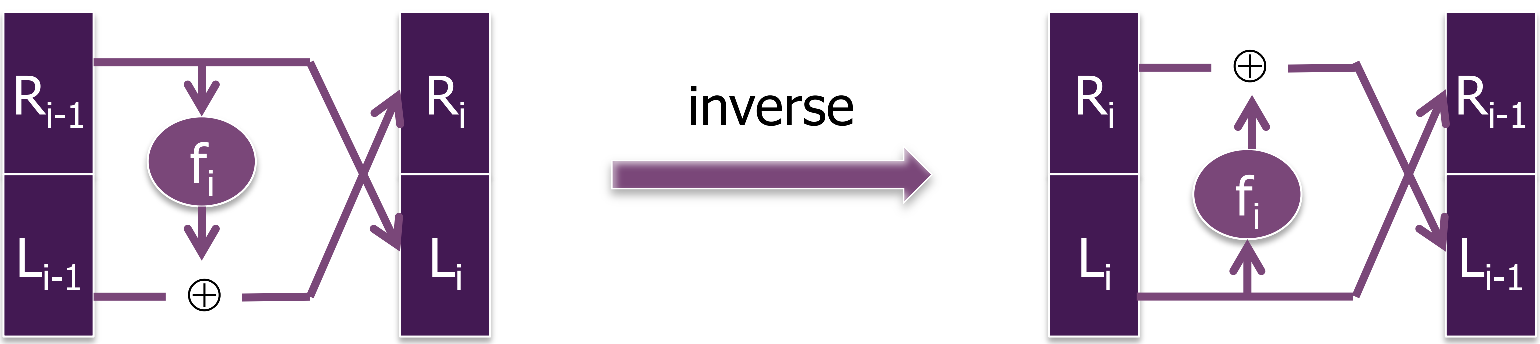
$$\begin{cases} R_{i-1} = L_i \\ L_{i-1} = \end{cases}$$

Feistel Network inverse construction

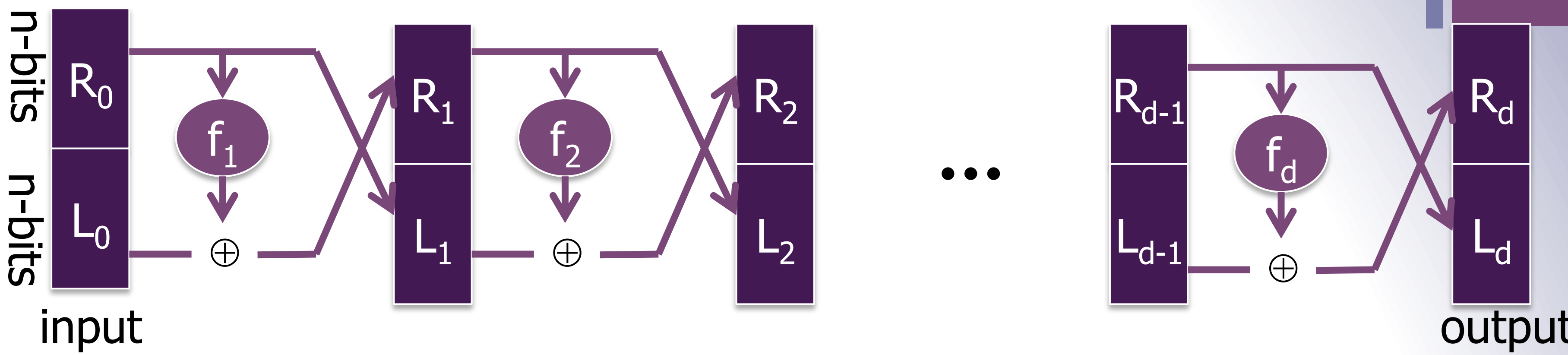


Feistel network F: $\{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$ is invertible

Construct inverse:

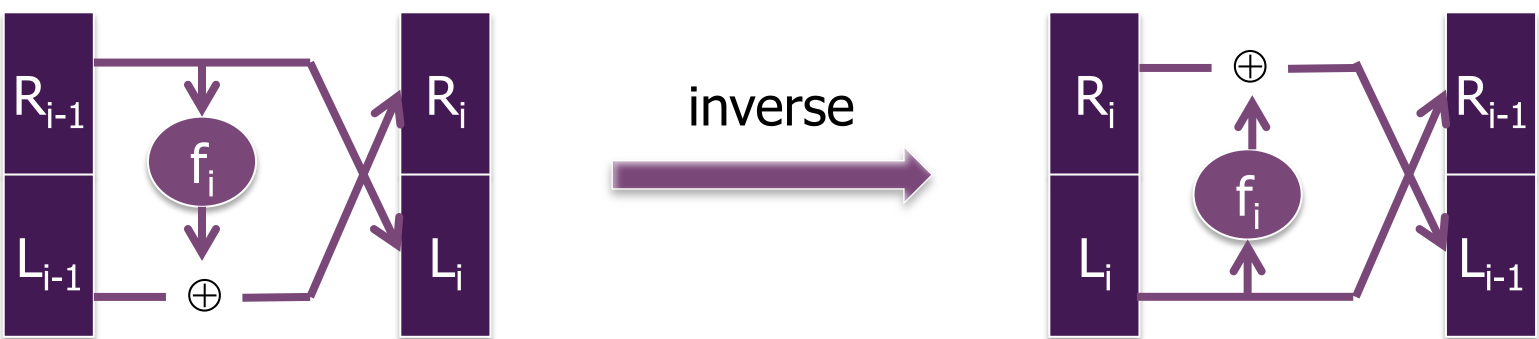


Feistel Network Decryption

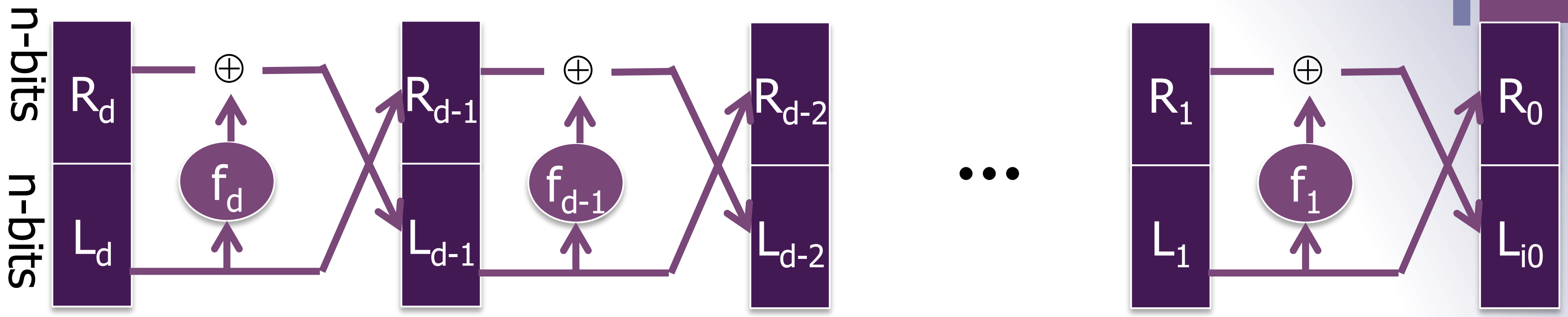


Feistel network F: $\{0,1\}^{2n} \longrightarrow \{0,1\}^{2n}$ is invertible

Construct inverse:



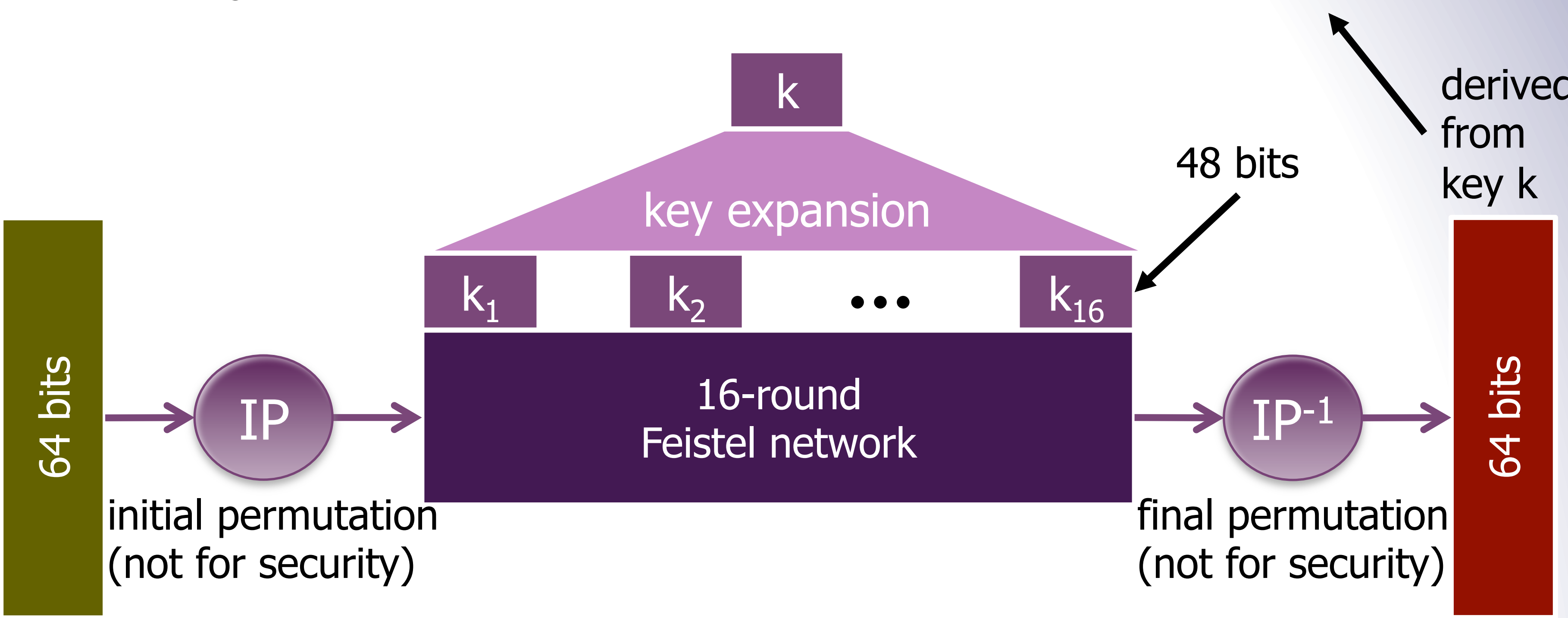
Feistel Network Decryption



- Inversion is basically the same circuit,
  with f_1, …, 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 $)

⇒ 56-bit ciphers should not be used !! (128-bit key ⇒ 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?

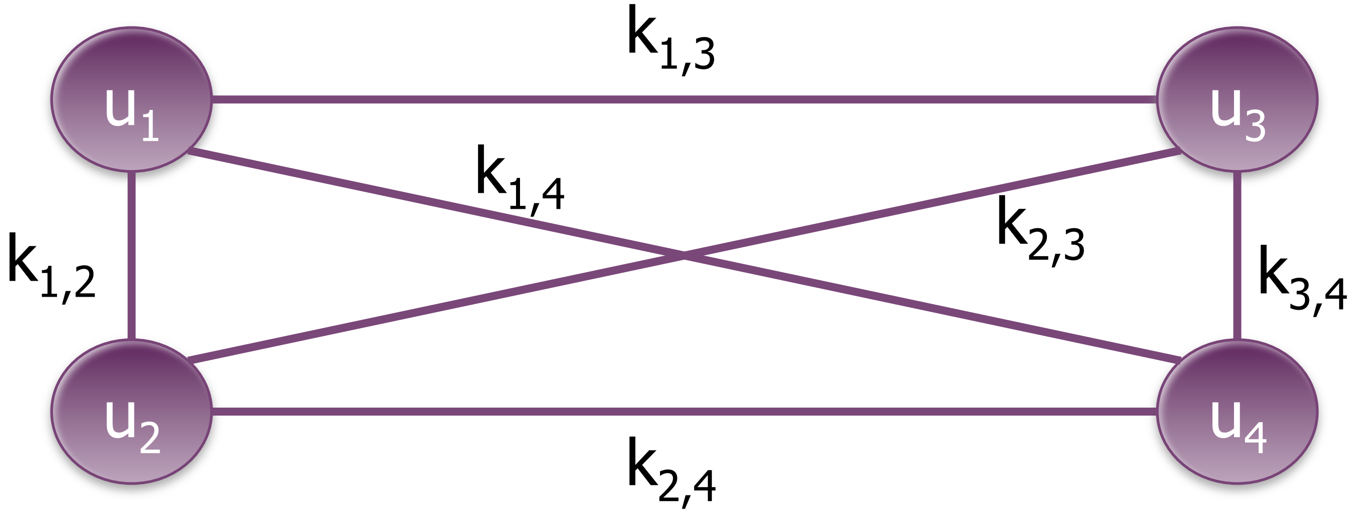
Trusted 3rd Parties

Basic key exchange

Key Management

Problem: n users

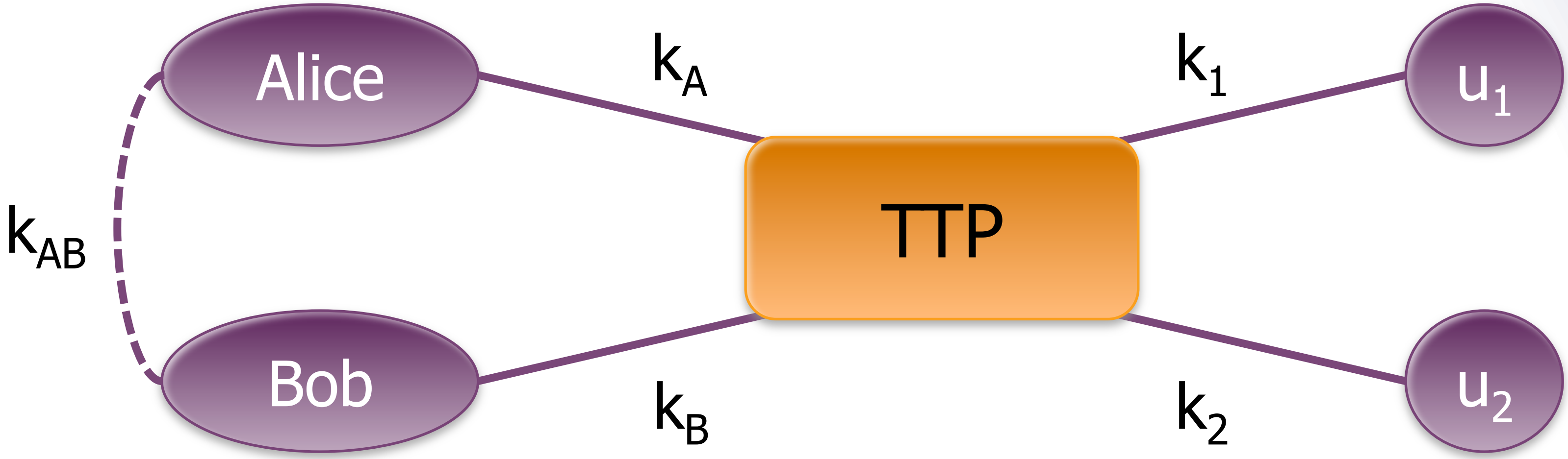
- Storing mutual secret keys is difficult



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}

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

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

← 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:

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

(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 merchant 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:

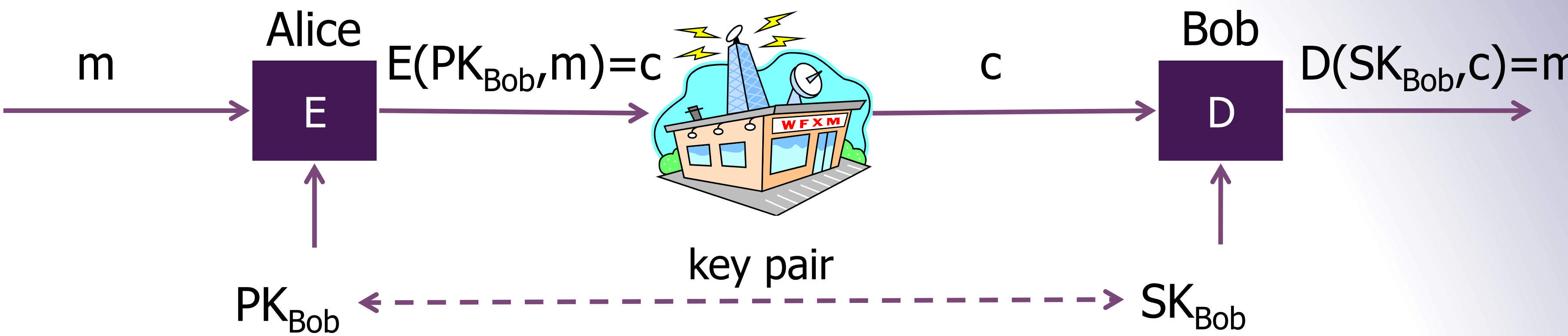
  - More recently: ID-based enc. (BF 2001), Functional enc. (BSW 2011)

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



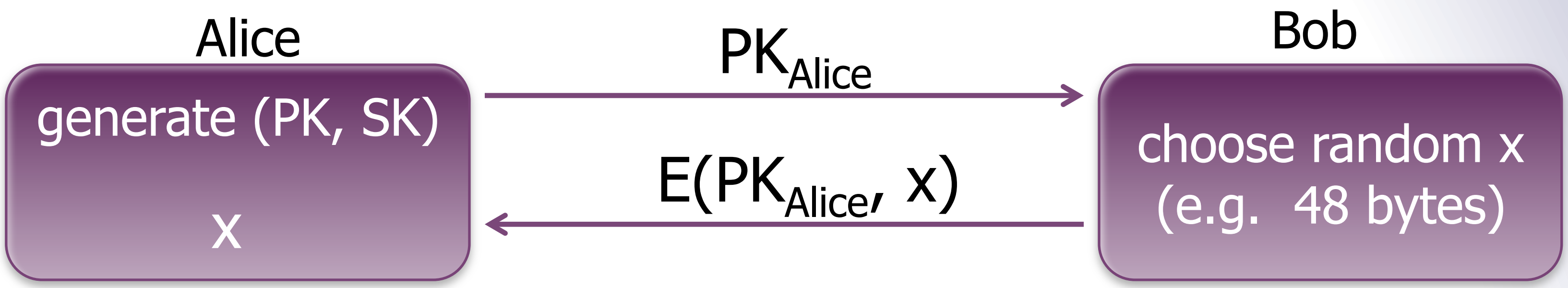
PK: public key , SK: secret key (e.g., 1024 bits)

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)

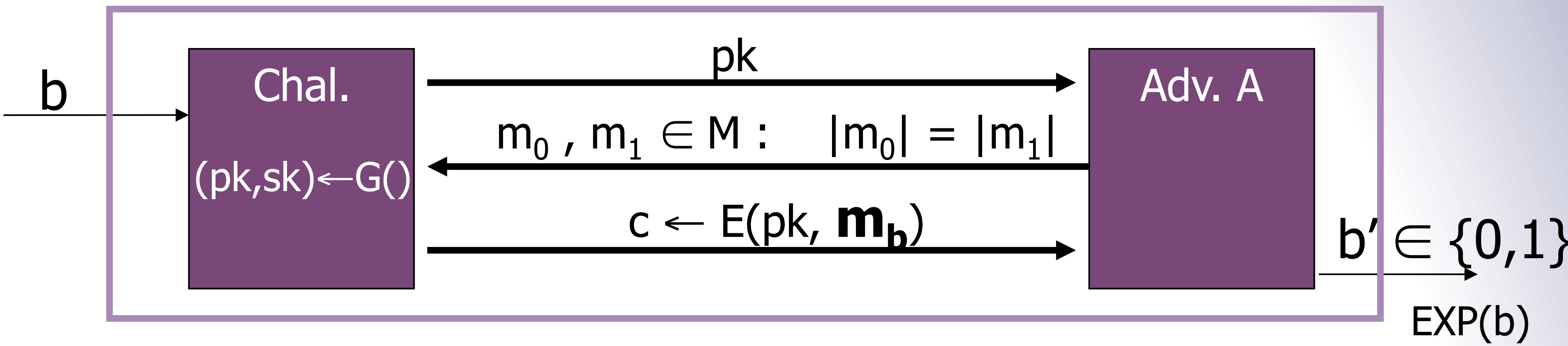
- $G()$: randomized alg. outputs a key pair (PK, SK)
- $E(PK, m)$: randomized alg. that takes $m \in M$ and outputs $c \in C$
- $D(SK, c)$: deterministic alg. that takes $c \in C$ and outputs $m \in M$ or $\perp$

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: E =(G,E,D) is sem. secure if for all efficient A:

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

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 ⇒

adversary cannot distinguish

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

⇒ 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()	
"Alice", pk $\rightarrow$	|| **"Alice", pk′** $\rightarrow$	
		choose random $x \in \{0,1\}^{128}$
	|| $\leftarrow$ "Bob", E(pk′, x)	
	x $\leftarrow$ D(sk′, E(pk′, x))	
$\leftarrow$ **"Bob", 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?