Cryptography

A historical moment ...

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The *enigma* machine was used to secure communication of german military throughout the second world war ...

... and it changed the course of human history.

Intuition

- Cryptography is the art (and sometimes science) of secret writing
  - Less well know is that it is also used to guarantee other properties, e.g., authenticity of data
  - This is an enormously deep and important field
  - However, much of our trust in these systems is based on faith (particularly in efficient secret key algorithms)
- *Cryptographers* create ciphers - Cryptography
- *Cryptanalyst* break ciphers - Cryptanalysis

The history of cryptography is an arms race between cryptographers and cryptanalysts.

Cryptosystem

A cryptosystem is a 5-tuple consisting of

$$(E, D, M, K, C)$$

Where,

E is an *encryption* algorithm

D is an *decryption* algorithm

M is the set of *plaintexts*

K is the set of *keys*

C is the set of *ciphertexts*

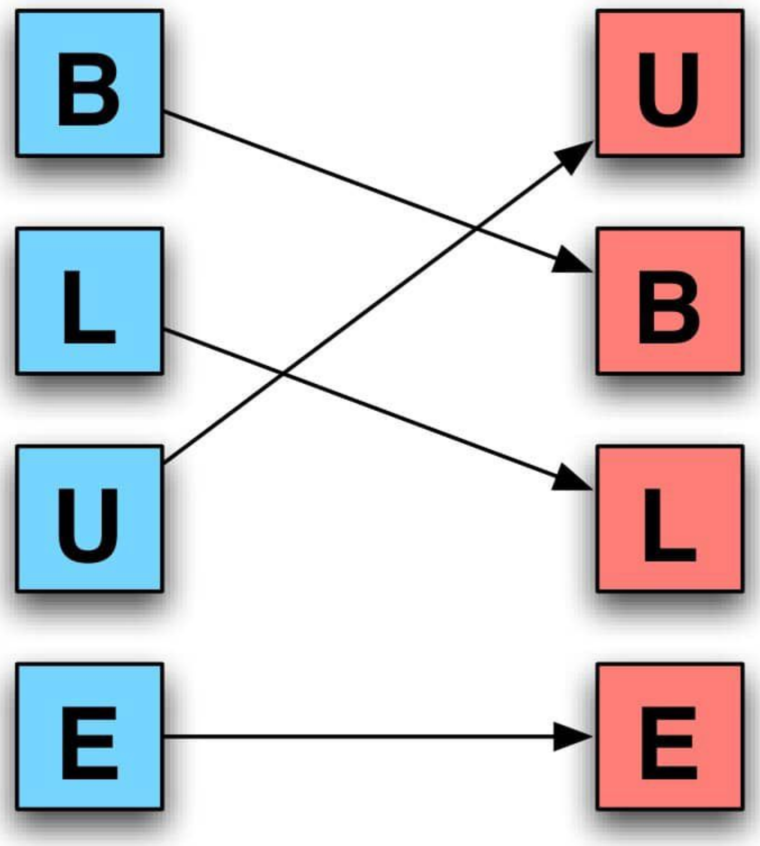
$$E : M \times K \rightarrow C \qquad D : C \times K \rightarrow M$$

What is a key?

- A key is an input to a cryptographic algorithm used to obtain confidentiality, integrity, authenticity or other property over some data.
  - The security of the cryptosystem often depends on keeping the key secret to some set of parties.
  - The *keyspace* is the set of all possible keys
  - *Entropy* is a measure of the variance in keys
    - typically measured in bits
- Keys are often stored in some secure place:
  - passwords, on disk keyrings, ...
  - TPM, secure co-processor, smartcards, ...
- ... and sometimes not, e.g., certificates

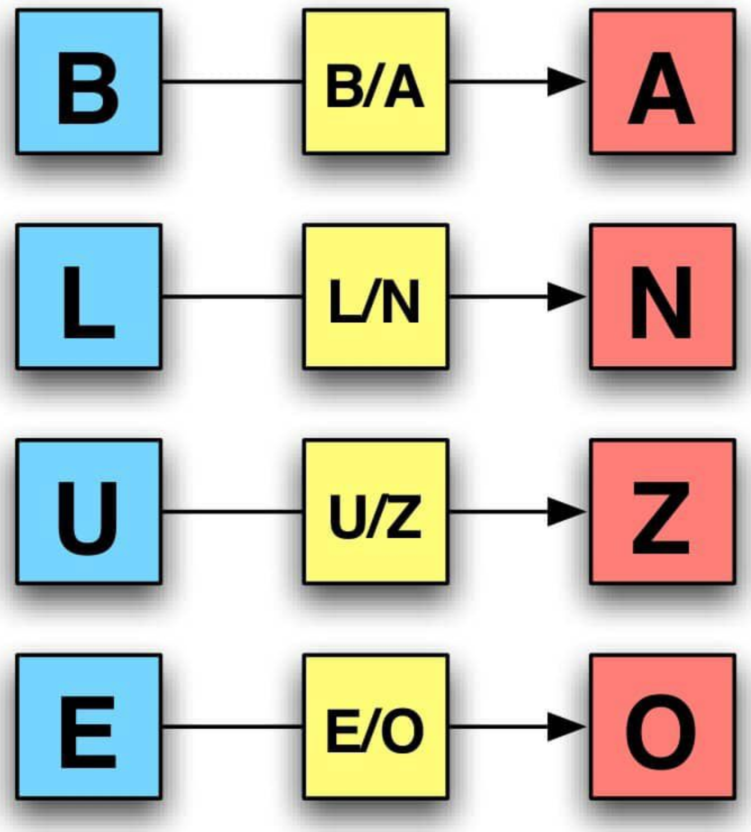
Transposition Ciphers

- Scrambles the symbols to produce output
- The key is the permutation of symbols



Substitution Ciphers

- Substitutes one symbol for another (codebook)
- The key is the permutation



Encryption algorithm

- Algorithm used to make content unreadable by all but the intended receivers

E(key,plaintext) = ciphertext

D(key,ciphertext) = plaintext

- *Algorithm is public, key is private*
- Block vs. Stream Ciphers
  - Block: input is fixed blocks of same length
  - Stream: stream of input

Example: Caesar Cipher

- Substitution cipher
- Every character is replaced with the character three slots to the right

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

- Q: What is the key?

S E C U R I T Y A N D P R I V A C Y

V H F X U L W B D Q G S U L Y D F B

Cyptanalyze this ….

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" AVGGNALYVBAF"

Cryptanalysis of ROTx Ciphers

- Goal: to find plaintext of encoded message
- Given: ciphertext
- How: simply try all possible keys
  - Known as a brute force attack

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

Shared key cryptography

- Traditional use of cryptography
- Symmetric keys, where A single key (k) is used is used for **E** and **D**

$$\mathbf{D}(k, \mathbf{E}(k, p)) = p$$

- All (intended) receivers have access to key
- Note: Management of keys determines who has access to encrypted data
  - E.g., password encrypted email
- Also known as symmetric key cryptography

The one-time pad (OTP)

- Assume you have a secret bit string s of length n known only to two parties, Alice and Bob
  - Alice sends a message m of length of n to bob
  - Alice uses the following encryption function to generate ciphertext c

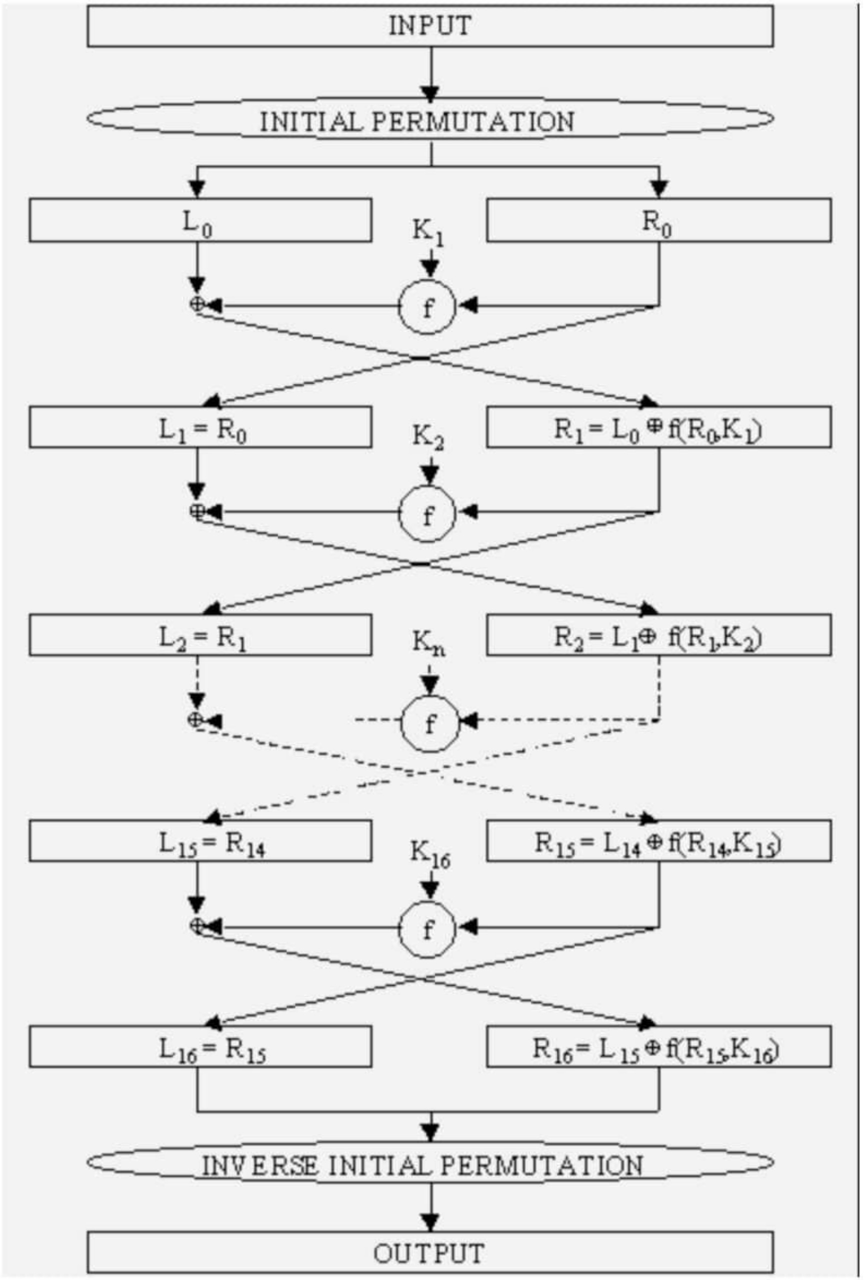
$$\textit{forall}\ i=1 \text{ to } n : c_i = m_i \oplus s_i$$

  - E.g., XOR the data with the secret bit string
  - An adversary Mallory cannot retrieve any part of the data

- Simple version of the proof of security:
  - Assume for simplicity that value of each bit in m is equally likely, then you have no information to work with.

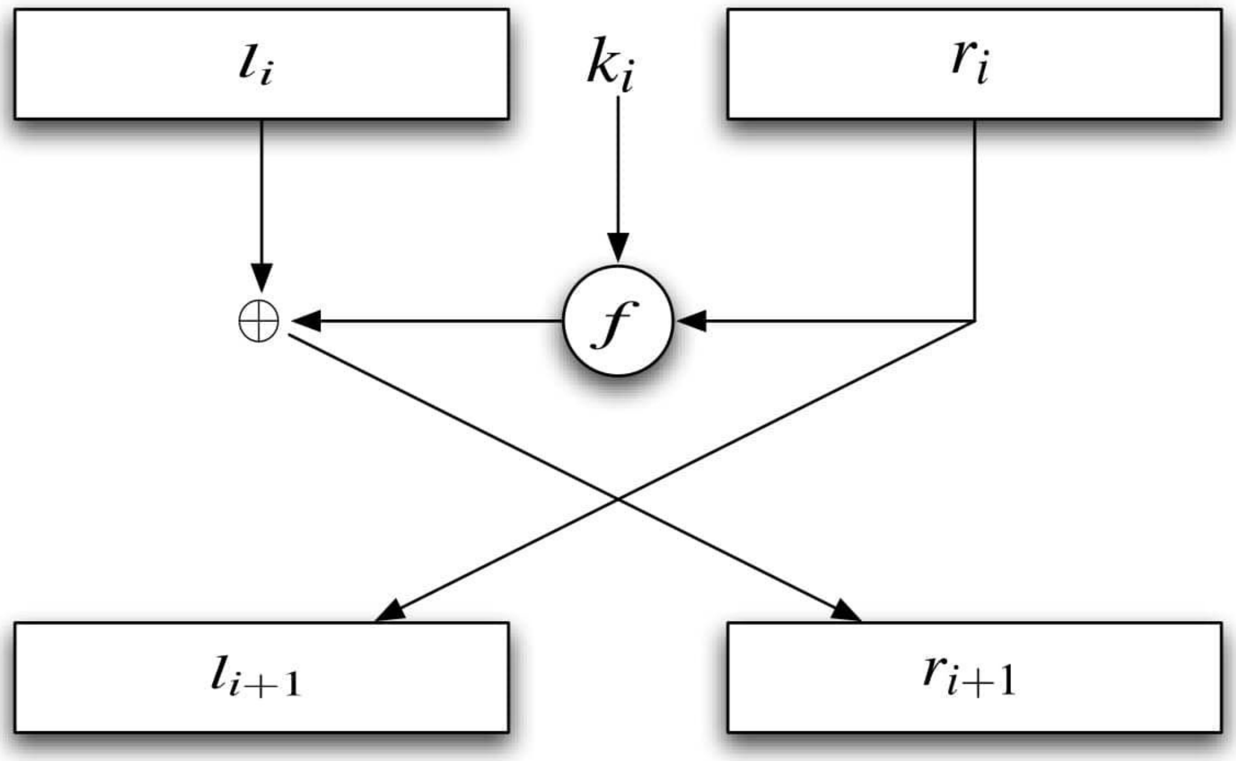
Data Encryption Standard (DES)

- Introduced by the US NBS (now NIST) in 1972
- Signaled the beginning of the modern area of cryptography
- Block cipher
  - Fixed sized input
- 8-byte input and a 8-byte key (56-bits+8 parity bits)



DES Round

- Initial round permutes input, then 16 rounds
- Each round key (*k_i*) is 48 bits of input key
- Function *f* is a substitution table (*s-boxes*)



Cryptanalysis of DES

- DES has an effective 56-bit key length
  – Wiener: 1,000,000$ - 3.5 hours (never built)
  – July 17, 1998, the EFF DES Cracker, which was built for less than $250,000 < 3 days
  – January 19, 1999, Distributed.Net (w/EFF), 22 hours and 15 minutes (over nearly 100,000 machines)
  – We all assume that NSA and agencies like it around the world can crack (recover key) DES in milliseconds
- What now? Give up on DES?

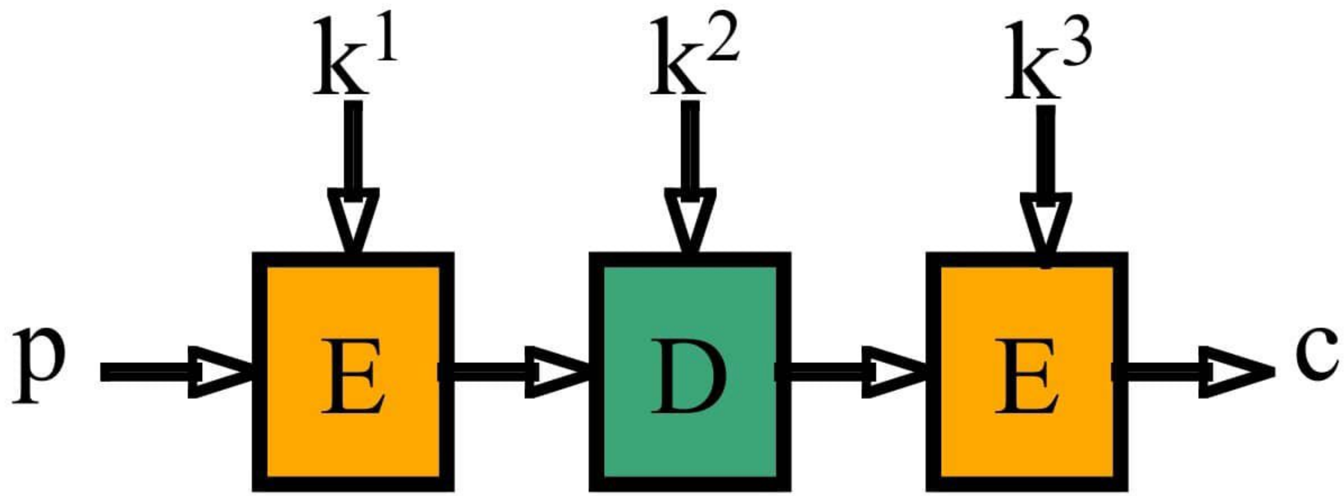
Variants of DES

DESX (two additional keys ~= 118-bits)

Triple DES (three DES keys ~= 112-bits)

Keys k1, k2, k3

$$c = E(k_3, D(k_2, E(k_1, p)))$$



Advanced Encryption Standard (AES)

- Result of international NIST bakeoff between cryptographers
  - Intended as replacement for DES
  - Rijndael (pronounced "Rhine-dall")
  - Currently implemented in many devices and software, but not yet fully embraced
  - Cryptography community is actively vetting the the theory and implementations (stay tuned)

Hardness

- Functions
  - Plaintext P
  - Ciphertext C
  - Encryption key k_e
  - Decryption key k_d

$$D(k_d, E(k_e, P)) = P$$

- Computing C from P is hard, computing C from P with k_e is easy
- Computing P from C is hard, computing P from C with k_d is easy

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