601.445/645 Practical Cryptographic Systems

Symmetric Cryptography

Instructor: Matthew Green

Housekeeping

- A1 due this Weds
  - See Piazza for some Q/A
  - Grading: several long ciphertexts
- TA Office Hours
  - Alishah Chator: Tues 5-7pm (this week)
  - Golang Review Session: Thurs 5/6pm
  - Bloomberg 178
- A2 out Thursday, due two weeks later

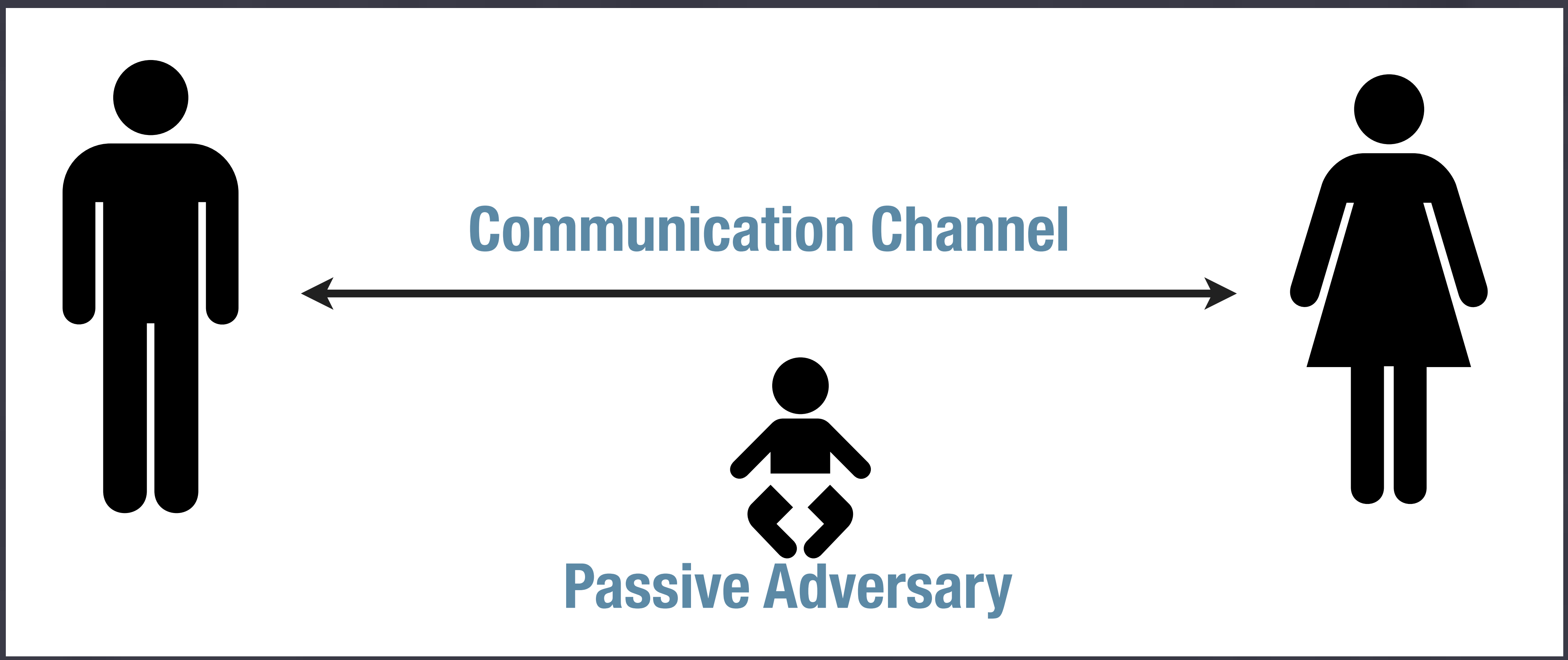
News

Review

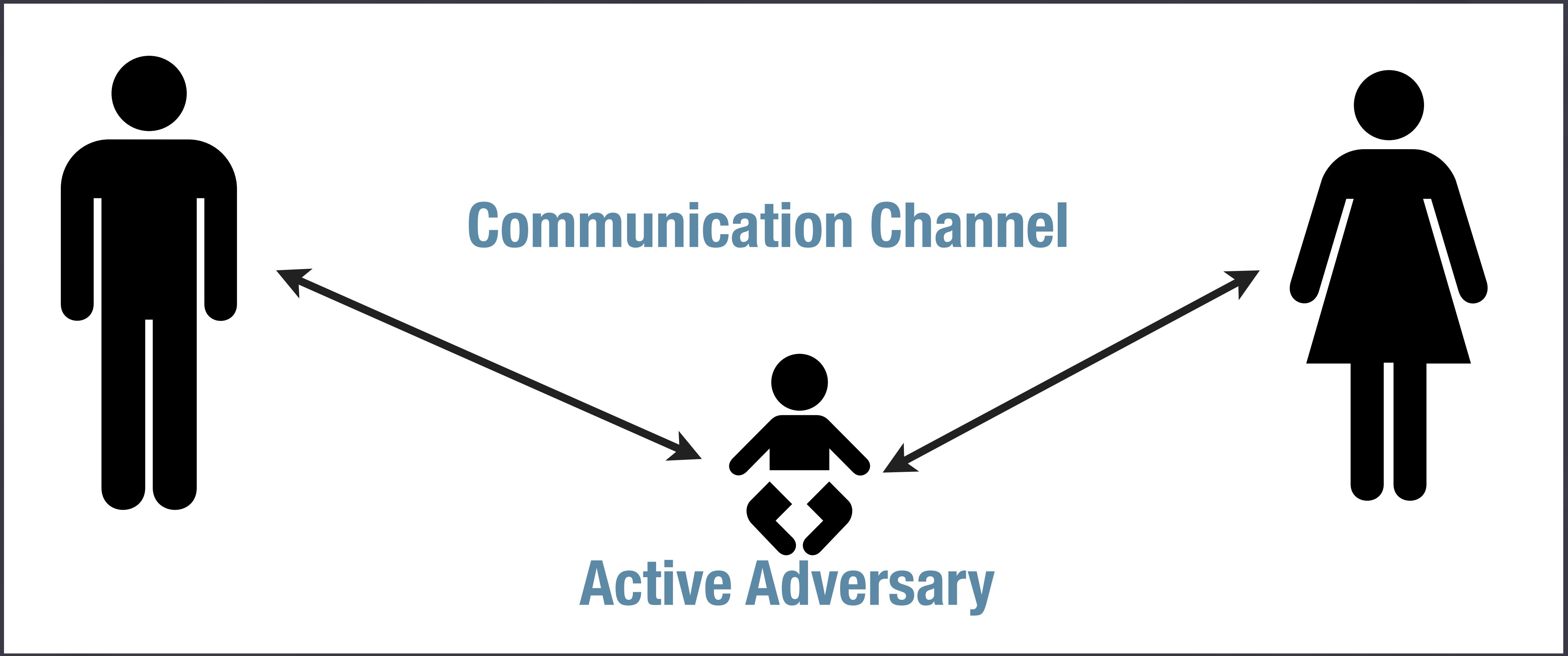
- Last time:
  - A (brief) tour through cryptologic history
  - Starting with symmetric (secret-key) crypto
- Today
  - More symmetric crypto, including modes of operation

Communication Model

Communication Model



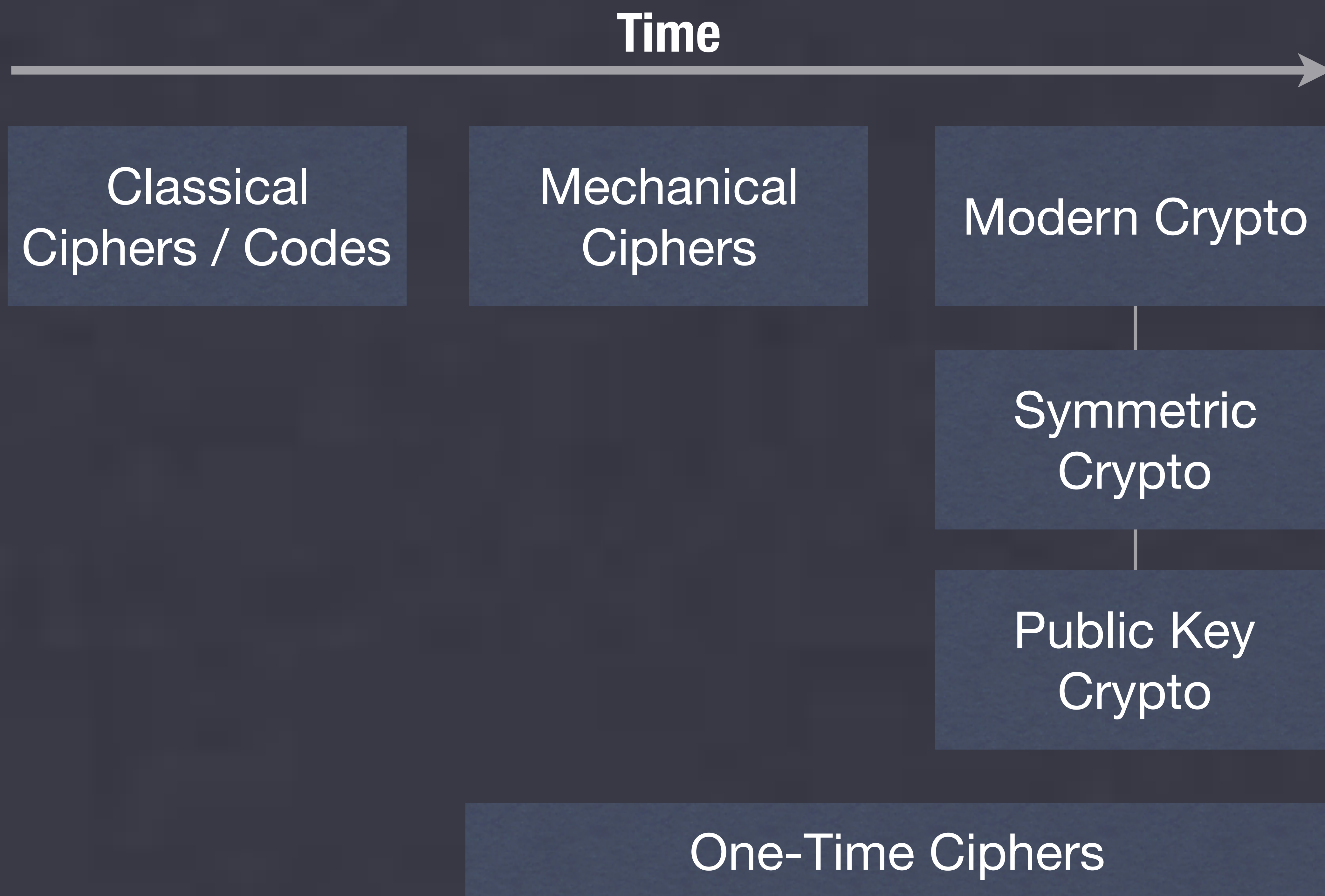
Communication Model



Secure Communication

- Two basic properties we like to achieve:
  - Data confidentiality
  - Data authenticity ("integrity")
- Tools:
  - Encryption
  - Message Authentication Codes (MACs)
  - Digital Signatures

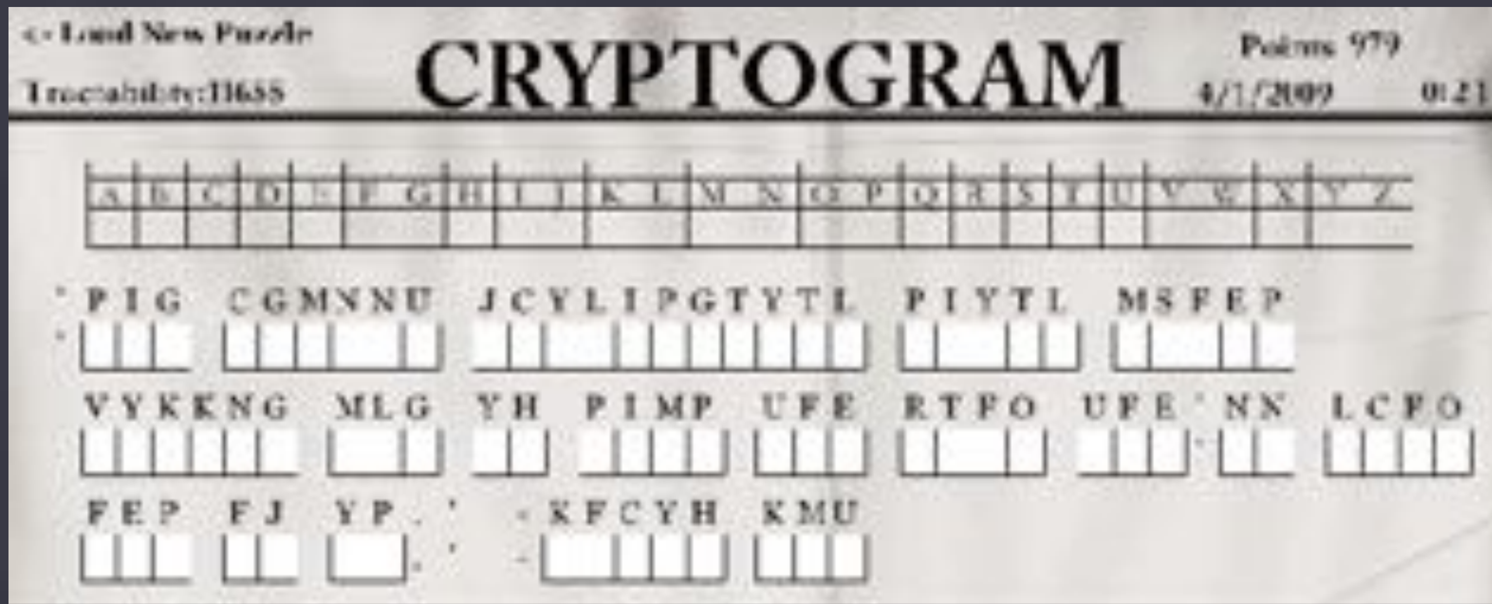
History of Encryption

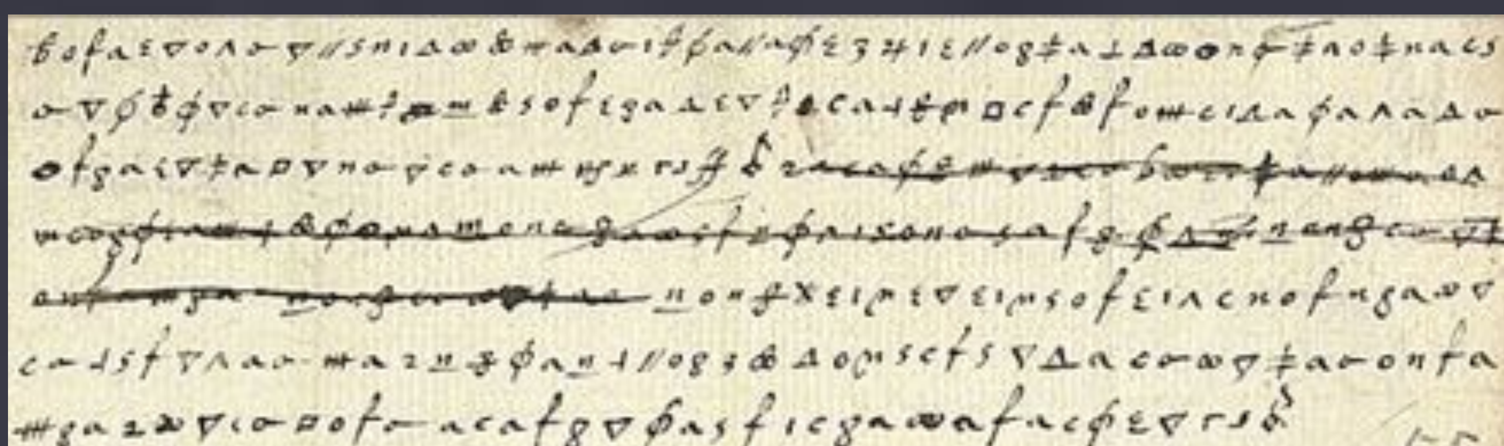


Classical Cryptography

- Beginning of time to 1900s or so
  - Shift (Caesar) cipher
  - Substitution ciphers
  - Polyalphabetic ciphers (Vigenère)
  - Digraph ciphers (Playfair)
  - A multitude of others...

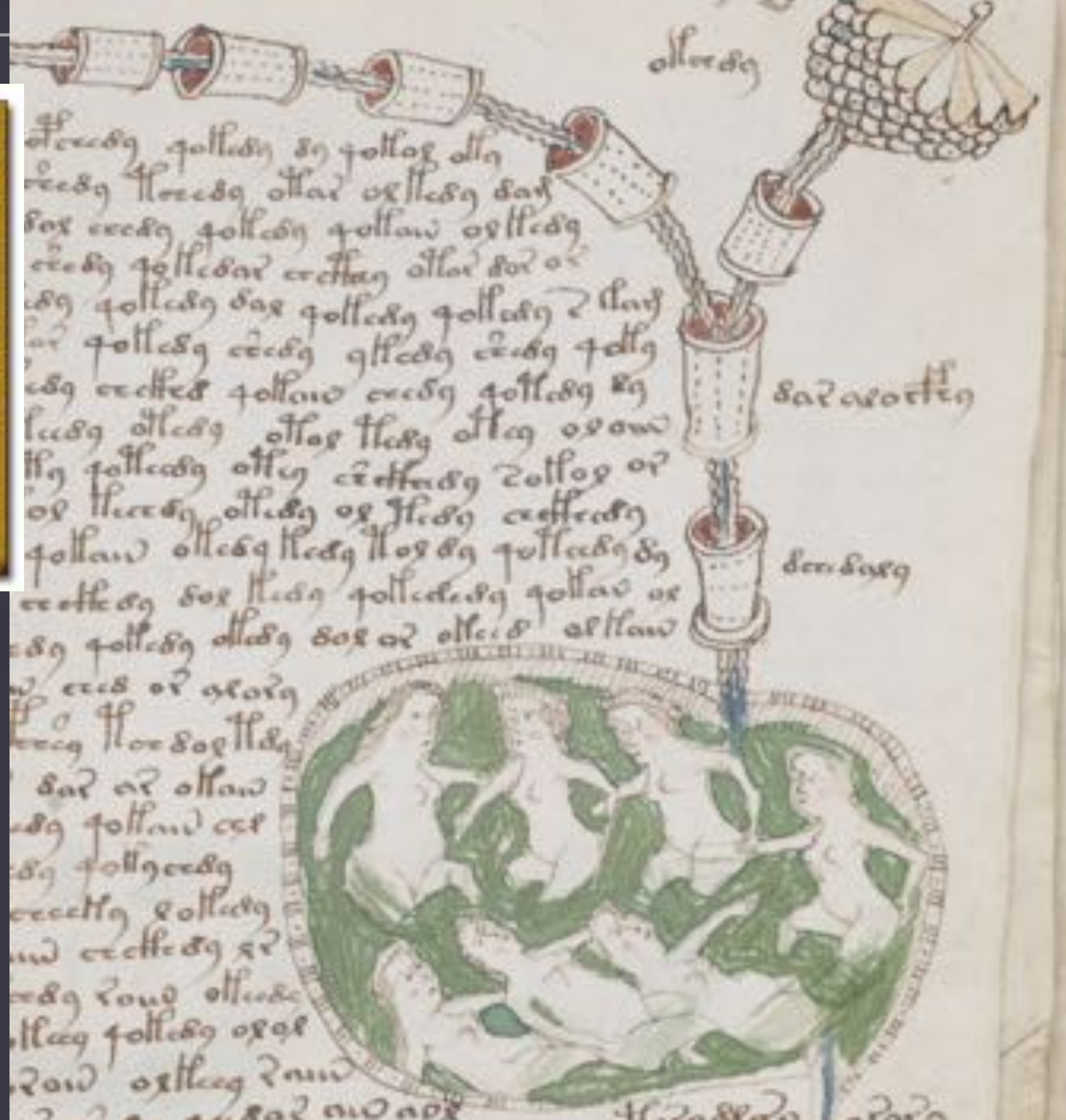
Increasing
Complexity





A	G	R	P	T
B	I	K	C	Q
S	L	D	M	E
N	Y	W	F	X
G	J	H	O	Z

S	E	N	D	R	E	I	N	F	O	R	C	E	M	E	N	T	S
V	I	G	E	N	E	R	E	V	I	G	E	N	E	R	E	V	I
N	M	T	H	E	I	Z	R	A	W	X	G	R	Q	V	R	O	A



One-Time Ciphers

- 1900s
  - Vernam & Mauborgne's "Unbreakable" cipher

-Based on Baudot code for Teletypes

-Added (XORed) a random Key (sequence of bits) to a binary message

  - Perfectly secure, provided:

-key is perfectly random

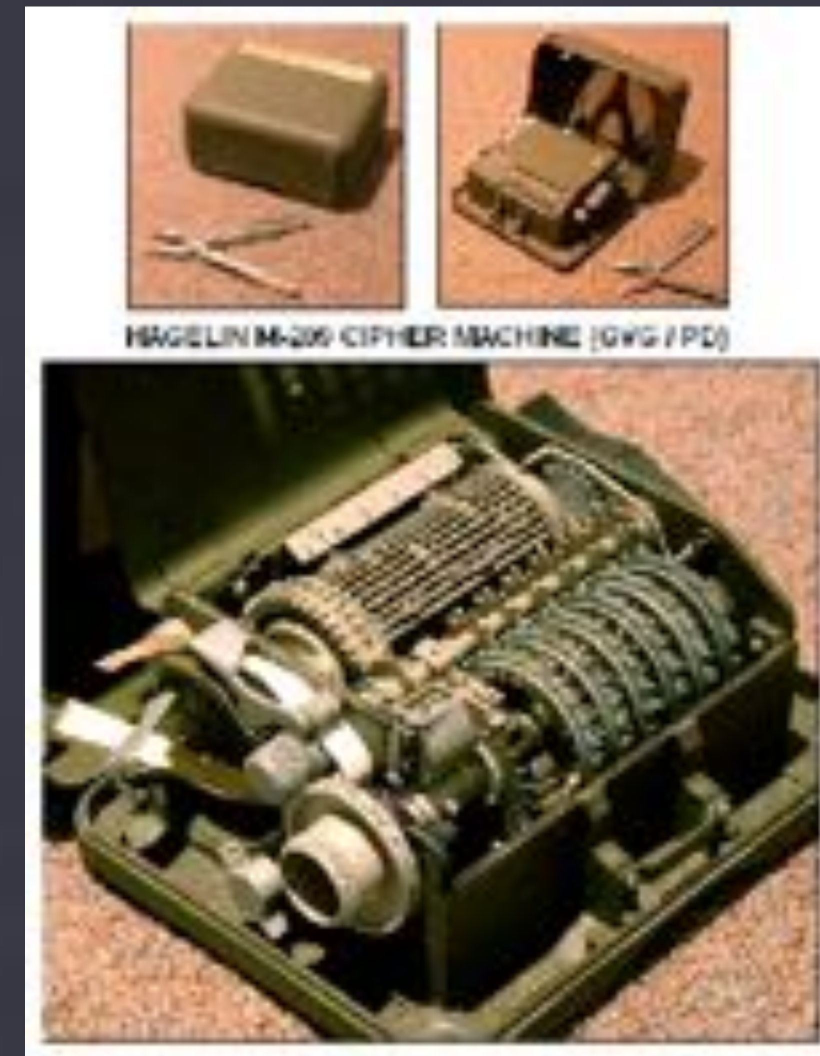
-key is at least as long as the message

-kev is never re-used

Mechanical Cryptography

- 1900s
  - Mass production and usage of cipher devices
  - Rotor ciphers
  - Electronic devices

M-94 Cipher Wheel image by Bob Lord, used under a Creative Commons license.
Remaining images: Wikipedia [M-94, Enigma] used under GFDL.

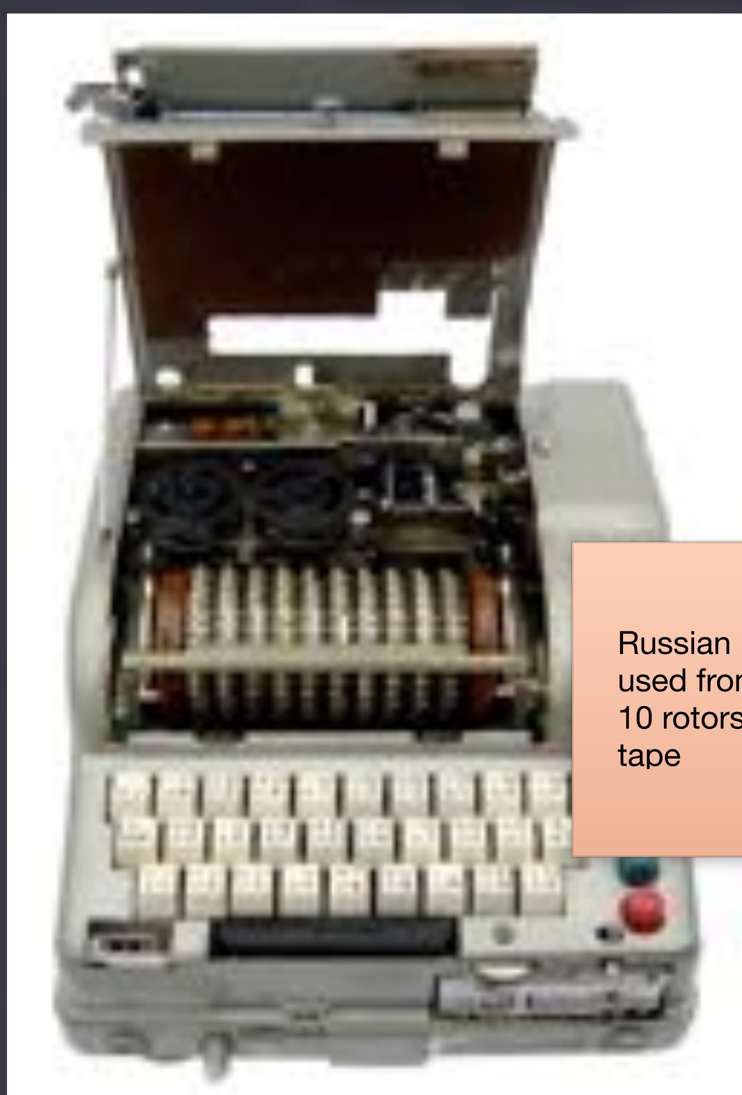


US M-209, broken by Germans in 1943 but still used

Purple Machine (top left) courtesy NSA, US Purple Replica (center) & M-209 images: Wikipedia used under GFDL/CC License.

Swedish AB Transvertex HC-9.
Commercial devices used for low-level communications until 1970s.

Swiss NEMA
Late 1940s. “Improved” version of the Enigma-K.
10 rotors.
Same weakness as Enigma: ciphertext never equals plaintext.
Declassified in 1992.
Simple attack = 2^41



Russian Fialka
used from 1965-1990s
10 rotors, reads and writes to tape

Summary

- **Most cryptosystems ultimately broken**
  - Sophistication of the attackers outpaces that of the cryptosystem
  - Security relies on secrecy of design
  - Not evaluated for chosen plaintext, known plaintext attacks
  - Key generation/distribution procedure
  - It’s an arms race...

Kerckhoffs' Principle

2. It must not be required to be secret, and it must be able to fall into the hands of the enemy without inconvenience;

"The enemy knows the System"
-- Claude Shannon's Maxim

Public Domain image from David Kahn's The Codebreakers, credited to "Eugen Drezen, Historio de la Mondo Lingvo (Leipzig, 1931), 102".

The 1970s

1972

1976
(1974) ⟵ U.K. GCHQ ⟶ (1973)

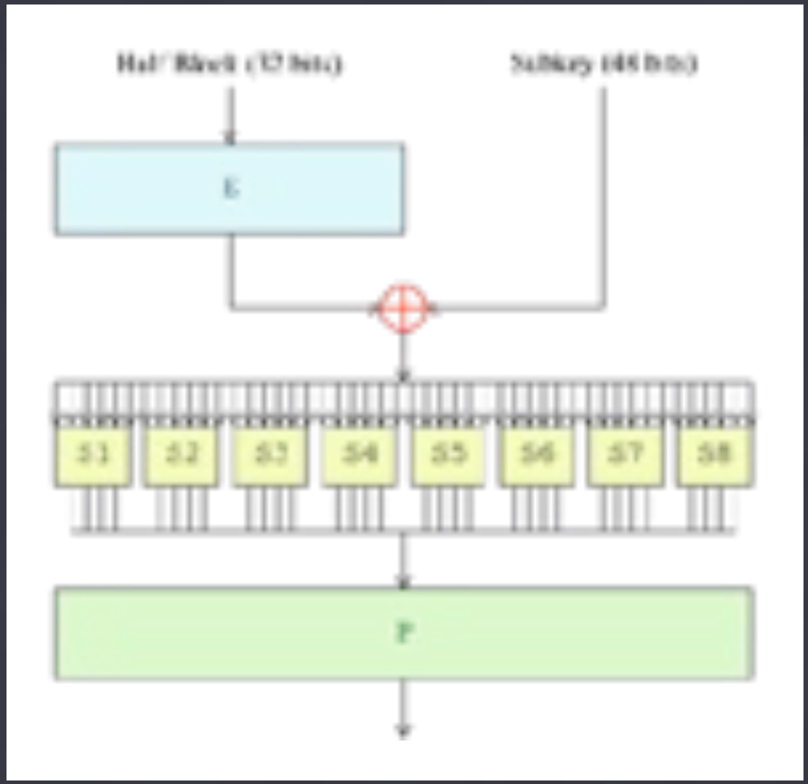
1977

The Implications

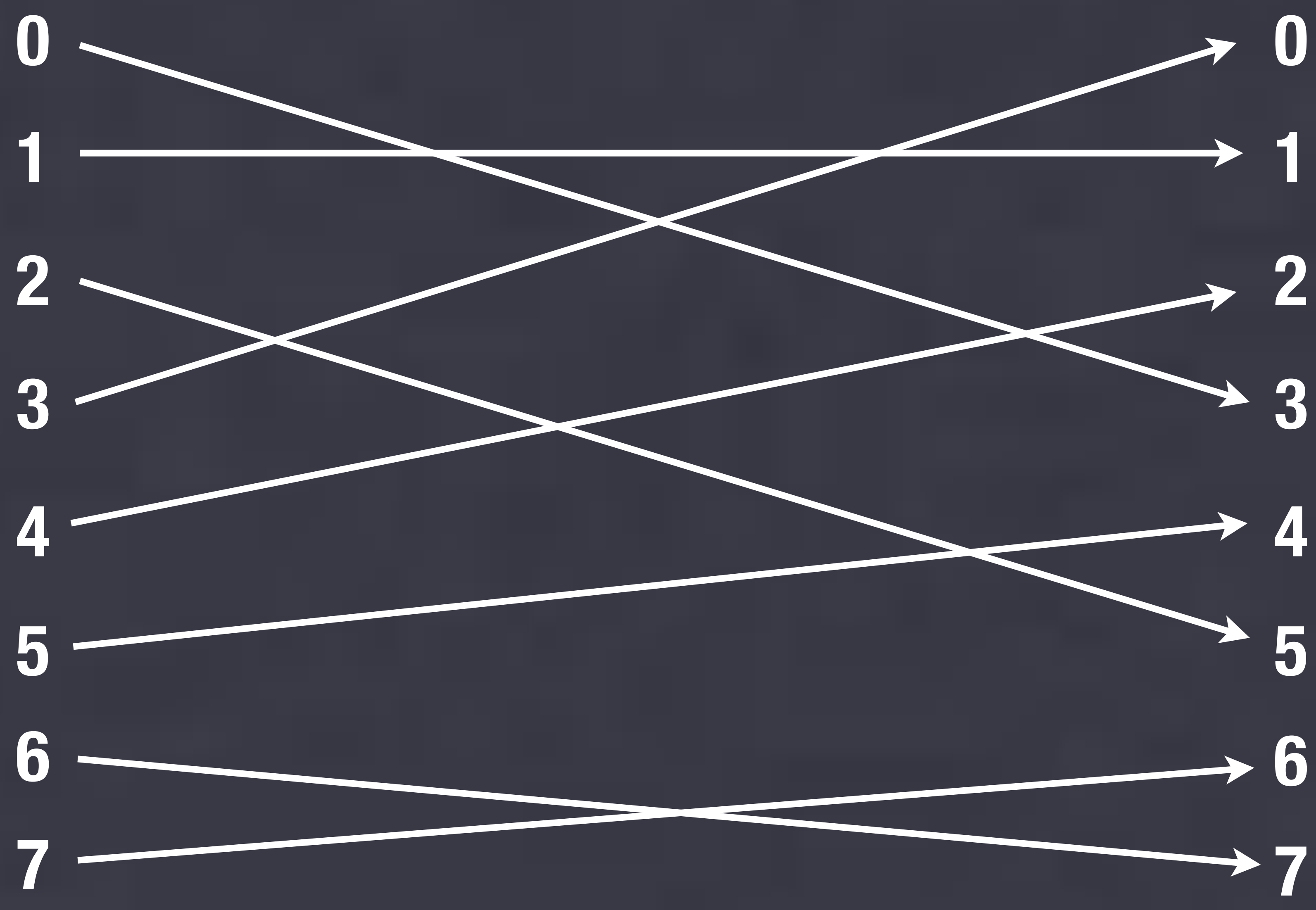
- Exponential increase in study & usage of cryptography in industry, academia
- Wide-scale deployment of cryptographic systems
- <u>Provable Security</u>
  - Cryptographic Systems can be <u>reduced</u> to some hard mathematical problem

Data Encryption Standard

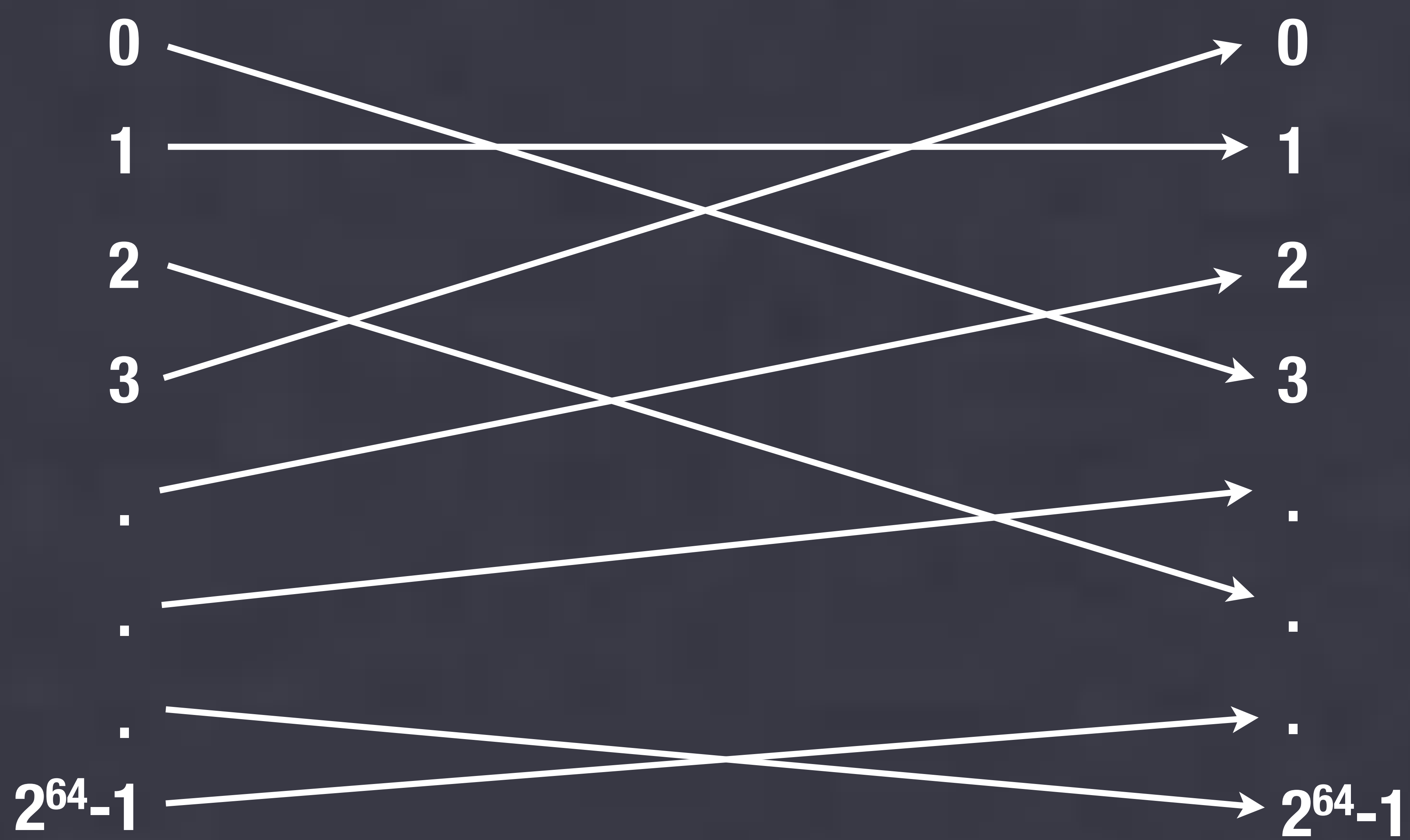
- Commercial-grade Block Cipher
  - 64-bit block size
  - 56 bit key (+ 8 bits parity)
  - “Feistel Network” Construction



Permutation



Permutation



Permutation Families

- Can't have just <u>one</u> permutation
  - Alice & Bob know the permutation
    Adversary doesn't
  - Permutation is "random" (ish)
  - But there are $2^{64}!$ possible permutations
  - DES has a 56 bit key...

Block Cipher

- Block cipher is a family of permutations
  - Indexed by a key (DES = 56 bit key)
  - “Pseudo-random”

Block Cipher

- Block cipher is a family of permutations
  - Indexed by a key (DES = 56 bit key)
  - Ideally: “Pseudo-random permutation (PRP)”

    (i.e., attacker who does not know the key can’t determine whether you’re using a random permutation, or a PRP)

DES: 64-bit Block, 56-bit Key

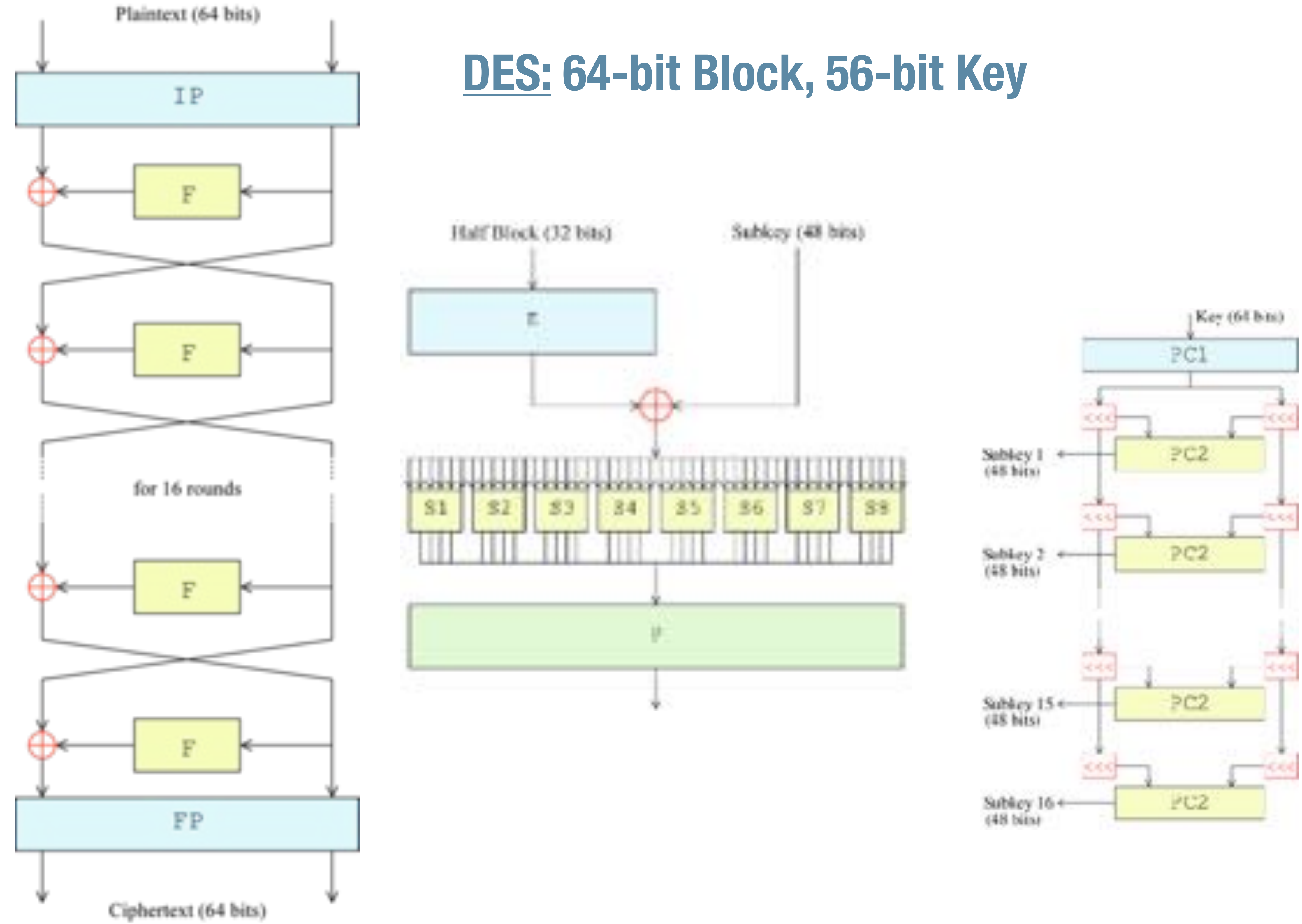
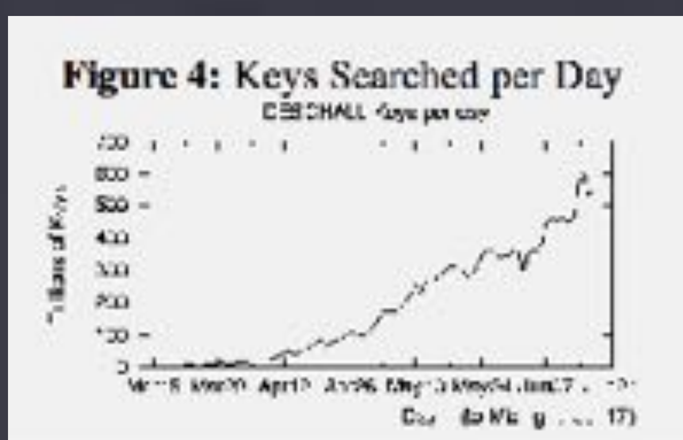


Image from Wikipedia, used under GFDL

DES

- Some "clever" attacks on DES
    - However: practical weakness = 56 bit key size
    - Practical solution: 3DES (now being deprecated)



U.S. Data-Scrambling Code Cracked With Homemade Equipment

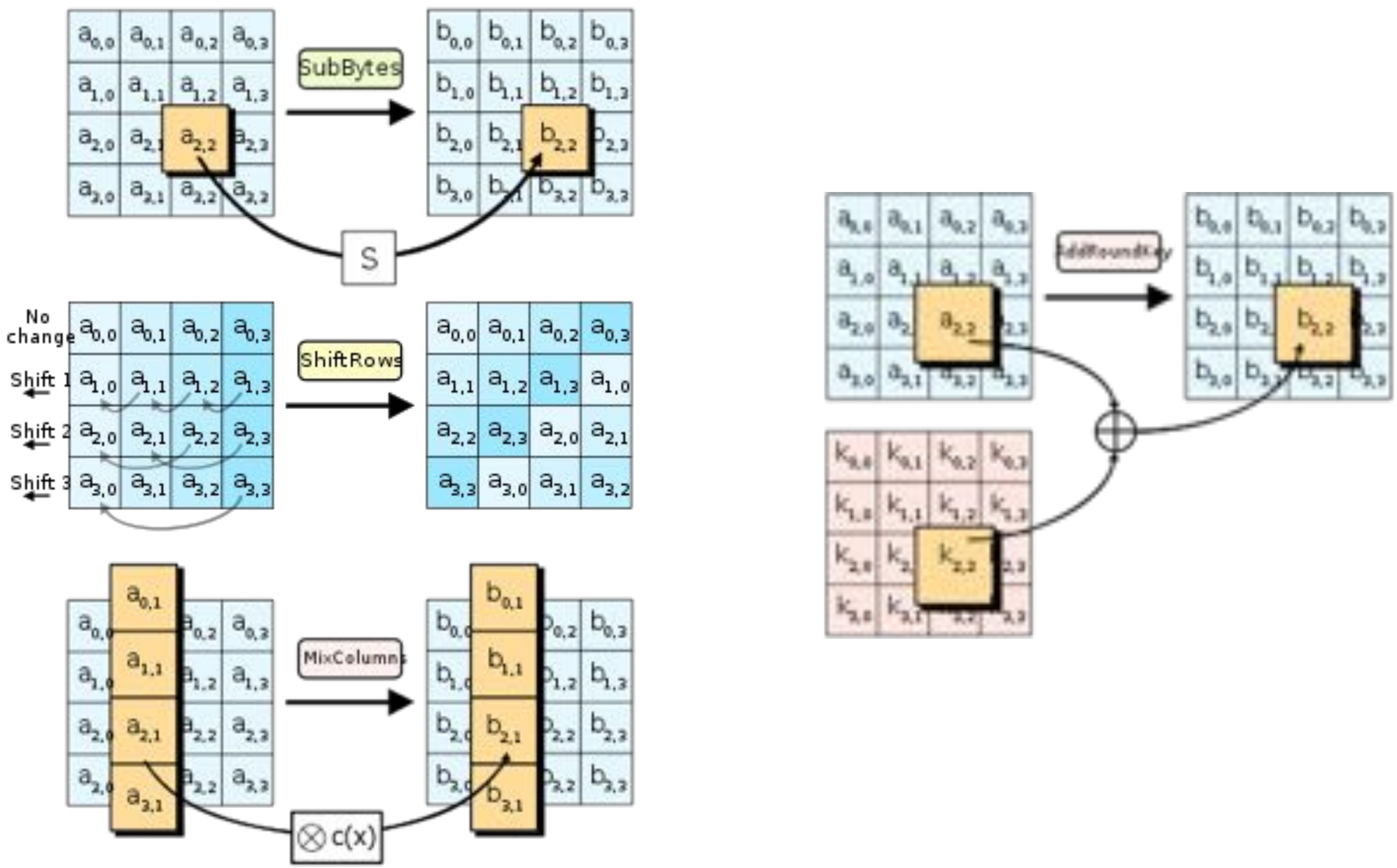
By JOHN MARKOFF

SAN FRANCISCO -- In a 1990s variant of a John Henry-style competition between man and machine, researchers using a homemade supercomputer have cracked the government's standard data-scrambling code in record time -- and have done it by out-calculating a team that had harnessed thousands of computers, including some of the world's most powerful.

AES

- NIST open competition:
  - Fast in software & hardware
  - Larger block size (128 bit)
  - Longer keys (128/192/256-bit)
- 5 finalists:
  - MARS, RC6, Rijndael, Serpent, and Twofish

AES: 128-bit Block, 128/192/256-bit Key



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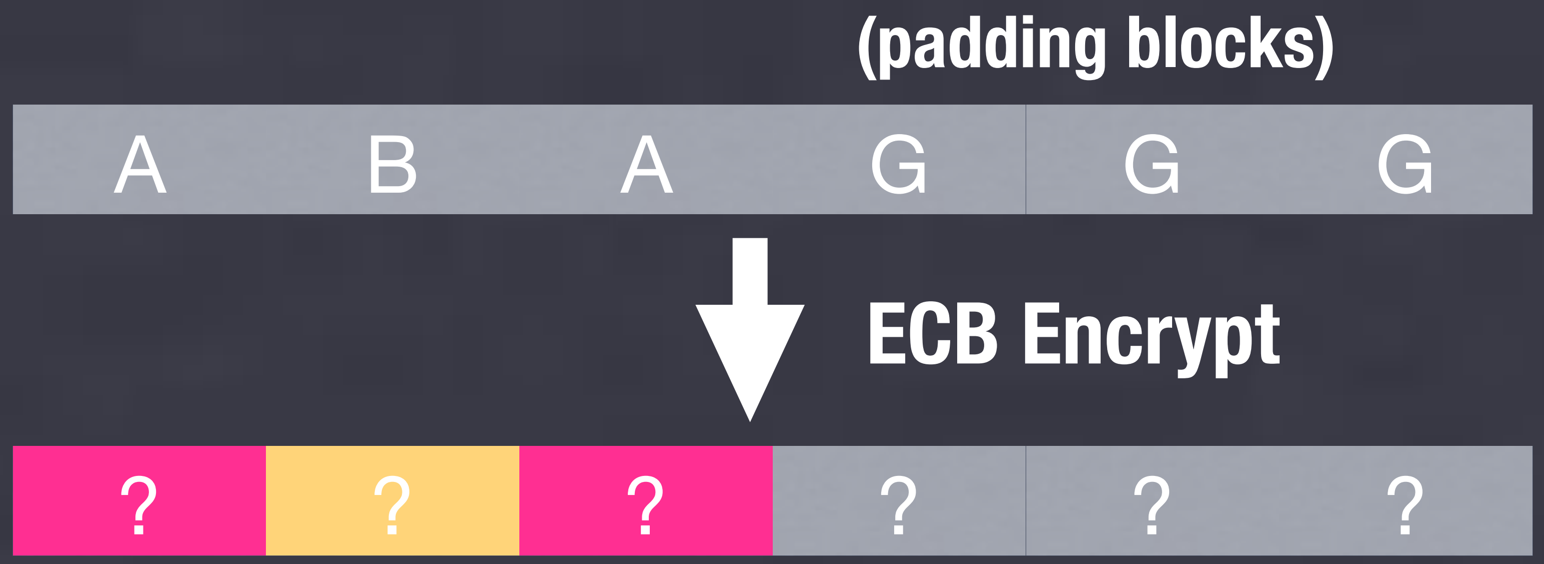
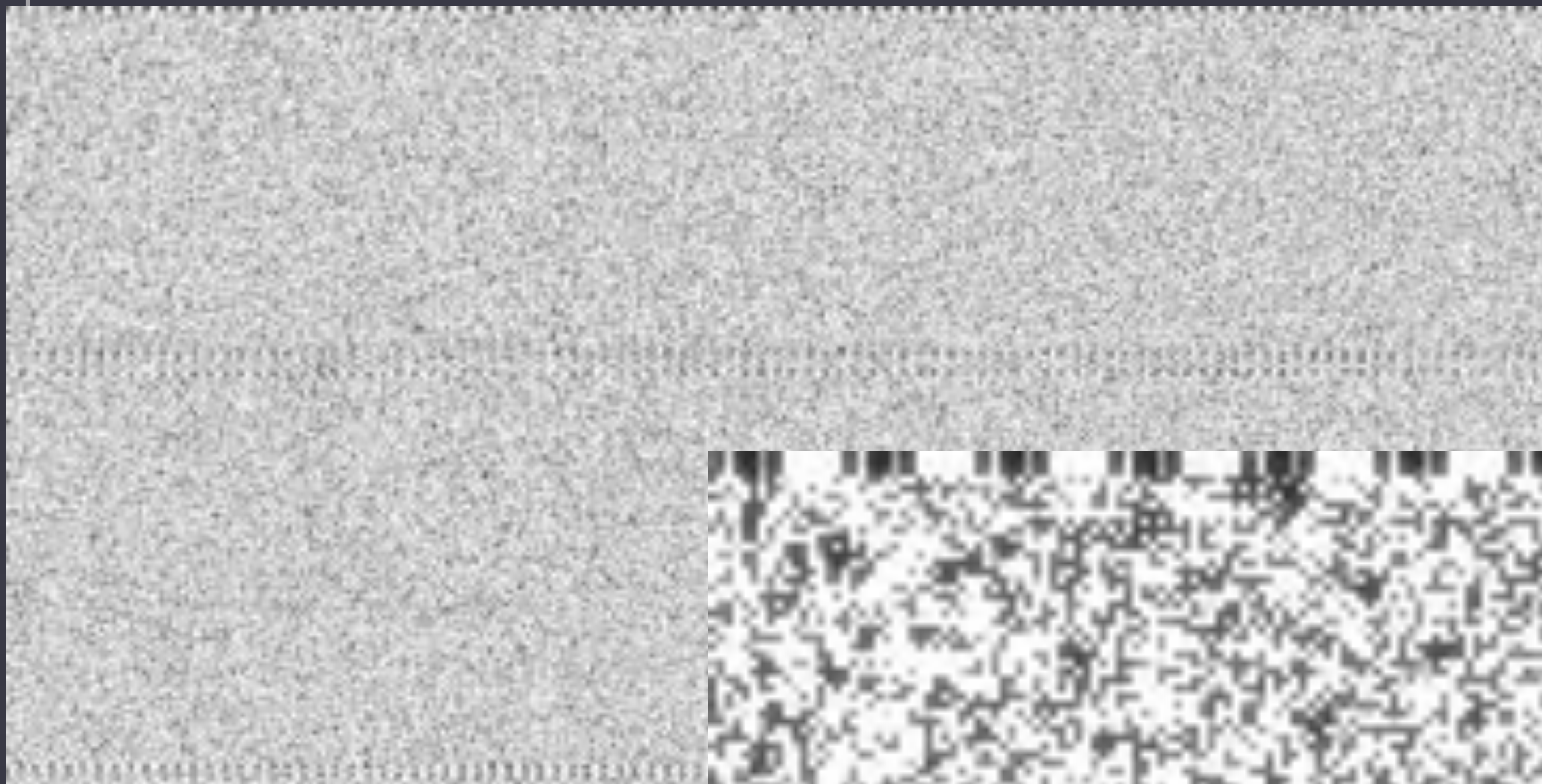
Review

- **ECB Mode: Encrypt each block separately**
  - **Problems?**





ECB Mode

- ECB is <u>deterministic</u>
  - Leads to problems, e.g.,:

Game server

E(Attack Monster) ←

E(Monster Attacks) →

Game client

Security of Encryption

- Semantic Security
  - Due to Goldwasser & Micali (1980s)
  - Informally: An encryption scheme is secure if adversary who sees ciphertext “learns as much”
    as adversary who doesn’t see ciphertext.

-Even if adversary can request chosen plaintexts

  - How do we state this formally?

Review

- **Semantic Security (IND-CPA)**

$b \xleftarrow{\$} \{0, 1\}$

Adversary

$M_1, \ldots, M_n$

$E(k, M_1), \ldots, E(k, M_n)$

M_0, M_1

$E(M_b)$

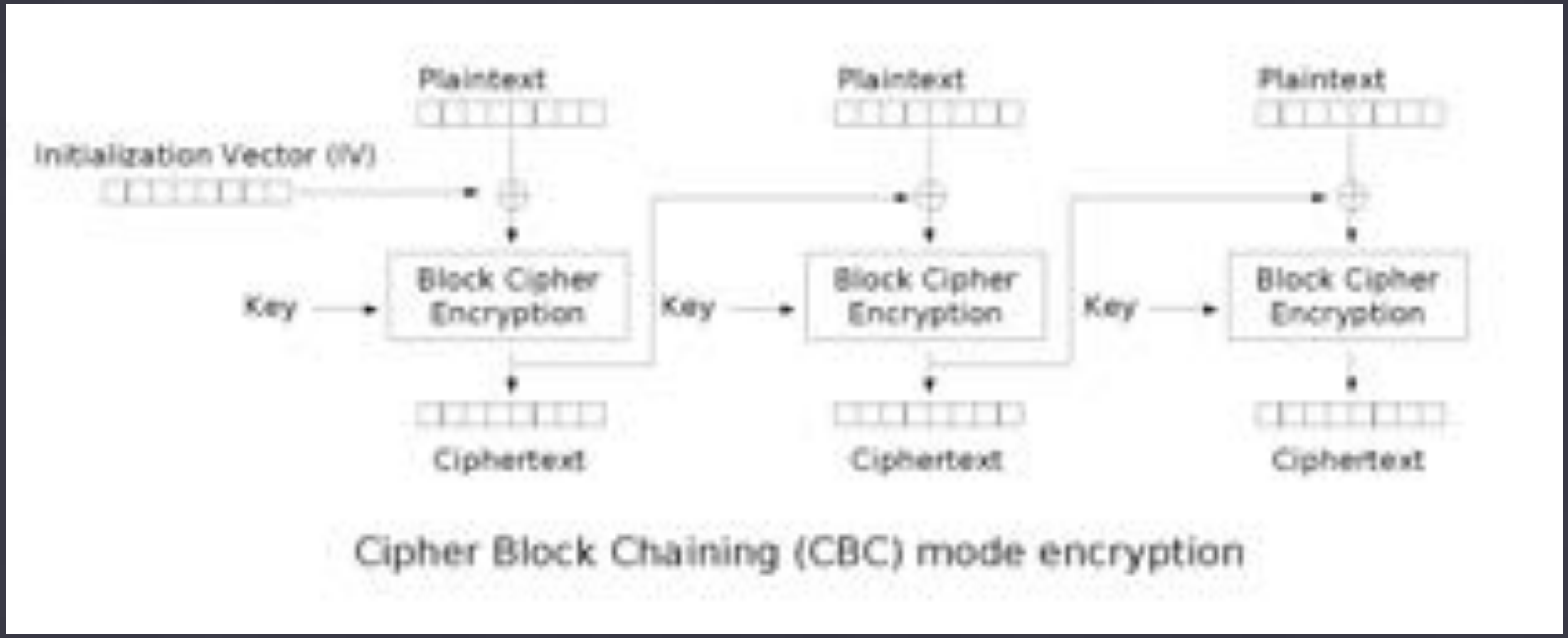
k

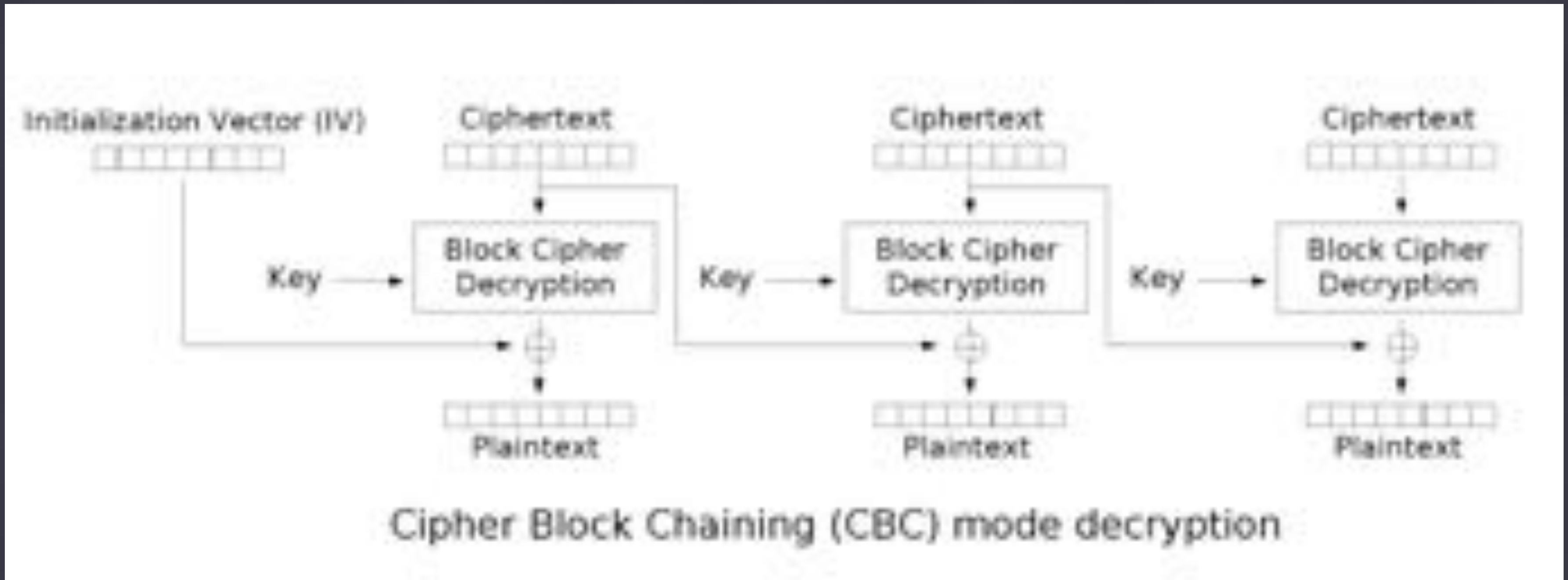
b?

Using Block Ciphers

- ECB is not semantically secure, hence we use a “mode of operation”
  - e.g., CBC, CTR, CFB, OFB (and others)
- These provide:
  - Security for multi-block messages
  - Randomization (through an <u>Initialization Vector</u>)

CBC Mode





Public domain image courtesy Wikipedia.

Security of CBC

- Is CBC a secure encryption scheme?
  - Yes, assuming a secure block cipher
  - Correct (random) IV generation
  - Can <u>prove</u> this under assumption that block cipher = Pseudo-Random Permutation (PRP)

-Bellare, Desai, Jokipii & Rogaway (2000)

- Easy to use wrong...
  - Most important: use a unique & random IV!

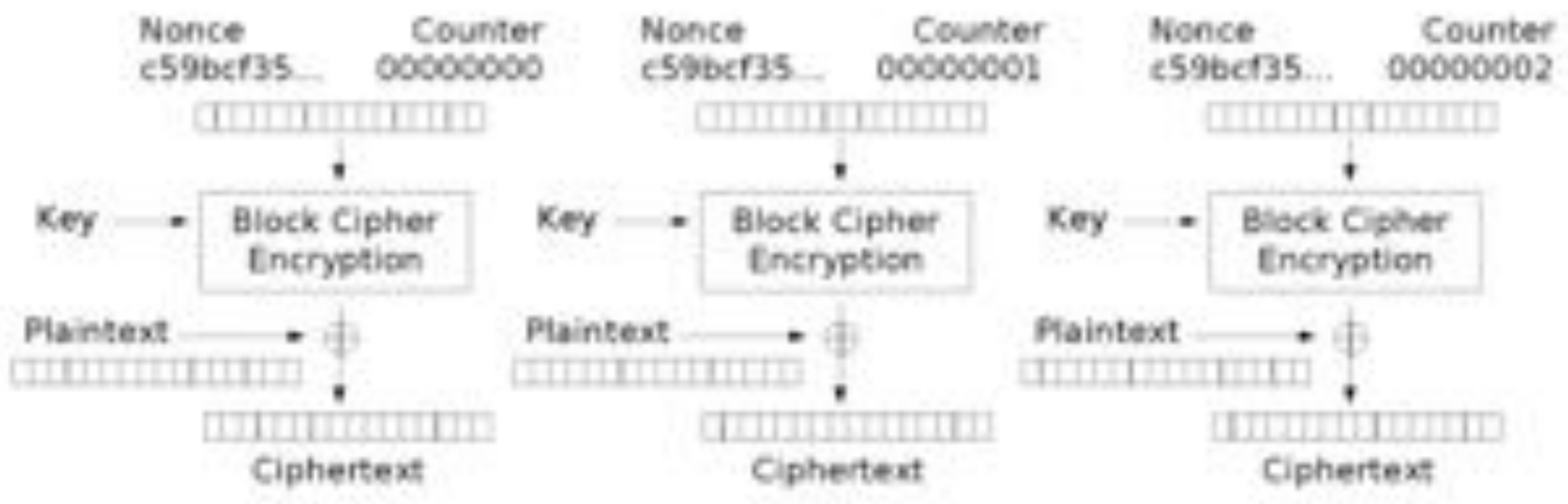
The size of the frame of data to be encrypted or decrypted (i.e. how often a new CBC chain is started) depends on the particular application, and is defined for each in the corresponding format specific books of this specification. Unless otherwise specified, the Initialization Vector used at the beginning of a CBC encryption or decryption chain is a constant, iv_0, which is:

$$0BA0F8DDFEA61FB3D8DF9F566A050F78_{16}$$

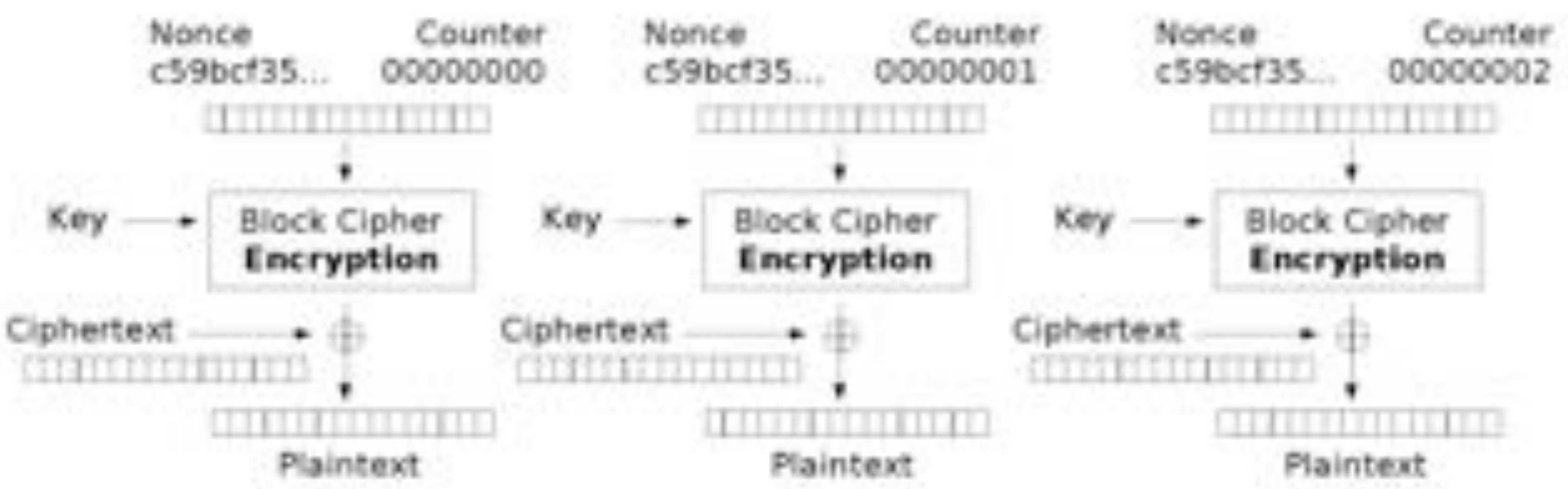
Advanced Access Content System (AACS)

Introduction and Common Cryptographic Elements

CTR Mode



Counter (CTR) mode encryption



Counter (CTR) mode decryption

Public domain image courtesy Wikipedia.

Security of CTR

- Yes, assuming secure block cipher (PRP)
- However, counter range must <u>never</u> be re-used

$$(\text{Plaintext 1} \oplus \cancel{\text{Keystream}}) \oplus (\text{Plaintext 2} \oplus \cancel{\text{Keystream}}) = \text{Plaintext 1} \oplus \text{Plaintext 2}$$

- Similar example: MS Word 2003
  - (they used RC4, but same problem)

Point of order

- **Proofs of security:**
  - We <u>don't</u> know how to prove that DES or AES are secure block ciphers
  - But if we assume that the block ciphers <u>are</u> secure PRPs then:

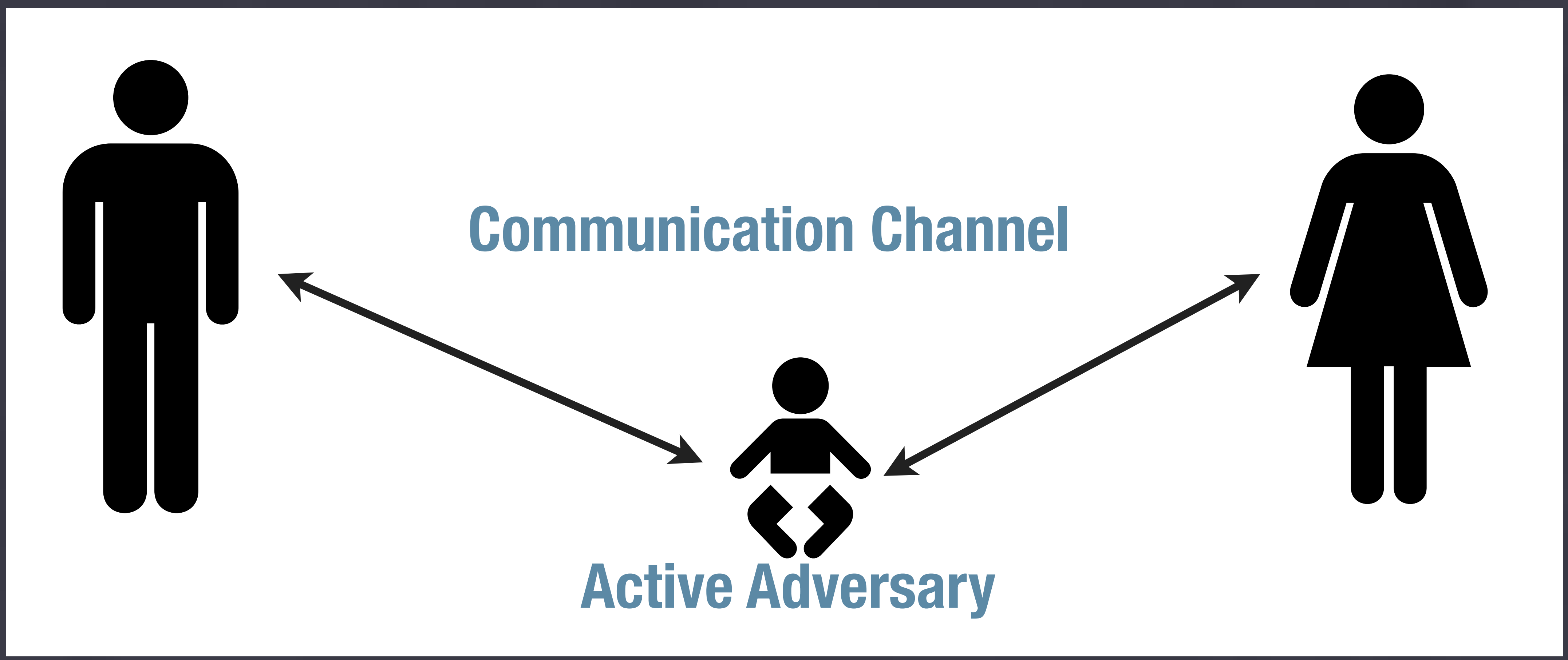
-We can prove that CBC & CTR & OFB & CFB etc. are secure encryption modes.

http://www.cs.ucdavis.edu/~rogaway/papers/sym-enc-abstract.html

Malleability

- The ability to modify a ciphertext
  - Such that the plaintext is meaningfully altered
  - CTR Mode (bad)
  - CBC Mode (somewhat bad)

Authenticated Encryption



MACs

- Symmetric-key primitive
  - Given a key and a message, compute a “tag”
  - Tag can be verified using the same key
  - Any changes to the message detectable
- To prevent malleability:
  - Encrypt <u>then</u> MAC
  - Under separate keys

MACs

- Definitions of Security
  - Existential Unforgeability under Chosen Message Attack (EU-CMA)
- Examples:
  - HMAC (based on hash functions)
  - CMAC/CBC-MAC (block ciphers)

Authenticated Encryption

- Two ways to get there:
  - Generic composition
    Encrypt (e.g., CBC mode) then MAC

-two different keys, multiple primitives

  - Authenticated mode of operation

-Integrates both encryption & authentication

-Single key, typically uses only one primitive (e.g., block cipher)

-Ex: CCM, OCB, GCM modes