Computer Security (2017)

Classical Cryptography

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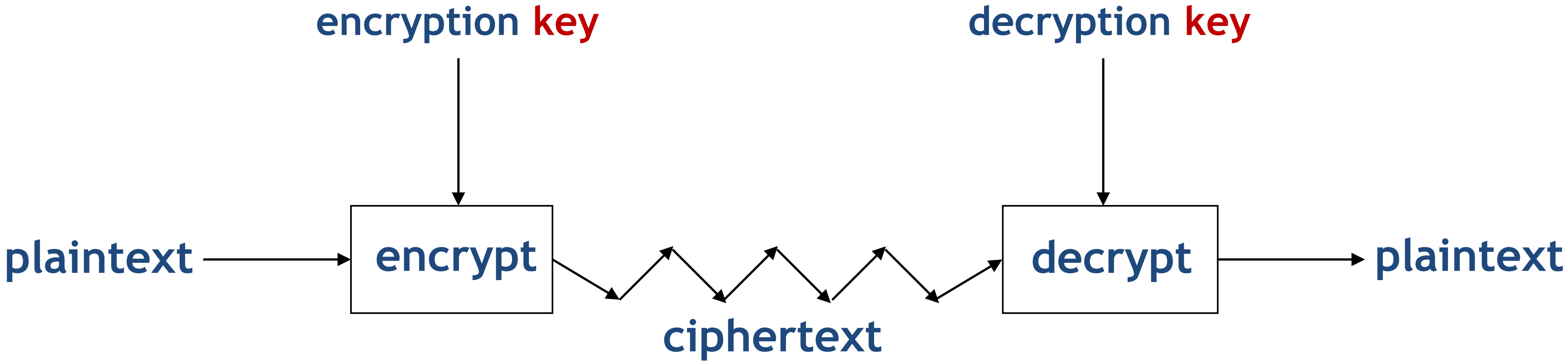
Cryptography

“secret” “writing”

Crypto as black box



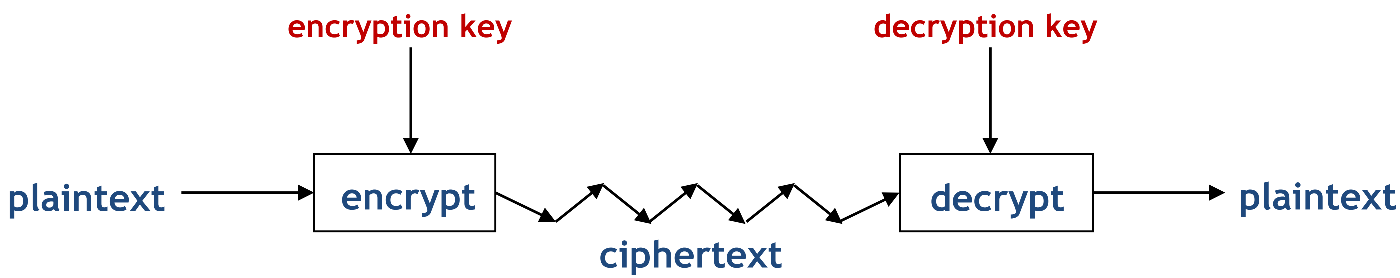
A generic view of key crypto

Tools for confidentiality and Integrity

Types of crypto systems

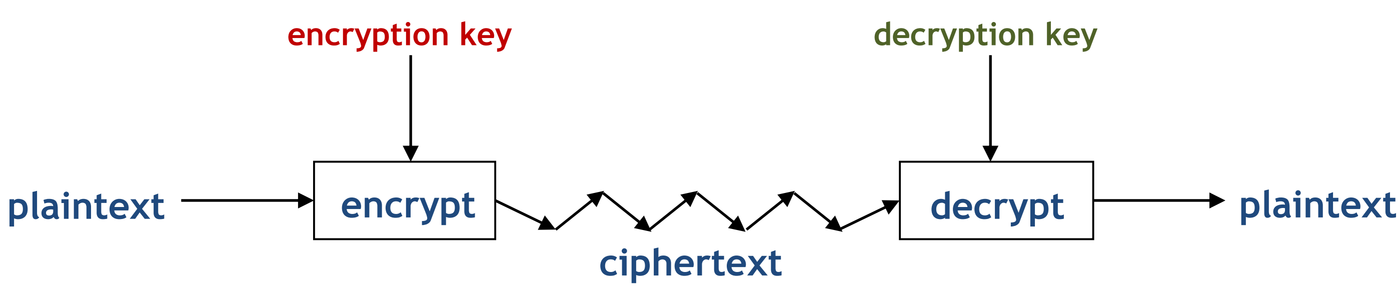
- Symmetric

(decryption key = encryption key)



- Public or Asymmetric

(decryption key != encryption key)



A framework for crypto

- Cryptography (making), cryptanalysis (breaking), cryptology (both)
- Traditional cryptanalysis – what goes wrong with the design of the algorithms
- Then – what goes wrong with their implementation (power analysis, timing attacks)
- Then – what goes wrong with their use

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
    - » too many examples of broken ad-hoc designs

"If you think cryptography is the answer to your problem, you don't know what your problem is."

Peter G. Neumann

The three steps in cryptography

1. Precisely specify a threat (or attack) model

2. Propose a construction

3. Prove that breaking construction under threat mode will solve an underlying hard problem (Security Proof)

Attack models

- Ciphertext only
- Known plaintext
- Chosen plaintext (CPA)
- Chosen ciphertext (CCA1, CCA2)
- Exhaustive key search (in honey encryption)

Ciphertext only attack

- Attacker has access to a set of ciphertexts
- Guess-and-check
- Frequency analysis

Known plaintext attack

- Attacker has the ciphertext and some samples of plaintext
- Apply the known plaintext to the ciphertext to help decryption
- Preferred over ciphertext-only

Chosen plaintext attack

- Chooses a plaintext and receives corresponding ciphertext
- Two variations
  - Batch Chosen-Plaintext
    - Attacker chooses a “batch” of plaintexts before any encrypted ciphertext is received
  - Adaptive chosen-plaintext
    - Attacker makes n-amounts of interactive queries and alters their plaintext based on the previous queries

Chosen ciphertext attack

- Tries to discover the key
- Uses a ciphertext chosen by attacker
- Relies on being able to obtain decrypted plaintext
- Two variations
  - Lunchtime attack (CCA1)
  - Adaptive chosen-ciphertext (CCA2)

Lunchtime attack (CCA1)

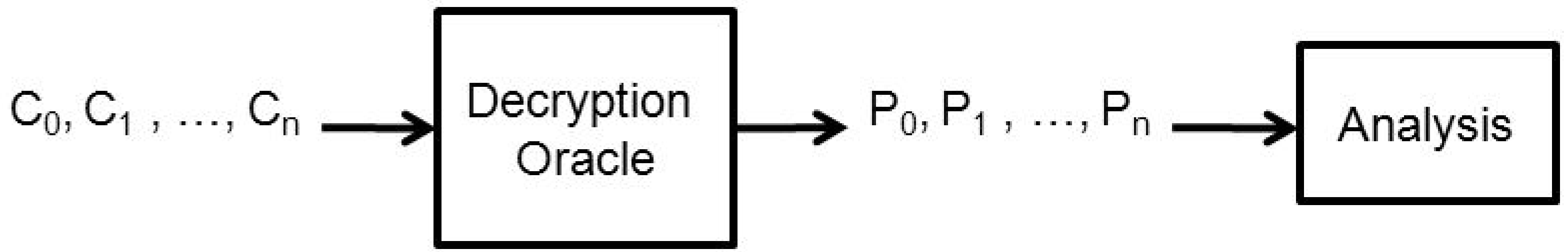
- Attacker can make queries but only up until a certain point
- Attacker cannot adapt queries
  - Results given after the ability to makes queries expires

Adaptive Chosen-Ciphertext (CCA2)

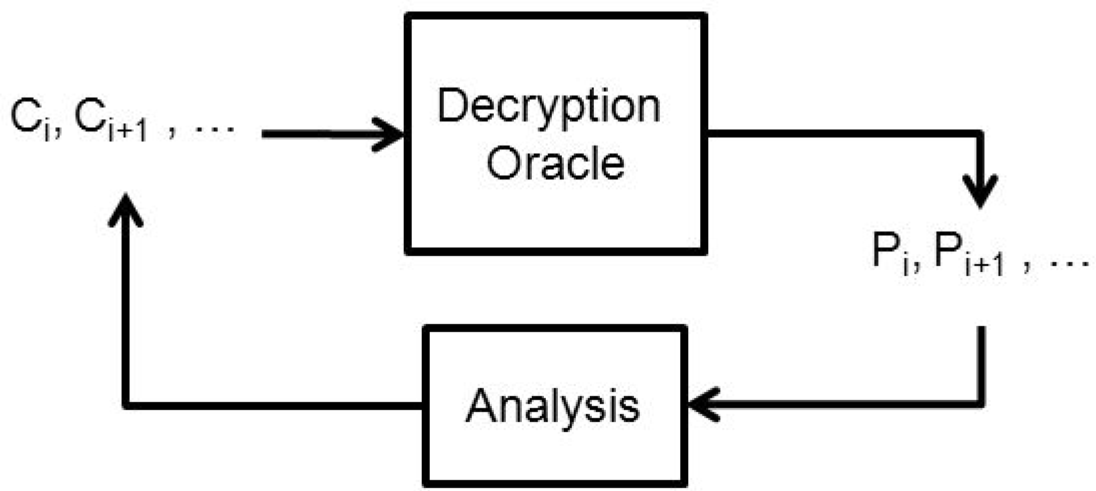
- Similar to normal chosen-ciphertext
- Ciphertext is chosen based on the result of the previous queries

CCA1 vs CCA2

- CCA1 (Lunchtime Attack)



- CCA2 (Adaptive Chosen Ciphertext Attack)



History

- Egyptians 4000 years ago
- World war 1&2

Enigma machine

- As a tool to protect national secrets and strategies

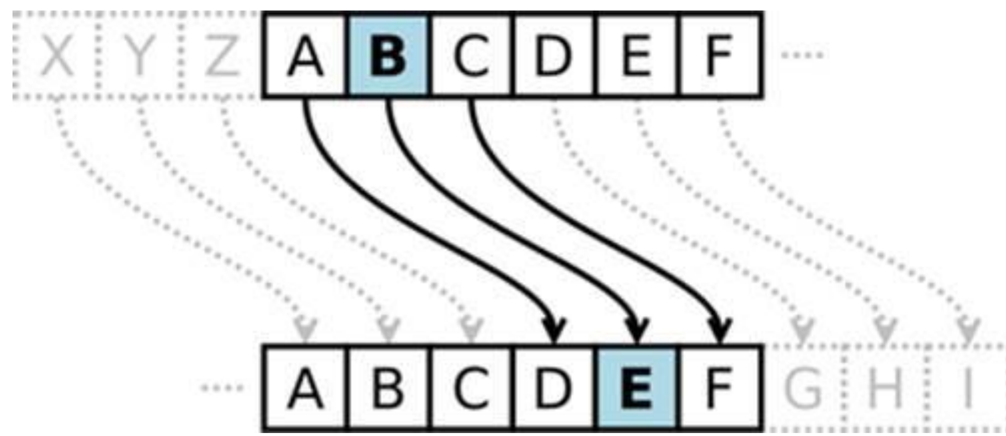
The Imitation game (movie)

https://www.youtube.com/watch?v=eYfCvBDVSQY

Ceasar cipher (no key)

Shift by 3

a → d
b → e
c → f
…
z → c



$$c = E_k(\text{“abbc”})$$

$$= \text{“deef”}$$

Basic assumptions

- The system is completely known to the attacker
- Only the key is secret
- That is, crypto algorithms are not secret
- This is known as **Kerckhoff's Principle**
- Why do we make this assumption?
  - Experience has shown that secret algorithms are weak when exposed
  - Secret algorithms never remain secret
  - Better to find weaknesses beforehand

Substitution cipher with shift

Shift by k

a → c
b → d
c → e
…
z → b

Key k

$c = E_k(\text{“abbc”}),\ k = 2$

$= \text{“cdde”}$

How to break this cipher? Try them all

- A simple substitution (shift by n) is used
  - But the key is unknown
- Given ciphertext: cdde
- How to find the key?
- Only 26 possible keys — try them all!
- **Exhaustive key search**
- Solution: key is $\mathrm{k} = 2$

Substitution cipher with permutation

Use any permutation of letters

a → e
b → c
c → q
…
z → a

Key permutation

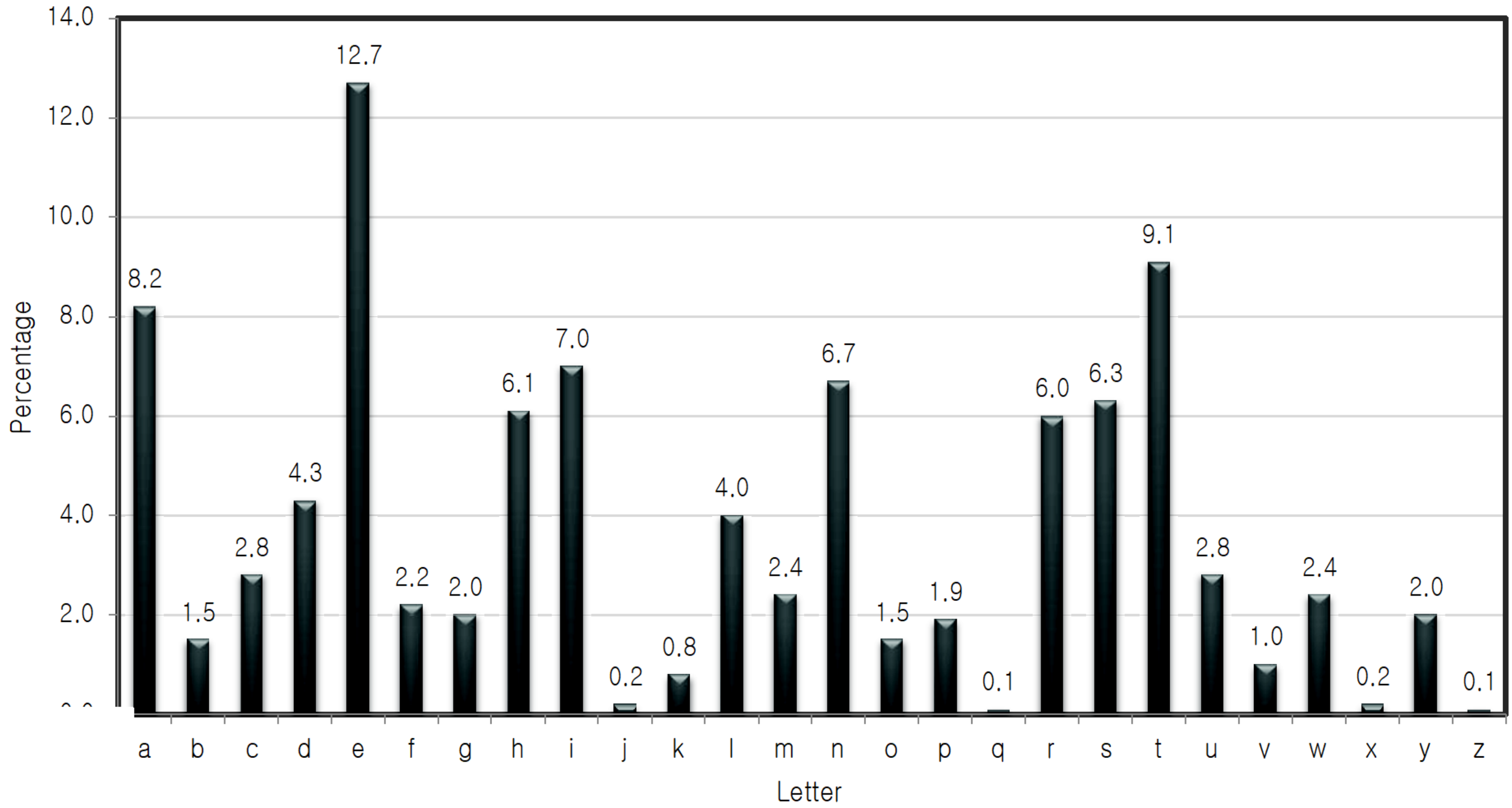
$$c = E_k(\text{“abbc”})$$

$$= \text{“eccq”}$$

Then $26! > 2^{88}$ possible keys!

How to break this cipher?

- Use letter frequencies; most common letters in English are e, t, a, I, o, n, s, h, r, d, l, u



An example of cryptanalysis

- Ciphertext:

PBFPVYFBQXZTYFPBFEQJHDXXQVAPTPQJKTOYQWIPBVWLXTOXBTFXQWAXBVCXQWAXFQJVWLE
QNTOZQGGQLFXQWAKVWLXQWAEBIPBFXFQVXGTVJVWLBTPQWAEBFPBFHCVLXBQUFEVWLXG
DPEQVPQGVPPBFTIXPFHXZHVFAGFOTHFEFBQUFTDHZBQPOTHXTYFTODXQHFTDPTOGHFQPBQ
WAQJJTODXQHFOQPWTBDHHIXQVAPBFZQHCFWPFHPBFIPBQWKFABVYYDZBOTHPBQPQJTQOT
OGHFQAPBFEQJHDXXQVAVXEBQPEFZBVFOJIWFFACFCCFHQWAUVWFLQHGFXVAFXQHFUFHILTT
AVWAFFAWTEVOITDHFHFQAITIXPFHXAFQHEFZQWGFLVWPTOFFA

Analyze this message using statistics below

Ciphertext frequency counts:

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
21	26	6	10	12	51	10	25	10	9	3	10	0	1	15	28	42	0	0	27	4	24	22	28	6	8

This might be ‘e’.

Vigenère cipher

- 16th century – the Vigenère

plaintext	tobeornottobethatistheques ···
key	runrunrunrunrunrunrunrunru ···
ciphertext	KIOVIEEIGKIOVNURNVJNUVKHVM ···

- Use repeated patterns at multiples of key length (Kasiski, 1883) – here, 'KIOV'
- Size of key space?
  – If keys are 14-character strings; then key space has size $26^{14} \approx 2^{66}$
- Modern cryptanalysis (1915): Using index of coincidence to guess the key length

Variant Vigenère cipher

- Easier to work with ASCII plaintext and hex ciphertext
  - Easier to implement
  - Easier to use (plaintext not limited to lowercase characters)

- Easier to work with byte-wise XOR rather than modular addition

Variant Vigenère cipher

- The key is a string of bytes
- The plaintext is a string of ASCII characters
- To encrypt, XOR each character in the plaintext with the next character of the key
- Decryption just reverses the process

Example

- Say plaintext is “Hello!” and key is 0xA1 2F
- “Hello!” = 0x48 65 6C 6C 6F 21
- XOR with 0xA1 2F A1 2F A1 2F
- 0x48 $\oplus$ 0xA1
  - 0100 1000 $\oplus$ 1010 0001 = 1110 1001 = 0xE9

- Ciphertext: 0xE9 4A CD 43 CE 0E

Attacking the Vigenère cipher

- Two steps:
  - Determine the key length
  - Determine each character of the key

Determining the key length

- Let p_i (for $0 \leq i \leq 255$) be the frequency of byte i in plaintext (assuming English text)
  - I.e., p_i =0 for i<0 or i>127
  - I.e., p_{97} = frequency of 'a'
  - The distribution is far from uniform
- If the key length is N, then every N^{th} character of the plaintext is encrypted using the same "shift"
  - If we take every N^{th} character and calculate frequencies, we should get the p_i's in permuted order
  - If we take every M^{th} character (M not a multiple of N) and calculate frequencies, we should get something close to uniform

Determining the key length

- How to distinguish these two?
- For some candidate distribution $q_0, \ldots, q_{255}$, compute $\Sigma\, q_i^2$
  - If close to uniform, $\Sigma\, q_i^2 \approx 256 \cdot (1/256)^2 = 1/256$
  - If a permutation of p_i, then $\Sigma\, q_i^2 \approx \Sigma\, p_i^2$
    - Could compute $\Sigma\, p_i^2$ (but somewhat difficult)
    - Key point: will be much larger than 1/256
- Try all possibilities for the key length, compute $\Sigma\, q_i^2$, and look for maximum value

Index of Coincidence - Plaintext

Letter	a	b	c	d	e	f	g	h	i	j	k	l	m
Frequency	.082	.015	.028	.043	.127	.022	.020	.061	.070	.002	.008	.040	.024
Letter	n	o	p	q	r	s	t	u	v	w	x	y	z
Frequency	.067	.075	.019	.001	.060	.063	.091	.028	.010	.023	.001	.020	.001

Beker and Piper, *Cipher Systems: The Protection of Communications*, Wiley.

$$\begin{array}{ccccccccc} \text{aa} & \text{or} & \text{bb} & \text{or} & \text{cc} & \text{or} & \ldots & \text{or} & \text{zz} \\ .082\times.082 & + & .015\times.015 & + & .028\times.028 & + & \ldots & + & .001\times.001 \end{array}$$

$$I \approx 0.0656010$$

Index of Coincidence - Uniform

$$I \approx \underbrace{\left(\frac{1}{26}\times\frac{1}{26}\right)+\left(\frac{1}{26}\times\frac{1}{26}\right)+\left(\frac{1}{26}\times\frac{1}{26}\right)+\ldots+\left(\frac{1}{26}\times\frac{1}{26}\right)}_{\text{26 terms}}=\frac{1}{26}\approx 0.038$$

Determining the i^{th} byte of the key

- Assume the key length N is known
- Look at every N^{th} character of the ciphertext, starting with the i^{th} character
  - Call this the i^{th} ciphertext "stream"
  - Note that all bytes in this stream were generated by XORing plaintext with the same byte of the key
- Try decrypting the stream using every possible byte value B
  - Get a candidate plaintext stream for each value

Determining the i^{th} byte of the key

- When the guess B is correct:
  - All bytes in the plaintext stream will be between 0 and 127
  - Frequencies of lowercase letters (as a fraction of all lowercase letters) should be close to known English-letter frequencies
    - Tabulate $q_a, \ldots, q_z$
    - Should find $\Sigma\, q_i\, p_i \approx \Sigma\, p_i^2 \approx 0.065$
    - In practice, take B that maximizes $\Sigma\, q_i\, p_i$, subject to caveat above (and possibly others)

Attack time?

- The key length is between 1 and L
- Determining the key length: $\approx 256\, L$
- Determining all bytes of the key:
  - Guessing B at ith character: 256
  - Calculating $\Sigma\, q_i\, p_i$ at ith character: 256
  - Total: $256^2\, L$

- Brute-force key search: $\approx 256^L$

The attack in practice

- Attacks get more reliable as the ciphertext length grows larger

- Attacks still work for short(er) ciphertexts, but more “tweaking” and manual involvement is needed

One Time Pad (OTP)

First example of a "secure" cipher

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

Choose key k as random bit string as long the message!

$\mathcal{K} = \{0, 1\}^n$

$$\boxed{\text{Encryption: } c = k \oplus m}$$

Very fast enc/dec !!

… but long keys (as long as plaintext)

Quiz

You are given a message (m) and its OTP encryption (c).

Q. Can you compute the OTP key from m and c ?

Yes, the key is $k = m \oplus c$.

OTP has perfect secrecy

Q. What is the perfect secrecy?

Information Theoretic Security

(Shannon 1949)

Def: A cipher $(\boldsymbol{E}, \boldsymbol{D})$ over $(\mathcal{K}, \mathcal{M}, \mathcal{C})$ has **perfect secrecy** if

$\forall m_0, m_1 \in \mathcal{M} \quad (|m_0| = |m_1|)$ and $\forall c \in \mathcal{C}$

$$Pr[\, \boldsymbol{E}(\boldsymbol{k}, \boldsymbol{m_0}) = \boldsymbol{c} \,] = Pr[\, \boldsymbol{E}(\boldsymbol{k}, \boldsymbol{m_1}) = \boldsymbol{c} \,] \quad \text{where} \quad k \overset{R}{\leftarrow} \mathcal{K}$$

- Given *c*, we can't tell if *m* is m_0 or m_1
- Any adversary can't learn any information about *m* from *c*
- In other words, *m* and *c* are independent
- No ciphertext only attack!! (but other attacks might be possible)

Claude Shannon

Claude Shannon

Scholar

About 60,400 results (**0.03** sec)

Articles

Case law

My library

A mathematical theory of communication

CE **Shannon** - ACM SIGMOBILE Mobile Computing and ..., 2001 - dl.acm.org

T HE recent development of various methods of modulation such as PCM and PPM which exchange band-width for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist 1

Cited by 93703 Related articles All 677 versions Cite Saved

OTP has perfect secrecy
(Shannon 1949)

Proof:

$\forall m, c$ **:**

$$\Pr_k[E(k, m) = c] = |\{ k \in \mathcal{K} : E(k, m) = c \}| \,/\, |\mathcal{K}|$$

$$= 1 \,/\, |\mathcal{K}|$$

Unfortunately …

(Shannon's theorem)

<u>Thm</u>: If a shared-key encryption has perfect secrecy

$\Rightarrow \quad |\mathcal{K}| \geq |\mathcal{M}|$

- That is, key length should be greater than message length to achieve perfect secrecy.
- It is hard to use in practice!!!

Using the same key twice?

- $c_1 = k \oplus m_1$

  $c_2 = k \oplus m_2$

- Attacker can compute

  $c_1 \oplus c_2 = (k \oplus m_1) \oplus (k \oplus m_2) = m_1 \oplus m_2$

- This leaks information about m_1, m_2!
  - No longer perfectly secret! (e.g., $m_1 \oplus m_2$ reveals where m1, m2 differ)
  - Frequency analysis

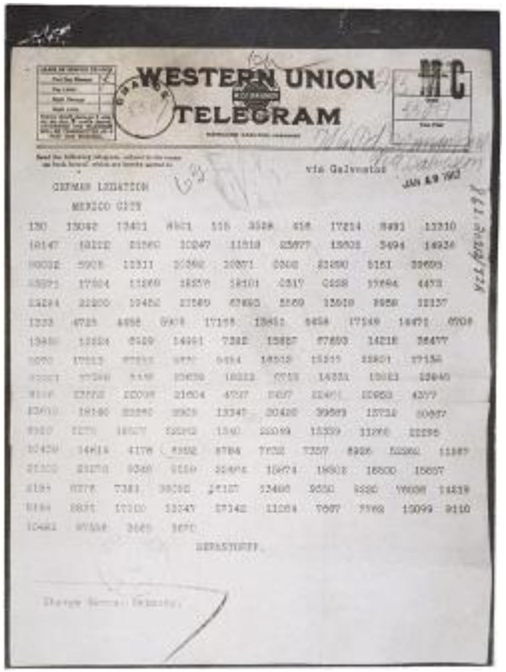
OTP in practice: The Moscow-Washington hotline

- A device called *Electronic Teleprinter Cryptographic Regenerative Repeater Mixer II* (ETCRRM II) encrypted the teletype messages.
- ETCRRM II used OTP.
- Each country delivered keying tapes used to encode its messages via its **embassy** abroad.

Codebook Cipher

- Literally, a book filled with “codewords”
- Zimmerman Telegram encrypted via codebook

Februar	13605
fest	13732
finanzielle	13850
folgender	13918
Frieden	17142
Friedenschluss	17149
:	:



- Modern block ciphers are codebooks!

One more thing!

- Fundamental concepts
  - **Confusion** —— obscure relationship between plaintext and ciphertext
  - **Diffusion** —— spread plaintext statistics through the ciphertext
- One-time pad is confusion-only

Double transposition

Plaintext: attackxatxdawn

	col 1	col 2	col 3
row 1	a	t	t
row 2	a	c	k
row 3	x	a	t
row 4	x	d	a
row 5	w	n	x

Permute rows and columns

	col 1	col 3	col 2
row 3	x	t	a
row 5	w	x	n
row 1	a	t	t
row 4	x	a	d
row 2	a	k	c

- Ciphertext: xtawxnattxadakc
- What is the key?
- Key is matrix size and permutations: (3,5,1,4,2) and (1,3,2)
- Double transposition is diffusion-only

Modern Cipher Systems

- Many systems from the last century use stream ciphers for speed / low gate count
- Bank systems use a 1970s block cipher, the data encryption standard or DES; recently moving to triple-DES for longer keys
- New systems mostly use the Advanced Encryption Standard (AES), regardless of whether a block cipher or stream cipher is needed

Questions?

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Suwon
School
Seoul
Natural
Graduate
campus
English
Korean
Social
Global
edit
constructed
Professors
Confucian
Humanities
lecturers
Building
Institute
Education
Business
schools
Science
Administration
Academic
ASLE-Korea
Advanced
Engineering
located
Joseon
Anniversary
University's
establishment
now
two
four
also
city
one
heart
trees