CSE 3400/CSE 5850 - Introduction to Cryptography and Cybersecurity/ Introduction to Cybersecurity

Lecture 2
Encryption – Part I

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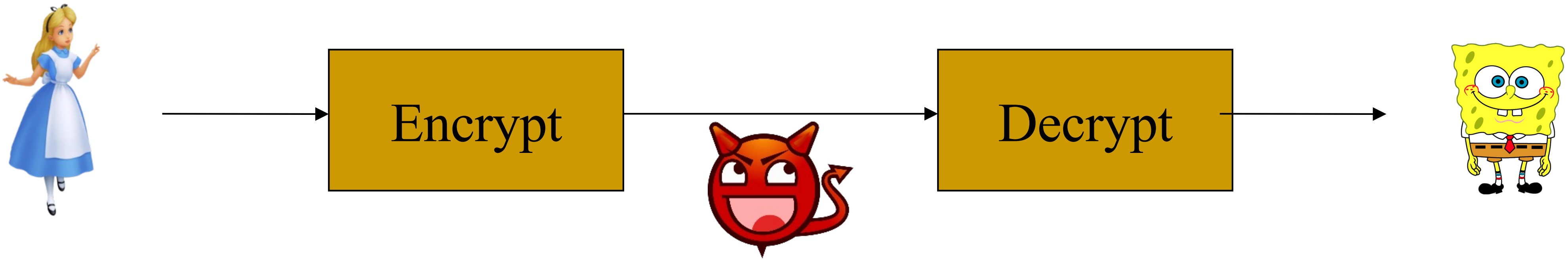
Adapted from the textbook slides

Outline

- Introduction and motivation.
- Ancient ciphers.
- Kerckhoffs' Principle.
- Encryption attacker models.

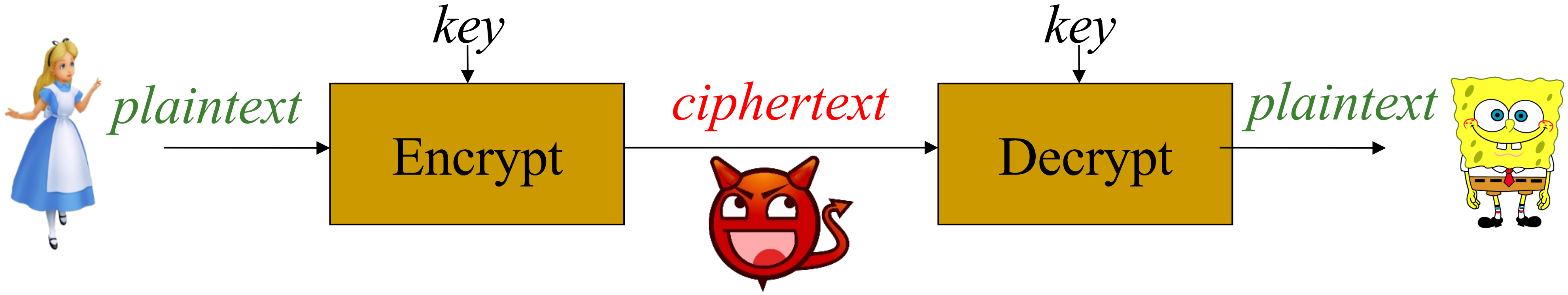
Encryption

- Prevention of exposure of secret information
- Earliest and `basic’ tool of cryptology
- Related terms:
  - Cryptography: `secret writing’
  - Cryptanalysis: `breaking’ encryption
  - Encryption scheme = Cryptosystem = Cipher



The Encryption World: basic terms

- Goal: **encrypt** plaintext into ciphertext
- Only legit-recipient can **decrypt** ciphertext to plaintext
  - Adversary cannot learn anything from ciphertext



key

key

plaintext

Encrypt

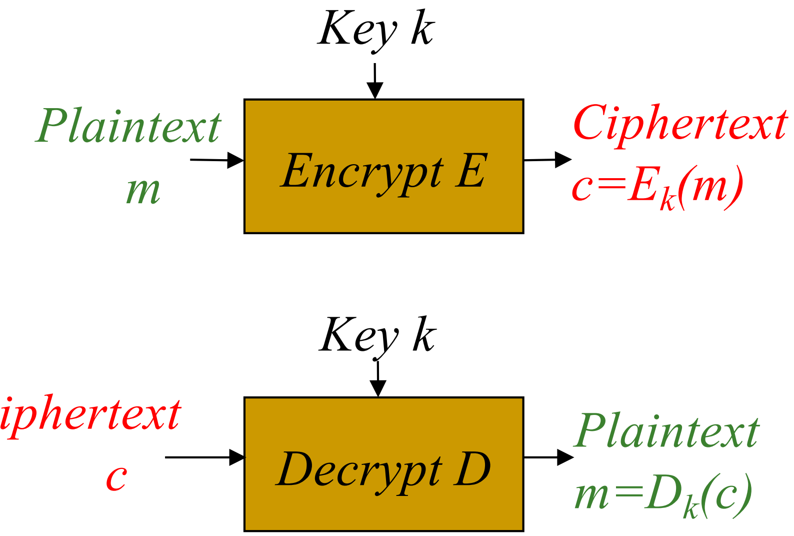
ciphertext

Decrypt

plaintext

- Variants of encryption schemes:
  - Keyed or unkeyed?
  - Shared key (symmetric) or public/private keys (asymmetric)?
  - Stateful / stateless ? Randomized ? Input size ?

Symmetric Encryption Scheme



Key k

Plaintext m

Encrypt E

Ciphertext $c=E_k(m)$

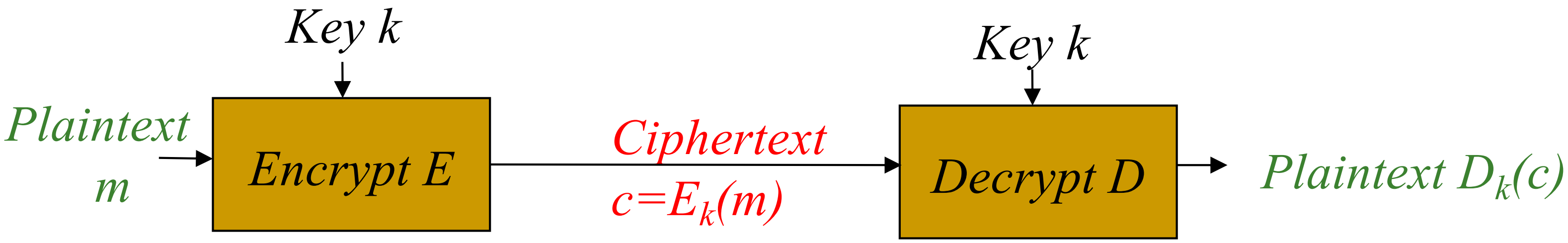
Key k

Ciphertext c

Decrypt D

Plaintext $m=D_k(c)$

This is a stateless encryption, stateful will additionally have state as input and updated state as output.



Key k

Plaintext m

Encrypt E

Ciphertext $c=E_k(m)$

Key k

Decrypt D

Plaintext $D_k(c)$

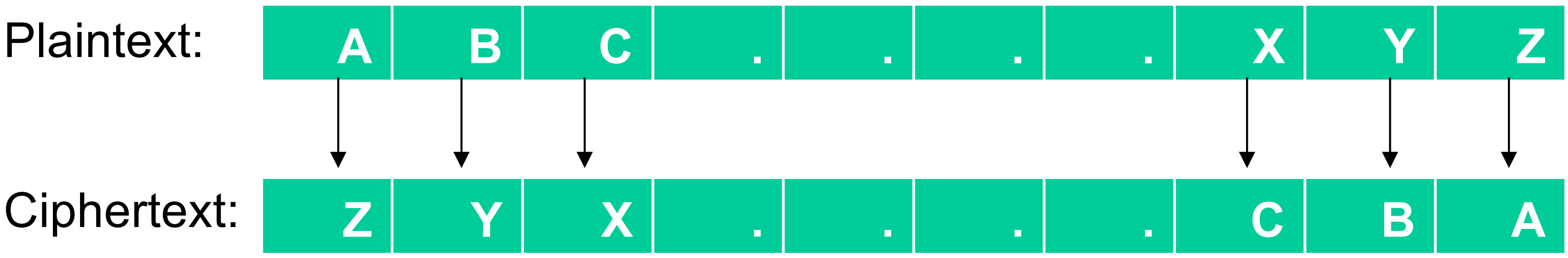
Correctness: $m=D_k(E_k(m))$

Ancient, Keyless Ciphers

- Ancient ciphers were simple, naive
  - No key: secrecy is in the algorithm
- Monoalphabetic ciphers: encrypt/decrypt one character at a time
  - Plaintext, ciphertext are both single letters
  - A set {<E,D>} of permutation + inverse: m=D(E(m))

Az-By Cipher

- Az-By Cipher
  - Substitute the first letter of alphabet by the last… and so on:
- Mathematically: Let A be 0, B be 1, …, Z be 25. Let m denote plaintext and c denote ciphertext.
  - c = Enc(m) = 25 – m
  - m = Dec(c) = 25 - c

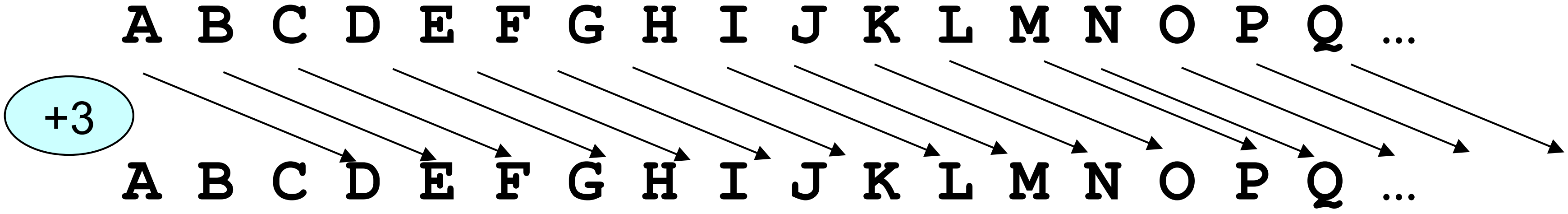


Plaintext: A B C . . . . X Y Z

Ciphertext: Z Y X . . . . C B A

(Unkeyed) Caesar Cipher

- Used by Julius Caesar
- Rotate the 26 letters of the alphabet by 3:



A B C D E F G H I J K L M N O P Q …

+3

A B C D E F G H I J K L M N O P Q …

- As formula:

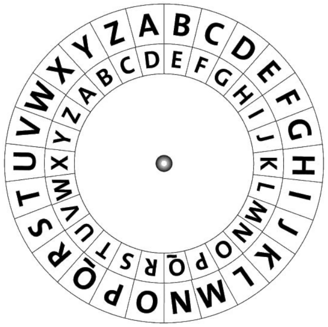
$$c = E(m) = m+3 \pmod{26}$$

$$m = D(c) = c-3 \pmod{26}$$

- Ceasar and AzBy are trivial to cryptanalyze
  - No key – algorithm itself is \`secret\`
  - ‘Security by obscurity’

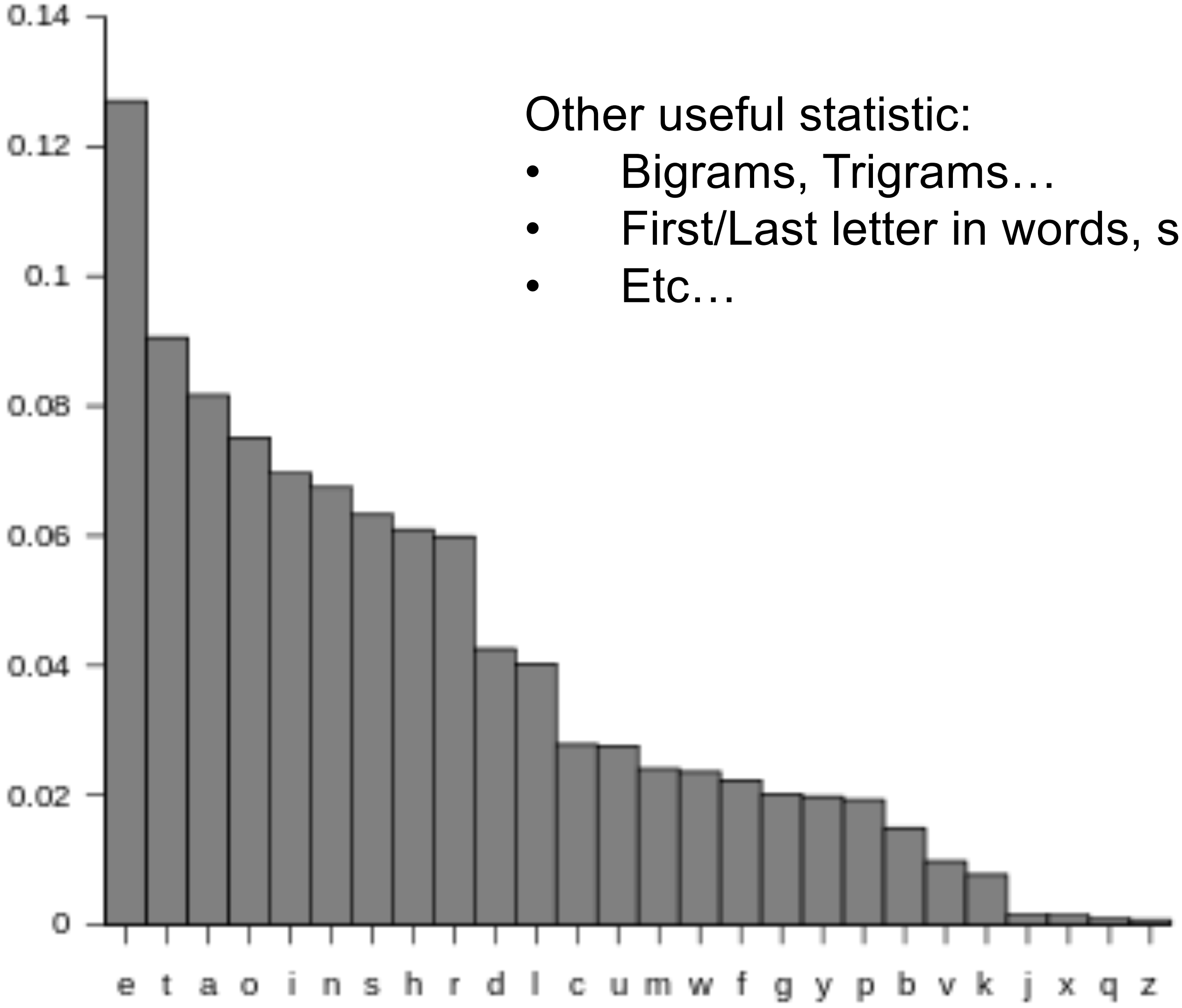
Monoalphabetic Substitution Ciphers

- Generalize Caesar and Az-By:
  - Other permutations of letters
    - To letters or to other symbols (no real difference)
  - Keyed: Given key k, cipher E_k is a permutation
  - Or: the ‘key’ is simply the permutation (table)
  - Classical, `elementary school’ cryptosystem
  - Examples:


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
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

- Vulnerable to letter-frequency cryptanalysis

Letter frequencies (in English)



Other useful statistic:

- Bigrams, Trigrams…
- First/Last letter in words, sentences
- Etc…

Example: Frequency Cryptanalysis

Given ciphertext:

UZQSOVUOHXMOPVGPOZPEVSGZWSZOPFPESXUDBMETSXAIZ

VUEPHZHMDZSHZOWSFPAPPDTSVPQUZWYMXUZUHSX

EPYEPOPDZSZUFPOMBZWPFUPZHMDJUDTMOHMQ

Count relative letter frequencies:

A	B	C	D	E	F	G	H	I	J	K	L	M
2	2	0	6	6	4	2	7	1	1	0	0	8

N	O	P	Q	R	S	T	U	V	W	X	Y	Z
0	9	16	3	0	10	3	10	5	4	5	2	14

Example: Frequency Cryptanalysis

Given ciphertext:

```
UZQSOVUOHXMOPVGPOZPEVSGZWSZOPFPESXUDBMETSXAIZ
VUEPHZHMDZSHZOWSFPAPPDTSVPQUZWYMXUZUHSX
EPYEPOPDZSZUFPOMBZWPFUPZHMDJUDTMOHMQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t											
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0

Most frequent letter is e, so: P=E(e)
Second frequent is t, so: Z=E(t) … let's replace…

Example: Frequency Cryptanalysis

Given ciphertext:

```
UtQSOVUOHXMOeVGeOteEVSGtWStOeFeESXUDBMETSXAIt
VUEeHtHMDtSHtOWSFeAeeDTSVeQUtWYMXUtUHSX
EeYEeOeDtStUFeOMBtWeFUetHMDJUDTMOHMQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t											
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0

In English texts, \`t\` is often followed by \`h\`. Count chars following Z (t):
Twice: W, H, U and O; once: Q, V, D & S. Pick W, since this gives \`the'…

Example: Frequency Cryptanalysis

Given ciphertext:

UtQSOVUOHXMOeVGeOteEVSGthStOeFeESXUDBMETSXAIt

VUEeHtHMDtSHtOhSFeAeeDTSVeQUthYMXUtUHSX

EeYEeOeDtStUFeOMBtheFUetHMDJUDTMOHMQ

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a										h

Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0

We have thSt with S being third-most common. After e and t, most common letters are: aoinshr (in this order). Only `a` fits, so…

Example: Frequency Cryptanalysis

Given ciphertext:

```
UtQaOVUOHXMOeVGeOteEVaGthatOeFeEaXUDBMETaXAIt
VUEeHtHMDtaHtOhaFeAeeDTaVeQUthYMXUtUHaX
EeYEeOeDtatUFeOMBtheFUetHMDJUDTMOHMQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a										h

Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0

Next common in ciphertext is U and in English are oinshr (in this order).
Few, rare words begin with `ot’ (and not `oth’), but `it` is common, so: U=E(i) !

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQaOViOHXMOeVGeOteEVaGthatOeFeEaXiDBMETaXAIt
ViEeHtHMDtaHtOhaFeAeeDTaVeQithYMXitiHaX
EeYEeOeDtatiFeOMBtheFietHMDJiDTMOHMQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i									h

Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0

Next common in ciphertext are OMH and in English are onsr (in this order).
‘O’=E(‘o’) is unlikely since it gives `that oeFeEa…` ➔ try ‘M’=E(‘o’)…

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQaOViOHXoOeVGeOteEVaGthatOeFeEaXiDBoETaXAIt
ViEeHtHoDtaHtOhaFeAeeDTaVeQithYoXitiHaX
EeYEeOeDtatiFeOoBtheFietHoDJiDToOHoQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i		o							h

Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0

Next common in ciphertext is O and in English is s… go for it: O=E(s)!

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQasVisHXoseVGesteEVaG that seFeEaXiDBoETaXAIt
ViEeHtHoDtaHtshaFeAeeDTaVeQithYoXitiHaX
EeYEeseDtatiFesoBtheFietHoDJiDTosHoQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o							h
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0

`that’ is mostly one word. Most common last-letter not assigned yet is `y`, which is not a common word, so: G=E(y)…

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQasVisHXoseVyesteEVay that seFeEaXiDBoETaXAIt
ViEeHtHoDtaHtshaFeAeeDTaVeQithYoXitiHaX
EeYEeseDtatiFesoBtheFietHoDJiDTosHoQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o							h

Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0
				y								

We now simply recognize the (quite common) word `yesterday’, so:
E=E(r), V=E(d)…

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQasdisHXosed yesterday that seFeraXiDBorTaXAIt
direHtHoDtaHtshaFeAeeDTadeQithYoXitiHaX
reYreseDtatiFesoBtheFietHoDJiDTosHoQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o			r	d			h
Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0
				y								

Next unused common letter is n (by far). But H doesn’t seem to fit… so D=E(n)…

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQasdisHXosed yesterday that seFeraXinBorTaXAIt
direHtHontaHtshaFeAeenTadeQithYoXitiHaX
reYresentatiFesoBtheFietHonJinTosHoQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o		n	r	d			h
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0
				y								

Long string with only one cipher-letter, H… only c fits so: H=E(c)…

Example: Frequency Cryptanalysis

Given ciphertext:

itQasdiscXosed yesterday that seFeraXinBorTaXAIt
direct contacts haFeAeenTadeQithYoXiticaX
reYresentatiFesoBtheFietconJinToscoQ

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o	c	n	r	d			h
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0
				y								

Next common cipher-letter is X and plain-letter is l, and it indeed fits: X=E(l) !

Example: Frequency Cryptanalysis

Given ciphertext:

```
itQas disclosed yesterday that seFeralinBorTalAIt
direct contacts haFeAeenTadeQithYolitical
reYresentatiFesoBtheFietconJinToscoQ
```

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o	c	n	r	d	l		h
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0
				y								

Next identify text begins with `it was’ and also two quite common words so : Q=E(w), Y=E(p), F=E(v) !

Example: Frequency Cryptanalysis

Given ciphertext:

it was disclosed yesterday that several inBorTalAIt
direct contacts have AeenTade with political
representatives oBthevietconJinToscow

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o	c	n	r	d	l	v	h
Q	T	A	B	G	Y	I	J	C	K	L	N	R
3	3	2	2	2	2	1	1	0	0	0	0	0
w				y	p							

Next: `oB’->`of’, ‘Aeen’->been, `Tade’->made, `vietconJ’->Vietcong, ..

Example: Frequency Cryptanalysis

Given ciphertext:

it was disclosed yesterday that several informal bIt
direct contacts have been made with political
representatives of the vietcong in moscow

Sorted:

P	Z	S	U	O	M	H	D	E	V	X	F	W
16	14	10	10	9	8	7	6	6	5	5	4	4
e	t	a	i	s	o	c	n	r	d	l	v	h
Q	**T**	**A**	**B**	**G**	**Y**	**I**	**J**	**C**	**K**	**L**	**N**	**R**
3	3	2	2	2	2	1	1	0	0	0	0	0
w	m	b	f	y	p		g					

(finally: I=E(u))

Security-by-Obscurity Ciphers

- Previous ciphers' security relied on obscurity
  - I.e., hope attacker does not know cipher
- Used extensively until 1883
  - Usually cryptanalyzed especially after encryption devices were captured
- What happened in 1883??
  - A conceptual leap in cryptography and security

Kerckhoffs' Known Design Principle [1883]

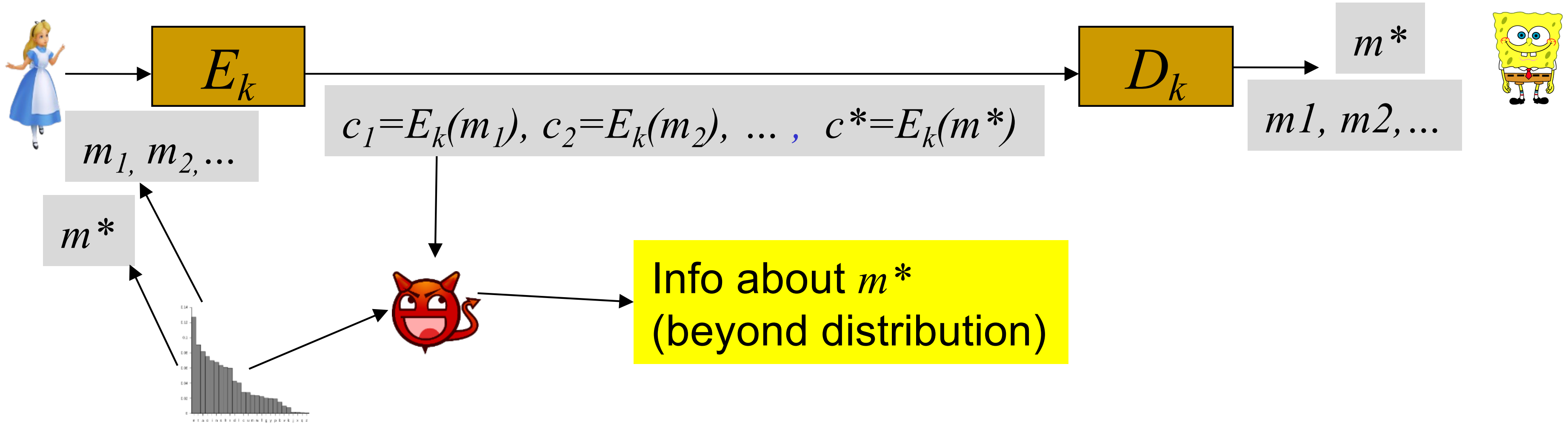
- Assume adversary knows the design – everything except the secret keys
- No `security by obscurity'
  - Although attacking obscure design <u>is</u> harder
- Why assume/use public design?
  - No need to replace system once design is exposed
  - Usually stronger
  - Establish standards for multiple applications:
    - Efficiency of production and of test attacks / cryptanalysis
- Secrecy is based only on secrecy of key

Exhaustive Key Search

- Kerckhoffs: Secrecy ≤ secrecy of key k
- Exhaustive Key Search: try all keys $k' \in \{0,1\}^{|k|}$
- How to identify correct key $k = k'$??
- Depends on **attacker capability (model)**
  - Critical element of security analysis!!
  - Attack models we will study:
    - Cipher-Text Only (COA) attack
    - Known-plaintext attack (KPA)
    - Chosen-plaintext attack (CPA)
    - Chosen-ciphertext attack (CCA)

Cipher-Text Only (COA) attack

- Adversary have previous knowledge about all possible plaintexts, like their distribution.
- Attacker's goal is to infer info about the challenge plaintext m* beyond the initial info it has.
  - This is given only ciphertexts and the plaintext distribution



E_k

$m_1, m_2, \ldots$

m^*

$c_1 = E_k(m_1),\ c_2 = E_k(m_2),\ \ldots ,\ c^* = E_k(m^*)$

D_k

m^*

$m1, m2, \ldots$

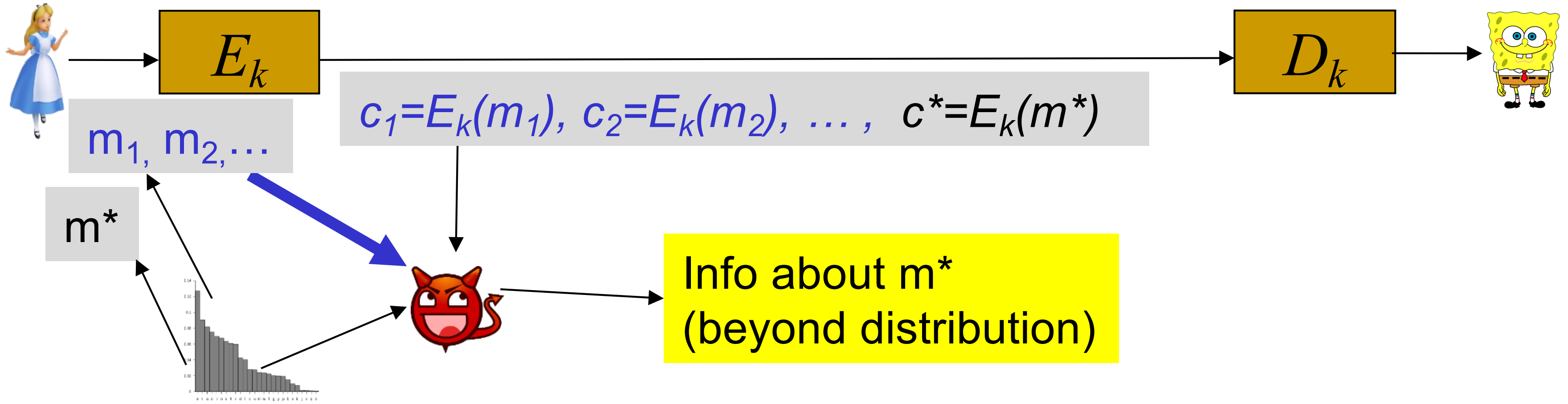
Info about m^*
(beyond distribution)

Exhaustive Key Search and COA

- Exhaustive Key Search: try all keys $k' \in \{0,1\}^{|k|}$
- How to identify correct key $k = k'$ given COA??
  - Decrypt ciphertexts, then check resulting `plaintext'
    - Let m_1 , m_2 , ... be a set of random plaintext samples (adversary does not know these)
    - Let $c_1=E_k(m_1)$, $c_2=E_k(m_2)$, ... be corresponding ciphertexts
    - To test if the key is k', compute set $M'=\{D_{k'}(c_1), D_{k'}(c_2), ...\}$
    - If M' fits plaintext distribution: k' is probably the key
    - Otherwise: k' is probably not the key
  - Challenge: test often is inconclusive

Known Plaintext Attack (KPA)

- Sample messages M={m_1, m_2,…} from a given distribution.
- Give M and ciphertexts $c_1=E_k(m_1)$, $c_2 =E_k(m_2)$, … to the attacker who is trying to infer more info about the challenge.

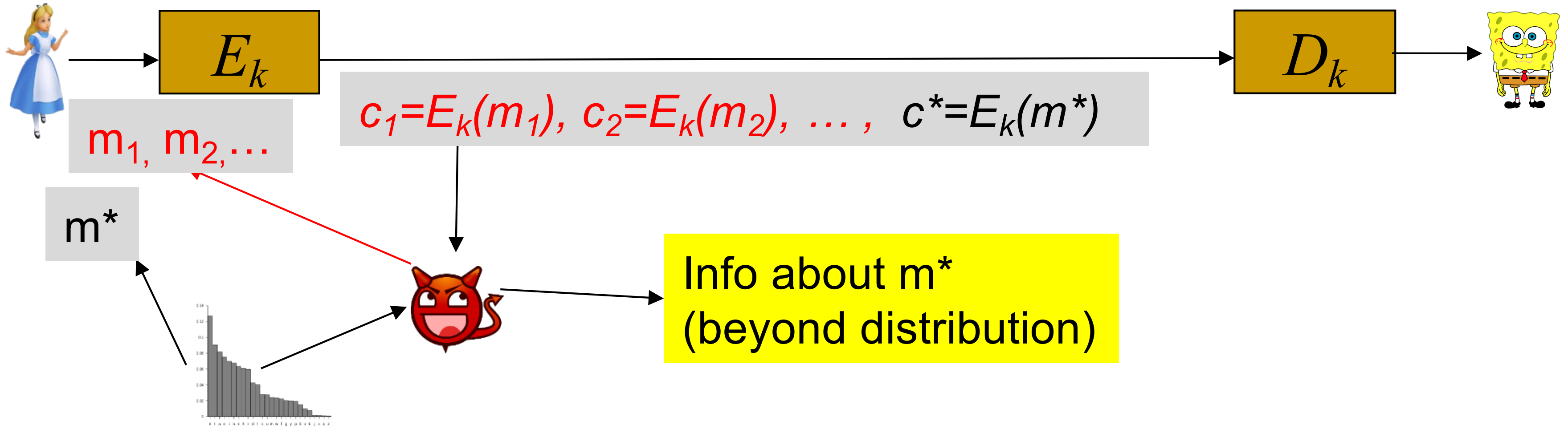


Exhaustive Key Search and KPA

- Exhaustive Key Search: try all keys $k' \in \{0,1\}^{|k|}$
- How to identify correct key $k = k'$ given KPA??
  - Attacker obtains known plaintext, ciphertext pairs: $(m_1, c_1=E_k(m_1)), (m_2, c_2=E_k(m_2)), \dots$
  - To test if the key is k', compute $m'_1=D_{k'}(c_1), m'_2=D_{k'}(c_2), \dots.$
  - If for every pair i holds $m'_i=m_i$ then k' is probably the key
  - Otherwise: k' is probably <u>not</u> the key
- COA and KPA attacks must test about half the keys.
  - On average, the attacker will find the key after trying half of all possible keys.

Chosen Plaintext Attack (CPA)

- Beside the plaintext distribution/initial info, attacker can choose messages m_1, m_2,…
- Give ciphertexts of these plaintext messages to the attacker who is trying to obtain more info about the challenge.



E_k

D_k

m_1, m_2,…

$c_1=E_k(m_1)$, $c_2=E_k(m_2)$, … , $c^*=E_k(m^*)$

m*

Info about m*
(beyond distribution)

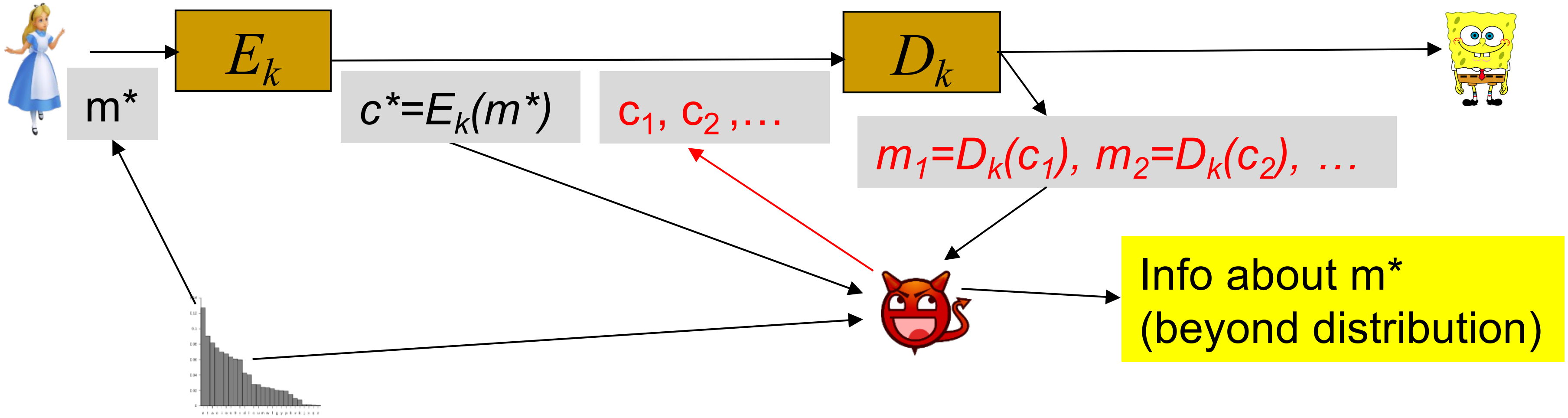
Exhaustive Key Search and CPA

- Generic CPA: Table-Lookup
  - Choose some fixed plaintext m
    - E.g., some default message: `good morning!’
    - Quite common in practice… e.g., in web (http), GSM,…
  - Offline: fill a table T. For every key k', compute $T(k')=E_{k'}(m)$
  - Online: select plaintext m, obtain $c=E_k(m)$
  - If $T(k')= c$ then k' probably the key: $k'=k$
  - Otherwise: k' is probably <u>not</u> the key
  - Time complexity $t=O(1)$ lookup time, requires $2^{|k|}$ memory
- More advanced: Time/Memory tradeoffs (e.g., rainbow tables)
  - Use hash functions, so we can’t yet discuss

As described here, this works only for deterministic encryption schemes!!

Chosen Ciphertext Attack (CCA)

- Beside being able to choose plaintexts and obtain their encryptions, attacker can select <u>ciphertexts</u> c_1, c_2,…, and receive decryptions (but not the challenge).
- Again, attacker tries to infer more info about the challenge.



m*

E_k

$c^*=E_k(m^*)$

c_1, c_2 ,…

D_k

$m_1=D_k(c_1)$, $m_2=D_k(c_2)$, …

Info about m*
(beyond distribution)

The Attack Models Championship

- We discussed several attack models:
  - COA, KPA, CPA, CCA
- Model A is stronger than model B, if a cipher secure against A is also secure against B
  - Notation: A > B
  - Example: KPA > COA [why?]
- KPA vs. CPA ?
- KPA vs. CCA?
- CPA vs. CCA ?

Sufficient Effective Key Length

- ***Sufficient Effective Key Length Principle:***
  - Keys should be long enough to make attacks infeasible, for best adversary resources expected, during `sensitivity period` of data
  - Exhaustive search – or other attacks
- Large key-space is necessary, but not sufficient
  - Monoalphabetic substitution cipher, with permutation as key: $26! = 4 \cdot 10^{26}$ keys… yet insecure!
  - **Effective key length:** log of number of trials by the most effective attack
    - Same as **number of bits for exhaustive search**
    - Defined for specific attack models

Covered Material From the Textbook

- Chapter 2:
  - From the chapter beginning until the end of section 2.4 except:
    - Section 2.1.3,
    - Section 2.2.5,
    - Section 2.4.2,
    - Any ancient ciphers from 2.2.1 that we did not study in class,

Thank You!