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

Lecture 2

Encryption – Part I

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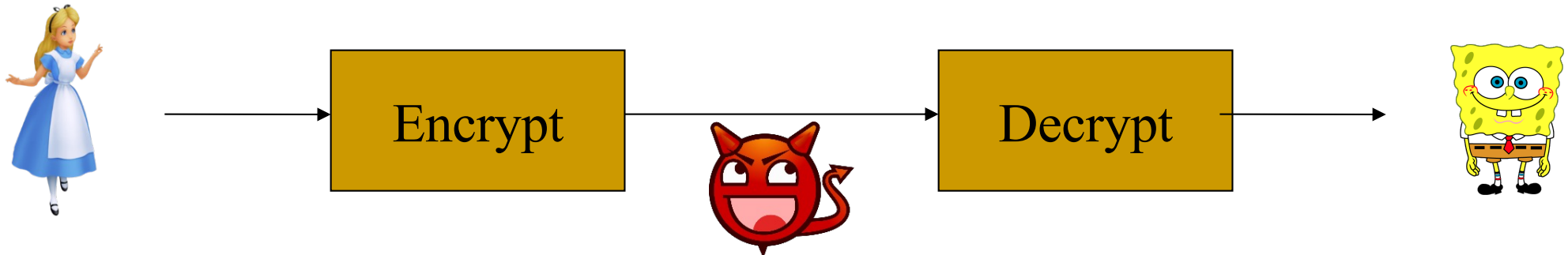
Adapted from the textbook slides

Outline

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

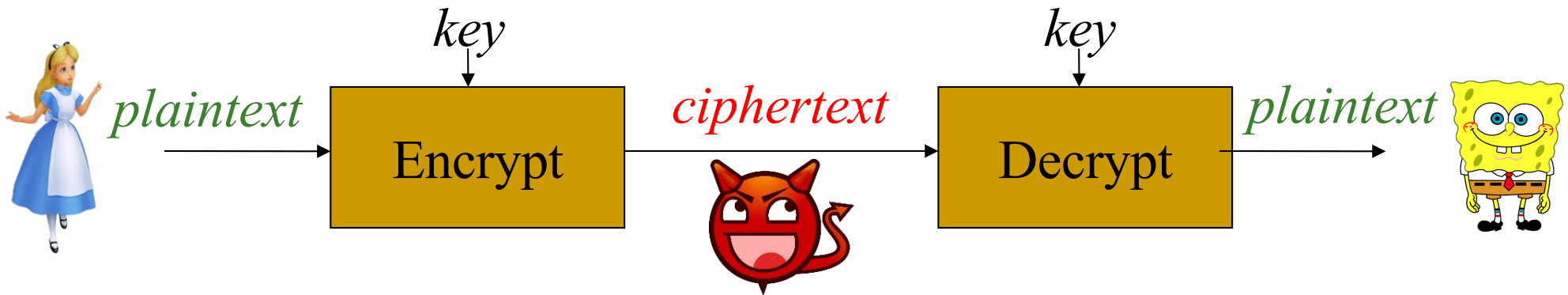
Encryption

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



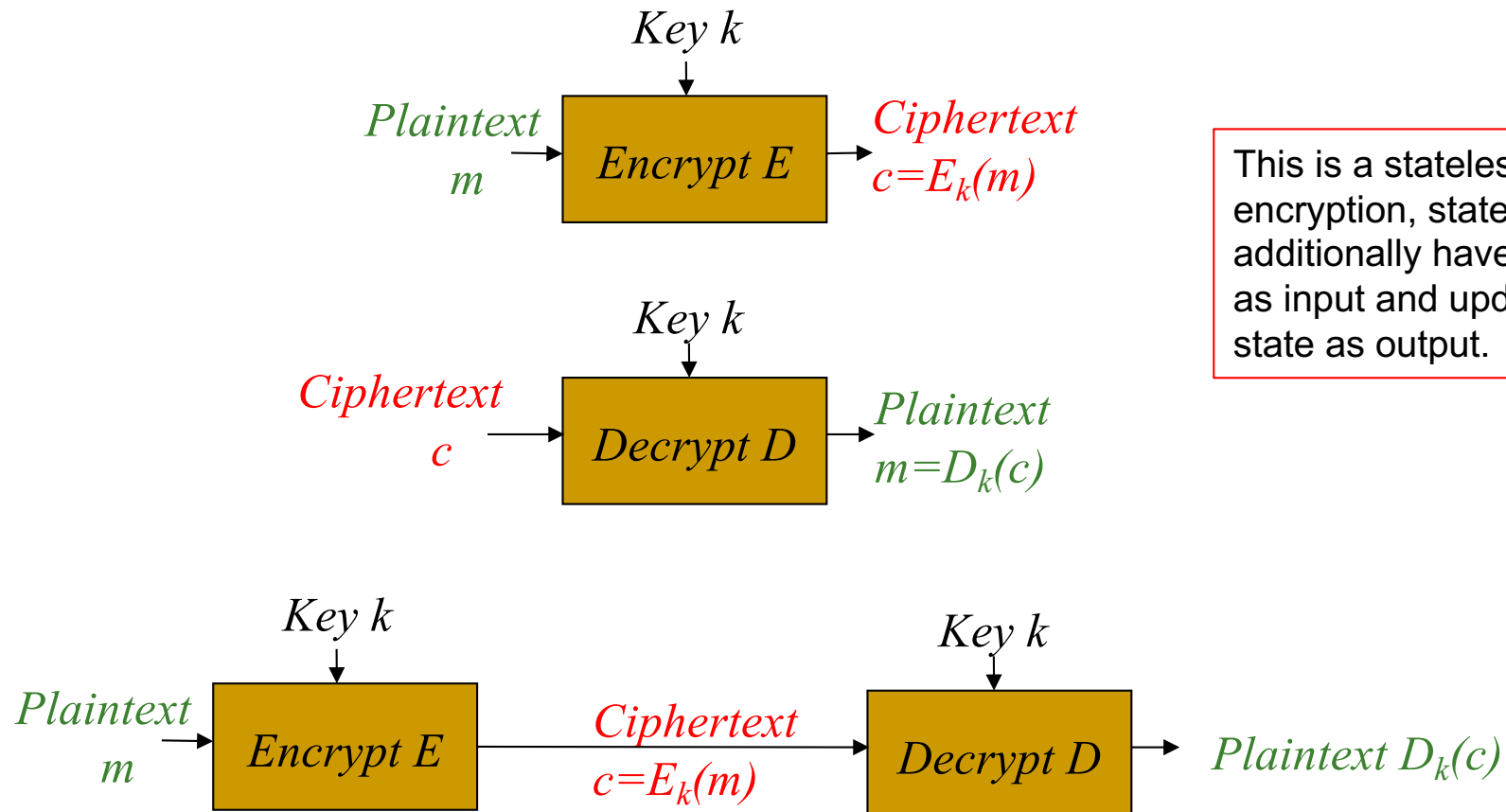
The Encryption World: basic terms

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



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

Symmetric Encryption Scheme



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

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: $m=D(E(m))$

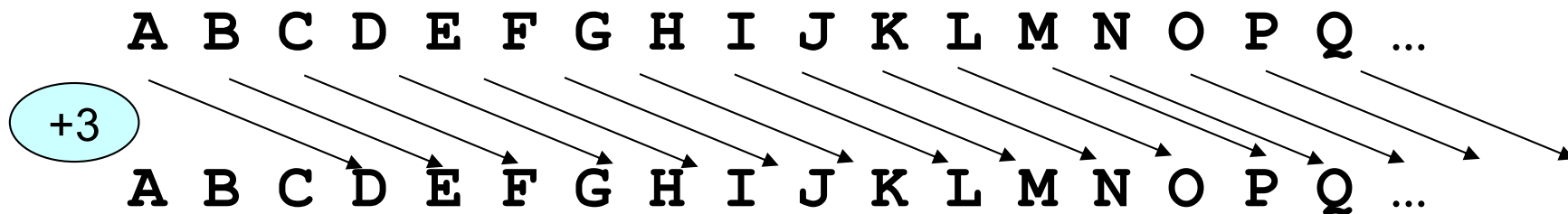
Az-By Cipher

- 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.
 - $c = \text{Enc}(m) = 25 - m$
 - $m = \text{Dec}(c) = 25 - c$

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:



- As formula:

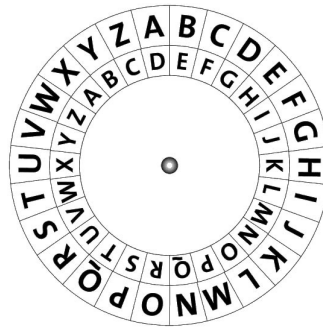
$$c = E(m) = m + 3 \pmod{26}$$

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

- Caesar and AzBy are trivial to cryptanalyze
 - No key – algorithm itself is `secret`
 - `Security by obscurity`

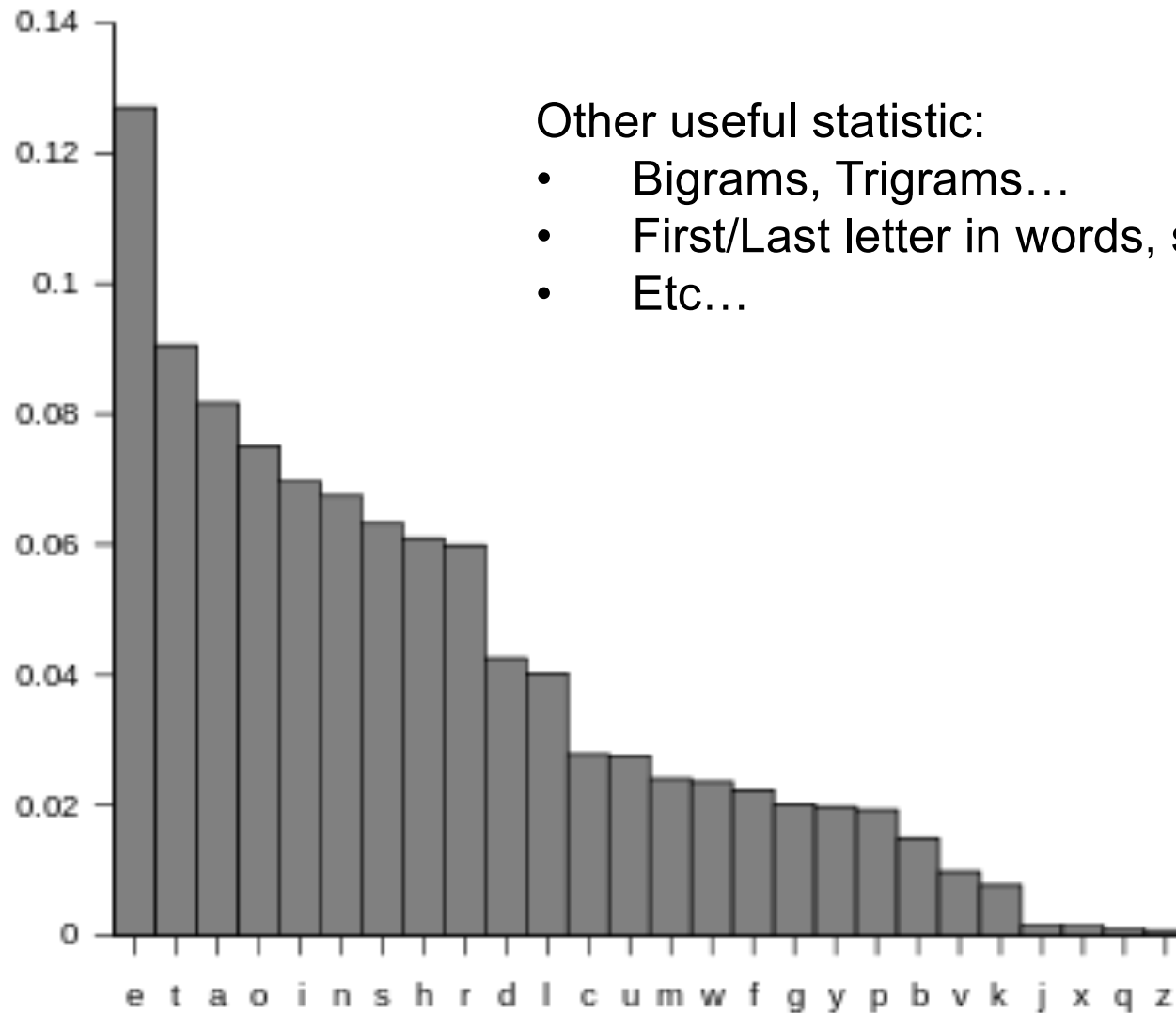
Monoalphabetic Substitution Ciphers

- Generalize Caesar and Az-By:
 - Other permutations of letters
 - Keyed: Given key k , cipher E_k is a permutation
 - Or: the 'key' is simply the permutation (table)
 - Classical, 'elementary school' cryptosystem
 - Examples:



- 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
VUEPHZHMDZSHZOWSFPAPPDTSVPPQUZWYMXUZUHSX
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
VUEPHZHMDZSHZOWSFPAPPDTSVPPQUZWYMXUZUHSX
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:

U t Q S O V U O H X M O e V G e O t e E V S G t W S t O e F e E S X U D B M E T S X A I t
V U E e H t H M D t S H t O W S F e A e e D T S V e Q U t W Y M X U t U H S X
E e Y E e O e D t S t U F e O M B t W e F U e t H M D J U D T M O H M Q

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:

UtQSOVUOHXMOeVGteEVSGthStOeFeESXUDBMETSXAIIt
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: **aoins**hr (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 seFeEaXiDBoETaXAI t
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:

itQasVisHXoseV~~vesteEVay~~ 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
direHtHoDtataHtshaFeAeeDTadeQithYoXitiHaX
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]

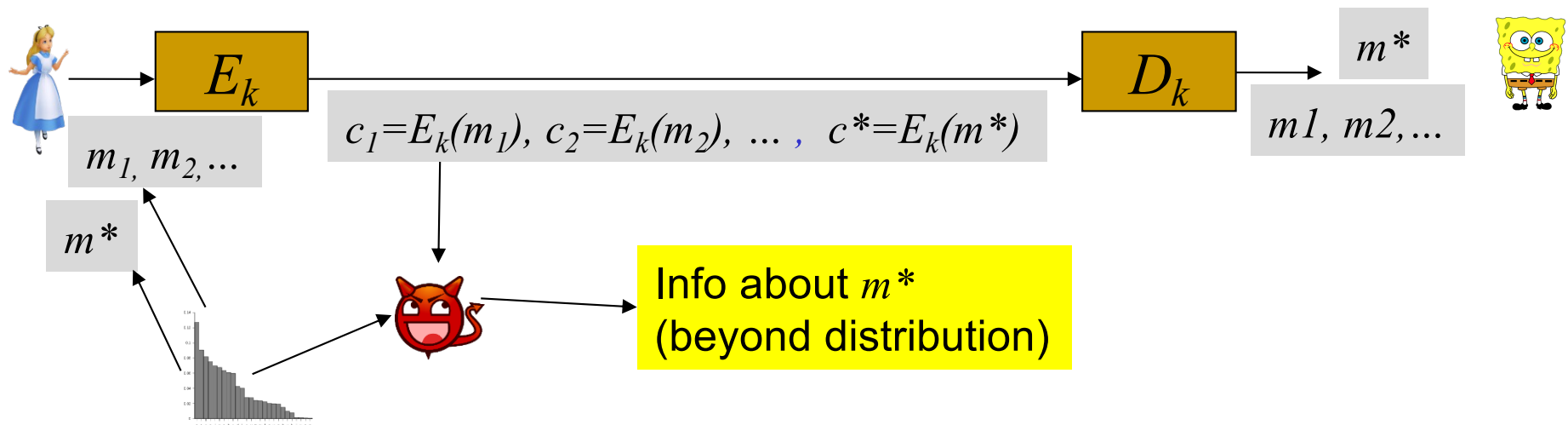
- Assume adversary knows the design – everything except the secret keys
- No `security by obscurity'
 - Although attacking obscure design is harder
- Why assume/use public design?
 - No need to replace system once design is exposed
 - Usually stronger
 - Establish standards for multiple applications: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

Exhaustive Key Search

- Kerckhoffs: $\text{Secrecy} \leq \text{secrecy of key } k$
- **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 attack (COA)
 - Known-plaintext attack (KPA)
 - Chosen-plaintext attack (CPA)
 - Chosen-ciphertext attack (CCA)

Cipher-Text Only (COA) attack

- Adversary (or attacker) has 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

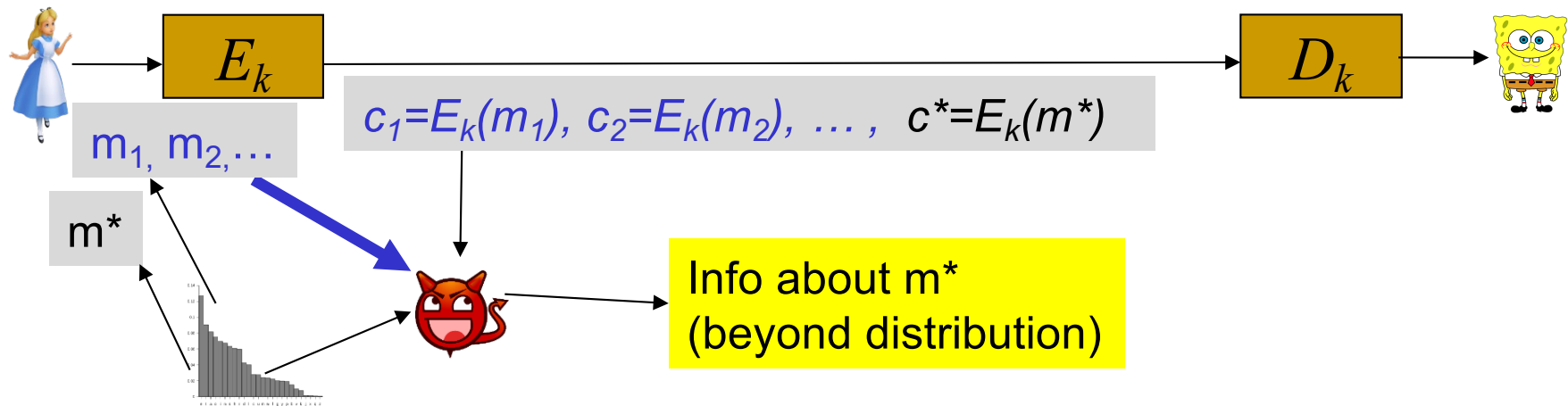


Exhaustive Key Search and COA

- **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 $m_1, m_2, \dots$ be a set of random plaintext samples (adversary does not know these)
 - Let $c_1 = E_k(m_1), c_2 = E_k(m_2), \dots$ be corresponding ciphertexts
 - To test if the key is k' , compute set $M' = \{D_{k'}(c_1), D_{k'}(c_2), \dots\}$
 - 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 $M=\{m_1, m_2, \dots\}$ from a given distribution.
- Give M and ciphertexts $c_1=E_k(m_1), c_2=E_k(m_2), \dots$ to the attacker who is trying to infer more info about the challenge m^* :
 - the challenge m^* is not given to the attacker, only its encryption c^* is given to the attacker.

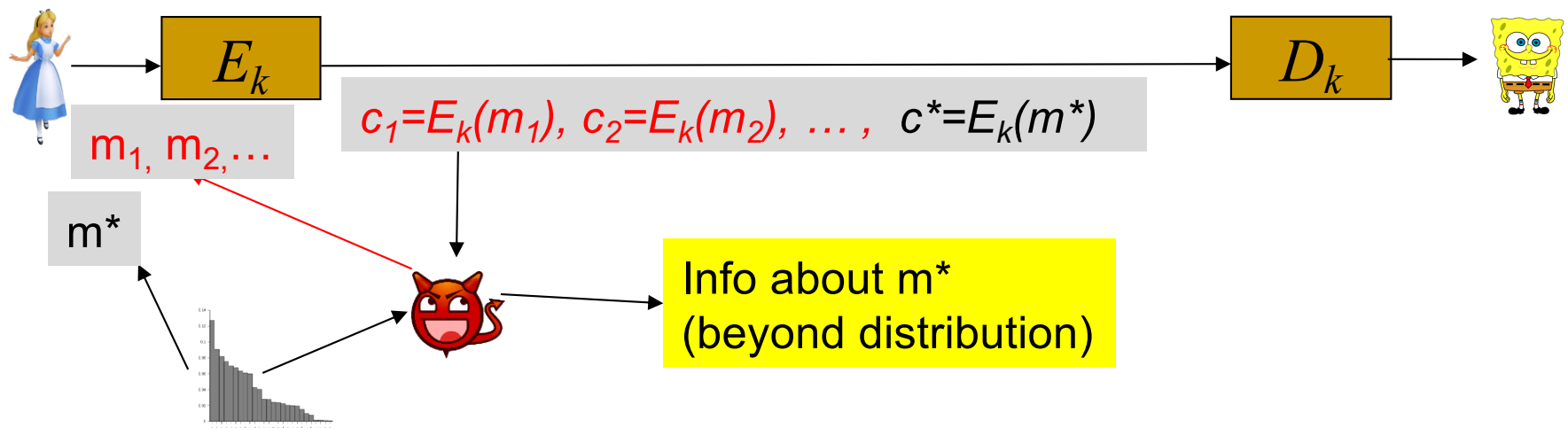


Exhaustive Key Search and KPA

- **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 not 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 $m_1, m_2, \dots$
- Give ciphertexts of these plaintext messages to the attacker who is trying to obtain more info about the challenge.
- Again, the challenge m^* is not given to the attacker, only its encryption c^* is given to the attacker.



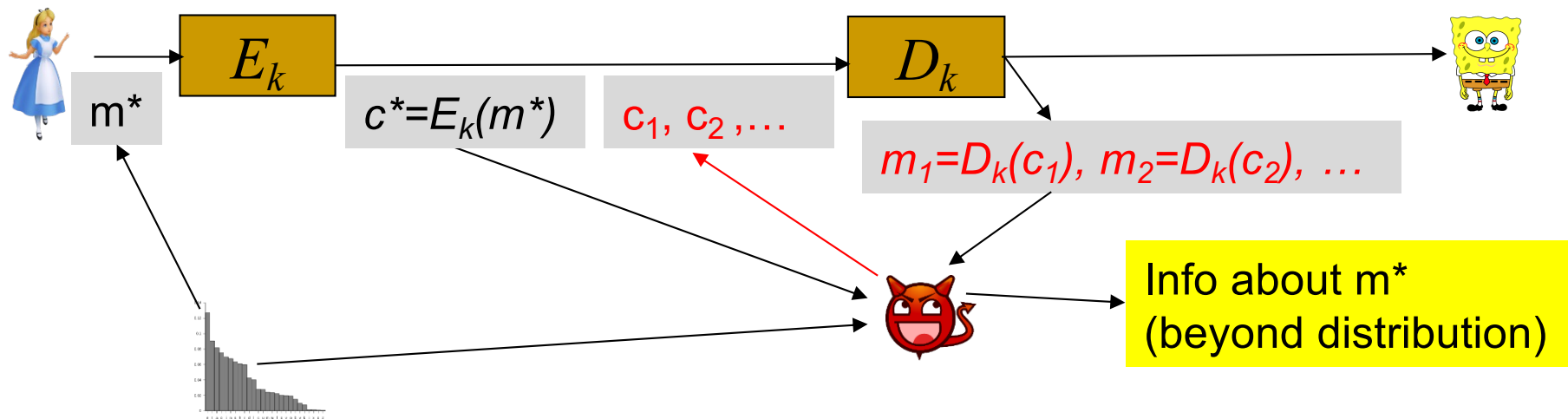
Exhaustive Key Search and CPA

■ 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 not the key
- Time complexity $t = O(1)$ lookup time, requires $2^{|k|}$ memory
- (more efficient and advanced ways exist).

Chosen Ciphertext Attack (CCA)

- Beside being able to choose plaintexts and obtain their encryptions, attacker can select ciphertexts $c_1, c_2, \dots$, and receive decryptions (but not the challenge).
- Again, attacker tries to infer more info about the challenge (and attacker is given c^* but not m^*).



The Attack Models Championship

- We discussed several attack models:
 - COA, KPA, CPA, CCA
- Model A is stronger than model B, if an encryption scheme is 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!

