Classical (Symmetric) Cryptography

Cryptography: terminology (1/2)

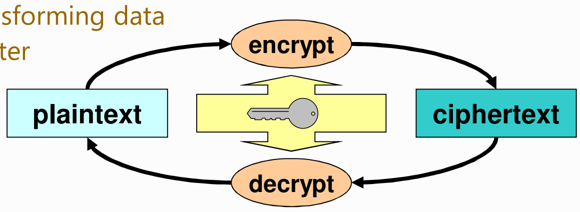
- Cryptography
  - Art or science of hidden writing
    - from Gr. *kryptós*, hidden + *graph*, r. of *graphein*, to write
  - It was initially used to maintain the confidentiality of information
  - Steganography
    - from Gr. *steganós*, hidden + *graph*, r. of *graphein*, to write
- Cryptanalysis
  - Art or science of breaking cryptographic systems or encrypted information
- Cryptology
  - Cryptography + cryptanalysis

Cryptography: terminology (2/2)

- Cipher
  - Specific cryptographic technique
- Cipher operation

  Encryption: plaintext (or cleartext) → ciphertext (or cryptogram)
  Decryption: ciphertext → plaintext

  Algorithm: way of transforming data
  Key: algorithm parameter



The players

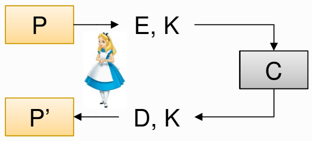
- Alice & Bob
  - The fundamental honest people
  - They represent two abstract interacting entities
- Carol, Dave, …
  - More honest entities for complex protocols
- Eve
  - Passive eavesdropper
- Mallory
  - Malicious attacker
- Trent
  - Trusted by all

I'VE DISCOVERED A WAY TO GET COMPUTER SCIENTISTS TO LISTEN TO ANY BORING STORY.

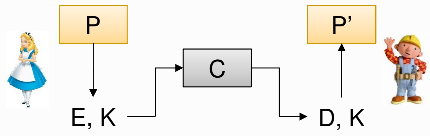
Who are Alice and Bob? (By Bruce Schneier)

Use cases

- Self-protection with key K
  - Alice encrypts plaintext P with key K
    - A: $C = \{P\}_K$
  - Alice decrypts cryptogram C with key K
    - A: $P' = \{C\}_K$
  - P' should be equal to P (requires checking)



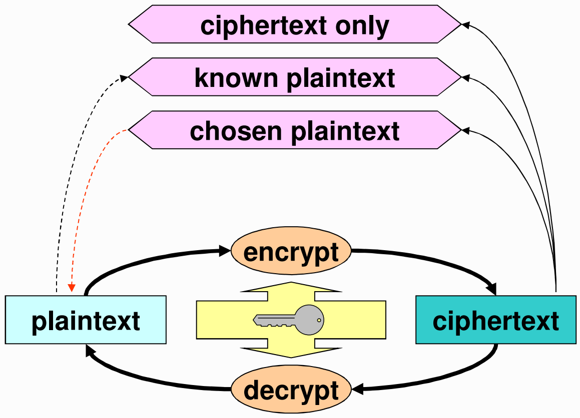
- Secure communication with key K
  - Alice encrypts plaintext P with key K
    - A: $C = \{P\}_K$
  - Bob decrypts C with key K
    - B: $P' = \{C\}_K$
  - P' should be equal to P (requires checking)



Cryptanalysis: goals

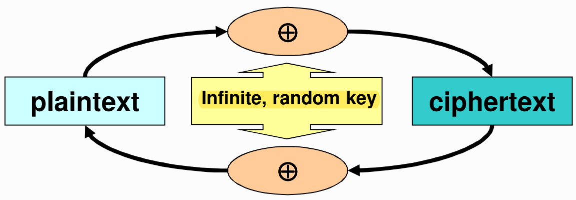
- Discover original plaintext
  - Which originated a given ciphertext
- Discover a cipher key
  - Allows the decryption of ciphertexts created with the same key
- Discover the cipher algorithm
  - Or an equivalent algorithm…
  - Usually algorithms are not secret, but there are exceptions
    - Lorenz, A5 (GSM), RC4 (WEP), Crypto-1 (Mifare)
    - Algorithms for DRM (Digital Rights Management)
  - Reverse engineering

Cryptanalysis attacks: approaches



Cryptography: Information-theoretic security

- Plaintext space
  - Set of all possible plaintext messages (M)
- Ciphertext space
  - Set of all possible ciphertext values (C)
- Key space
  - Set of all possible key values for a given algorithm (K)
- Perfect security
  - Given $c_j \in C$, $p(m_i, k_j) = p(m_i)$
  - $\#K \geq \#M$
  - Vernam cipher (one-time pad)
- The cipher cannot be broken
  - Even by adversaries with unlimited computing power



Cryptography: computational security

- The number of possible keys is finite
  - And much less than the number os possible messages
  - #K << #M
- Thus, security ultimately depends on the computing power of cryptanalysts go through all keys
  - Computations per time period
  - Storage capacity
  - Resistance time is mainly given by key length
- Provable security
  - The computational security can be demonstrated by comparing it with known hard problems

Key dimensions in perspective

- 2^{32} (4 Giga)
  - IPv4 address space
  - World population
  - Years for the Sun to become a white dwarf
- 2^{64}
  - Virtual address space of current CPU architectures
- 2^{128}
  - IPv6 address space
- 2^{166}
  - Earth atoms
- 2^{265}
  - Hydrogen atoms in the known universe
- 2^{1024} and beyond
  - Only cryptography uses them

Cryptanalysis attacks: approaches

- Brute force
  - Exhaustive search along the key space until finding a suitable key
  - Usually infeasible for a large key space
    - e.g. 2^{128} random keys (or keys with 128 bits)
    - Randomness is fundamental!
- Cleaver attacks
  - Reduce the search space to a smaller set of potential candidates

Cryptography: practical approaches (1/4)

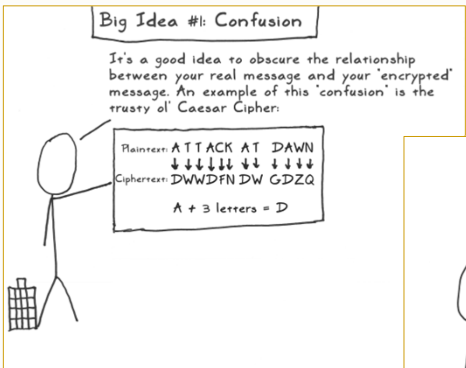
- Theoretical security vs. practical security
  - Expected use $\neq$ practical exploitation
  - Defective practices can introduce vulnerabilities
    - Example: reuse of keys
- Computational security
  - Computational complexity of break-in attacks
    - Using brute force
  - Security bounds:
    - Cost of cryptanalysis
    - Availability of cryptanalysis infra-structure
    - Lifetime of ciphertext

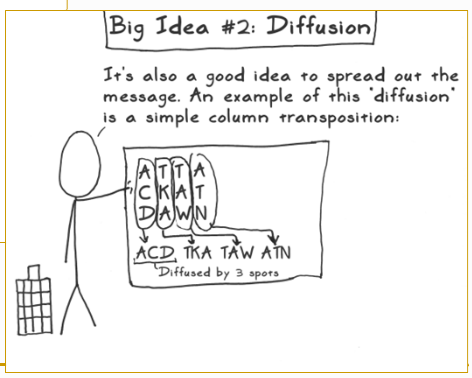
Cryptography: practical approaches (2/4)

- 5 Shannon criteria
  - The amount of offered secrecy
    - e.g. key length
  - Complexity of key selection
    - e.g. key generation, detection of weak keys
  - Implementation simplicity
  - Error propagation
    - Relevant in error-prone environments
    - e.g. noisy communication channels
  - Dimension of ciphertexts
    - Regarding the related plaintexts

Confusion & diffusion

http://www.moserware.com/2009/09/stick-figure-guide-to-advanced.html





Cryptography: practical approaches (3/4)

- Confusion
  - Complex relationship between the key, plaintext and the ciphertext
    - Output bits (ciphertext) should depend on the input bits (plaintext + key) in a very complex way
- Diffusion
  - Plaintext statistics are dissipated in the ciphertext
    - If one plaintext bit toggles, then the ciphertext changes substantially, in an unpredictable or pseudorandom manner
  - Avalanche effect

What should be secret?

http://www.moserware.com/2009/09/stick-figure-guide-to-advanced.html

Cryptography: practical approaches (4/4)

- Always assume the worst case
  - Cryptanalysts know the algorithm
    - Security lies in the key
  - Cryptanalysts know/have many ciphertext samples produced with the same algorithm & key
    - Ciphertext is not secret!
  - Cryptanalysts partially know original plaintexts
    - As they have some idea of what they are looking for
    - Know-plaintext attacks
    - Chosen-plaintext attacks

Cryptographic robustness

- The robustness of algorithms is their resistance to attacks
  - No one can evaluate it precisely
    - Only speculate or demonstrate using some other robustness assumptions
  - They are robust until someone breaks them
  - There are public guidelines with what should/must not be used
    - Sometimes antecipating future problems
- Algorithms with longer keys are probably stronger
  - And usually slower …
- Public algorithms w/o known attacks are probably stronger
  - More people looking for weaknesses

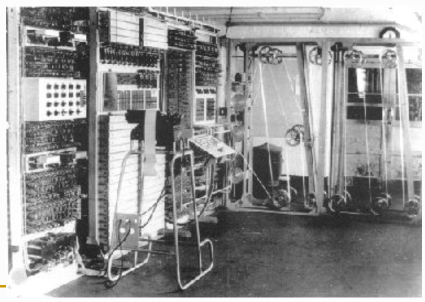
Cryptographic guidelines

- Guideline for Using Cryptographic Standards in the Federal Government: Cryptographic Mechanisms, NIST Special Publication 800-175B Rev. 1, July 2019
- Cryptographic Storage Cheat Sheet, OWASP Cheat Sheets (last revision: 6/Jun/2020)
- Guidelines on cryptographic algorithms usage and key management, European Payments Council, EPC342-08 v9.0, 9/Mar/2020
- Algorithms, Key Size and Protocols Report, ECRYPT – Coordination & Support Action, Deliverable D5.4, H2020-ICT-2014 Project 645421, 28/Feb/2018

Ciphers: evolution of technology

- Manual
  - Simple transposition or substitution algorithms
- Mechanic
  - From XIX cent.
    - Enigma machine
    - M-209 Converter
  - More complex substitution algorithms
- Informatics
  - Appear with computers
  - Highly complex substitution algorithms
  - Mathematical algorithms





Ciphers: basic types (1/3)

- ▷ Transposition
  - Original cleartext is scrambled
    `Onexcl raatre ilriad gctsm ilesb`
  - Block permutations
    (13524) → `boklc pruem ttoai ns`

O	N	E	X	C	L
R	A	A	T	R	E
I	L	R	I	A	D
G	C	T	S	M	
I	L	E	S	B	

- ▷ Substitution
  - Each original symbol is replaced by another
    - Original symbols were letters, digits and punctuation
    - Actually they are blocks of bits
  - Substitution strategies
    - Mono-alphabetic (one→one)
    - Polyalphabetic (many one→one)
    - Homophonic (one→many)

Ciphers: basic types (2/3): Mono-alphabetic

- ▷ Use a single substitution alphabet
  - With #α elements
- ▷ Examples
  - Additive (translation)
    - crypto-symbol = (symbol + key) mod # α
    - symbol = (crypto-symbol – key) mod # α
    - Possible keys = #α
    - Caesar Cipher (ROT-x)
  - With sentence key
    `ABCDEFGHIJKLMNOPQRSTUVWXYZ`
    `QRUVWXZSENTCKYABDFGHIJLMOP`
    - Possible keys = # α ! → 26! ≈ 2^{88}
- ▷ Problems
  - Reproduce plaintext pattern
    - Individual characters, digrams, trigrams, etc.
  - Statistical analysis facilitates cryptanalysis
    - "The Gold Bug", Edgar Alan Poe

```
53‡‡†305))6*;4826)4‡.)
4‡);806*;48†860))85;1‡
(;:‡*8†83(88)5*†;46(;8
8*96*?;8)*‡(;485);5*†2
:*‡(;4956*2(5*—4)88*;4
069285);)6†8)4‡‡;1(‡9;
48081;8:8‡1;48†85;4)48
5†528806*81(‡9;48;(88;
4(‡?34;48)4‡;161;:188;
‡?;
```

```
A good glass in the
bishop's hostel in the
devil's seat fifty-one
degrees and thirteen
minutes northeast and
by north main branch
seventh limb east side
shoot from the left eye
of the death's-head a
bee line from the tree
through the shot forty
feet out
```

Ciphers: basic types (3/3): Polyalphabetic

- ▷ Use N substitution alphabets
  - Periodical ciphers, with period N
- ▷ Example
  - Vigenère cipher
- ▷ Problems
  - Once known the period, are as easy to cryptanalyze as N mono-alphabetic ones
    - The period can be discovered using statistics
    - Kasiski method
      - Factoring of distances between equal ciphertext blocks
    - Coincidence index
      - Factoring of self-correlation offsets that yield higher coincidences

Vigenère cipher (or the Vigenère square)

	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	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
b	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
c	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
d	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
e	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
f	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
g	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
h	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
i	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
j	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
k	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
l	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
m	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
n	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
o	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
p	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
q	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
r	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
s	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
t	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
u	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
v	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
w	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
x	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
y	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
z	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

- ▷ Example of encryption of character M with key S, yielding cryptogram E
  - Decryption is the opposite, E and S yield M

Cryptanalysis of a Vigenère cryptogram: Example (1/2)

- Plaintext:
  Eles não sabem que o sonho é uma constante da vida
  tão concreta e definida como outra coisa qualquer,
  como esta pedra cinzenta em que me sento e descanso,
  como este ribeiro manso, em serenos sobressaltos
  como estes pinheiros altos
- Cipher with the Vigenère square and key "poema"

```
plaintext  elesnaosabemqueosonhoeumaconstantedavidataoconcretaedefinida
key        poemapoemapoemapoemapoemapoemapoemapoemapoemapoemapoemapoema
cryptogram tzienpcwmbtaugedgszhdsyyarcretpbxqdpjmpaiosoocqvqtpshqfxbmpa
```

- Kasiski test
  - With text above:

mpa	$20 = 2 \times 2 \times 5$
tp	$20 = 2 \times 2 \times 5$

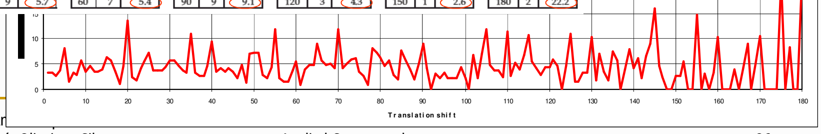
  - With the complete poem:

$175 = 5 \times 5 \times 7$	1
$105 = 3 \times 5 \times 7$	3
$35 = 5 \times 7$	1
$20 = 2 \times 2 \times 5$	4

Cryptanalysis of a Vigenère cryptogram: Example (2/2)

- Coincidence index (with full poem)

D	I	P (%)	D	I	P (%)	D	I	P (%)	D	I	P (%)	D	I	P (%)	D	I	P (%)
1	6	3.2	31	9	5.7	61	1	0.8	91	4	4.1	121	4	5.9	151	1	2.6
2	6	3.2	32	7	4.5	62	5	3.9	92	0	0.0	122	3	4.5	152	2	5.4
3	5	2.7	33	6	3.8	63	6	4.8	93	3	3.1	123	0	0.0	153	0	0.0
4	7	3.8	34	5	3.2	64	6	4.8	94	2	2.1	124	3	4.6	154	0	0.0
5	15	8.2	35	17	11.0	65	11	8.9	95	3	3.2	125	7	10.9	155	5	14.7
6	3	1.6	36	5	3.3	66	7	5.7	96	2	2.2	126	1	1.6	156	0	0.0
7	6	3.3	37	4	2.6	67	6	4.9	97	2	2.2	127	1	1.6	157	1	3.1
8	5	2.8	38	4	2.6	68	6	5.0	98	2	2.2	128	2	3.3	158	0	0.0
9	10	5.6	39	7	4.7	69	5	4.2	99	4	4.4	129	2	3.3	159	1	3.3
10	6	3.4	40	14	9.4	70	14	11.8	100	2	2.2	130	6	10.2	160	3	10.3
11	8	4.5	41	5	3.4	71	5	4.2	101	0	0.0	131	1	1.7	161	0	0.0
12	6	3.4	42	6	4.1	72	6	5.1	102	6	6.9	132	4	7.0	162	0	0.0
13	6	3.4	43	5	3.4	73	7	6.0	103	2	2.3	133	2	3.6	163	0	0.0
14	7	4.0	44	6	4.1	74	7	6.1	104	6	7.1	134	1	1.8	164	1	4.0
15	11	6.3	45	5	3.5	75	4	3.5	105	10	11.9	135	4	7.4	165	0	0.0
16	10	5.8	46	3	2.1	76	3	2.7	106	4	4.8	136	3	5.7	166	1	4.3
17	6	3.5	47	7	4.9	77	1	0.9	107	3	3.7	137	0	0.0	167	2	9.1
18	2	1.2	48	2	1.4	78	9	8.1	108	3	3.7	138	2	3.9	168	0	0.0
19	8	4.7	49	10	7.1	79	8	7.3	109	2	2.5	139	4	8.0	169	1	5.0
20	23	13.6	50	10	7.2	80	7	6.4	110	9	11.4	140	2	4.1	170	2	10.5
21	4	2.4	51	10	7.2	81	5	4.6	111	2	2.6	141	3	6.2	171	0	0.0
22	3	1.8	52	4	2.9	82	6	5.6	112	4	5.2	142	1	2.1	172	0	0.0
23	7	4.2	53	3	2.2	83	3	2.8	113	3	3.9	143	3	6.5	173	0	0.0
24	9	5.5	54	6	4.4	84	2	1.9	114	5	6.7	144	4	8.9	174	0	0.0
25	12	7.3	55	16	11.9	85	8	7.7	115	8	10.8	145	7	15.9	175	3	21.4
26	6	3.7	56	3	2.3	86	6	5.8	116	4	5.5	146	2	4.7	176	0	0.0
27	6	3.7	57	2	1.5	87	4	3.9	117	3	4.2	147	1	2.4	177	1	8.3
28	6	3.7	58	2	1.5	88	2	2.0	118	2	2.8	148	0	0.0	178	0	0.0
29	7	4.4	59	5	3.8	89	5	5.0	119	3	4.3	149	0	0.0	179	0	0.0
30	9	5.7	60	7	5.4	90	9	9.1	120	3	4.3	150	1	2.6	180	2	22.2

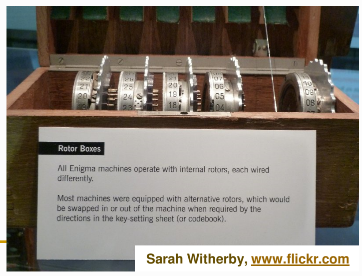


Rotor Machines

David J Morgan, www.flickr.com

Rotor machines

- Rotor machines implement complex polyalphabetic ciphers
  - Each rotor contains a permutation
    - Same as a set of substitutions
  - The position of a rotor implements a substitution alphabet
  - Spinning of a rotor implements a polyalphabetic cipher
  - Stacking several rotors and spinning them at different times adds complexity to the cipher
- The cipher key is:
  - The set of rotors used
  - The relative order of the rotors
  - The position of the spinning ring
  - The original position of all the rotors
- Symmetrical (two-way) rotors allow decryption by "double encryption"
  - Using a reflection disk (half-rotor)



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Rotor machines


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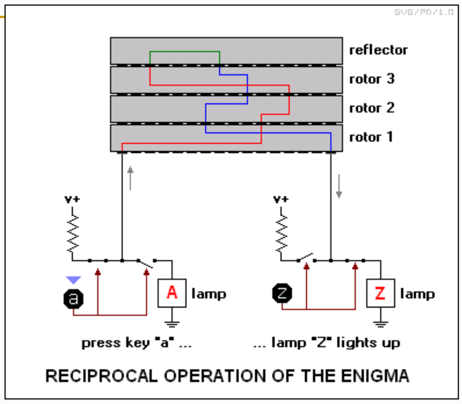
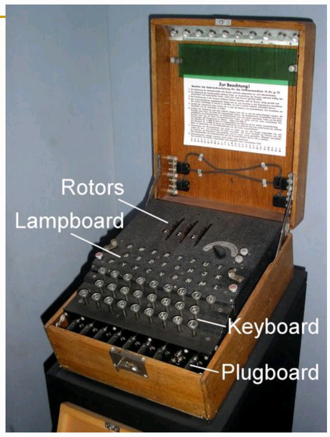


- ▷ Reciprocal operation with reflector
  - Sending operator types "A" as plaintext and gets "Z" as ciphertext, which is transmitted
  - Receiving operator types the received "Z" and gets the plaintext "A"
  - No letter could encrypt to itself !

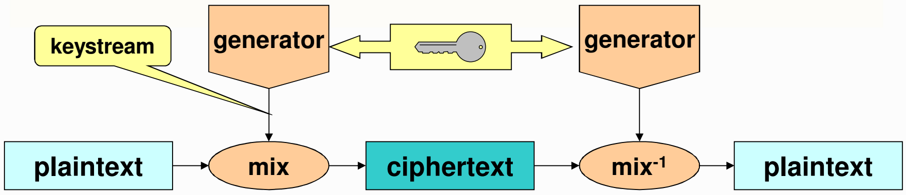
Enigma



- ▷ WWII German rotor machine
  - Many models used
- ▷ Initially presented in 1919
  - Enigma I, with 3 rotors
- ▷ Several variants where used
  - With different number of rotors
  - With patch cord to permute alphabets
- ▷ Key settings distributed in codebooks



Stream ciphers

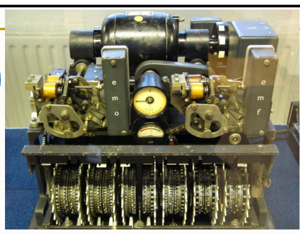


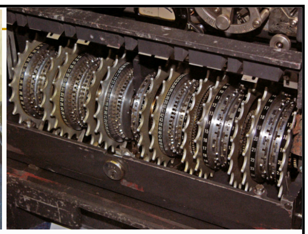
- ▷ Mixture of a keystream with the plaintext or ciphertext
  - Random keystream (Vernam's one-time pad)
  - Pseudo-random keystream (produced by generator using a finite key)
- ▷ Reversible mixture function
  - e.g. bitwise XOR
  - $C = P \oplus ks$ $\qquad$ $P = C \oplus ks$
- ▷ Polyalphabetic cipher
  - Each keystream symbol defines an alphabet

Stream ciphers

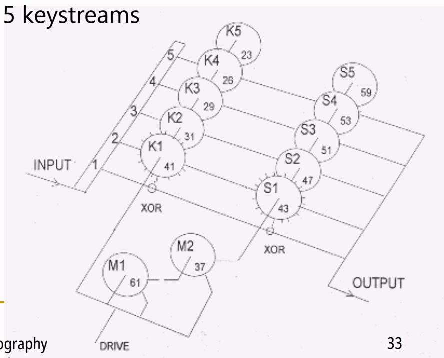
- ▷ Keystream may be infinite but with a finite period
  - The period depends on the generator
- ▷ Practical security issues
  - Each **keystream** should be used only **once**!
    - Otherwise, the sum of cryptograms yields the sum of plaintexts
      $C1 = P1 \oplus Ks$, $C2 = P2 \oplus Ks$ $\rightarrow$ $C1 \oplus C2 = P1 \oplus P2$
  - **Plaintext length** should be **smaller** than the **keystream period**
    - Total keystream exposure under know/chosen plaintext attacks
    - Keystream cycles help the cryptanalysts knowing plaintext samples
  - Integrity control is mandatory
    - No diffusion! (only confusion)
    - Ciphertexts can easily be changed deterministically

Lorenz (Tunny)



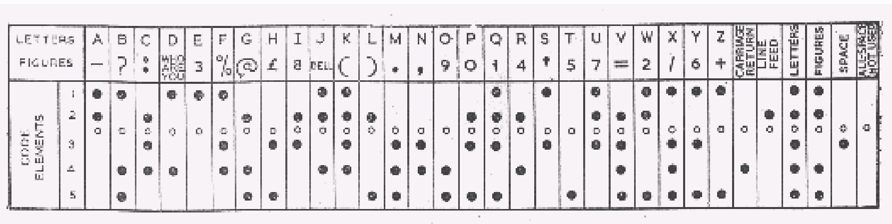


- 12-Rotor stream cipher
  - Used by the German high-command during the 2nd WW
  - Implements a stream cipher
    - Each 5-bit character is mixed with 5 keystreams
- Operation
  - 5 regularly stepped (χ) wheels
  - 5 irregularly stepped (ψ) wheels
    - All or none stepping
  - 2 motor wheels
    - For stepping the ψ wheels
  - Number of steps in all wheels is relatively prime



Cryptanalysis of Tunny in Bletchley Park

- They didn't know Lorenz internal structure
  - They observed one only at the end of the war
  - They knew about them because they could get 5-bit encrypted transmissions
    - Using the 32-symbol Baudot code instead of Morse code



LETTERS	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	CARRIAGE RETURN	LINE FEED	LETTERS	FIGURES	SPACE	ALL-SPACE NOT USED
FIGURES	—	?	:	WHO ARE YOU	3	%	@	£	8	BELL	(	)	.	,	9	0	1	4	'	5	7	=	2	/	6	+						
CODE ELEMENTS 1	●	●		●	●	●				●	●						●		●		●		●	●	●	●			●	●		
2	●		●				●		●	●	●	●				●	●	●			●	●	●					●	●	●		
3			●			●		●	●		●		●	●		●	●		●		●	●		●	●				●		●	
4		●	●	●		●	●			●	●		●	●	●			●				●		●			●		●	●		
5		●					●	●				●	●		●	●	●			●		●	●	●	●	●			●	●		

Cryptanalysis of Tunny in Bletchley Park: The mistake (30 August 1941)

- A German operator had a long message (~4,000) to send
  - He set up his Lorenz and sent a 12 letter indicator (wheel setup) to the receiver
  - After ~4,000 characters had been keyed, by hand, the receiver said "send it again"
- The operator resets the machine to the same initial setup
  - Same keystream! Absolutely forbidden!
- The sender began to key in the message again (by hand)
  - But he typed a slightly different message!

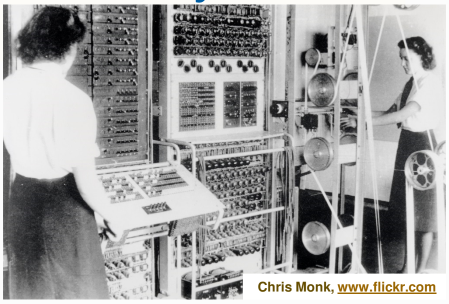
$C = M \oplus Ks$
$C' = M' \oplus Ks \rightarrow M' = C \oplus C' \oplus M \rightarrow$ text variations

  - Know parts of the initial text M reveal the variations, M'

Cryptanalysis of Tunny in Bletchley Park: Breakthrough

- Messages began with SPRUCHNUMMER — "msg number"
  - The first time the operator typed S P R U C H N U M M E R
  - The second time he typed S P R U C H N R
  - Thus, immediately following the N the two texts were different!
- John Tiltman at Bletchley Park was able to fully decrypt both messages (called *Depths*) using an additive combination of them
  - The 2nd message was ~500 characters shorter than the first one
  - Tiltman managed to discover the correct message for the 1st ciphertext
- They got for the 1st time a long stretch of the Lorenz keystream
  - They did not know how the machine did it, …
  - … but they knew that this was what it was generating!

Cryptanalysis of Tunny in Bletchley Park: Colossus


Chris Monk, www.flickr.com

- The cipher structure was determined from the keystream
  - But deciphering it required knowing the initial position of rotors
- Germans started using numbers for the initial wheels' state
  - Bill Tutte invented the double-delta method for finding that state
  - The Colossus was built to apply the double-delta method
- Colossus
  - Design started in March 1943
  - The 1,500 valve Colossus Mark 1 was operational in January 1944
  - Colossus reduced the time to break Lorenz from weeks to hours