Cryptography

Cryptography: terminology (1/2)

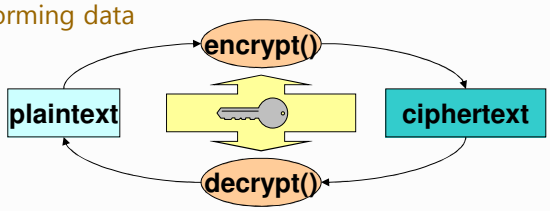
- Cryptography
  - Art or science of hidden writing
    - from Gr. *kryptós*, hidden + *graph*, r. of *graphein*, to write
  - It was initially used to maintain the confidentiality of information
  - Steganography
    - from Gr. *steganós*, hidden + *graph*, r. of *graphein*, to write
- Cryptanalysis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



Use cases (symmetric cryptography)

- 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

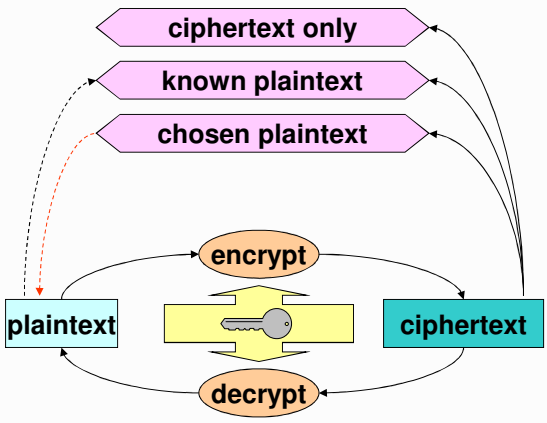
    A: $C = \{P\}_K$
  - Bob decrypts C with key K

    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



Cryptanalysis attacks: approaches

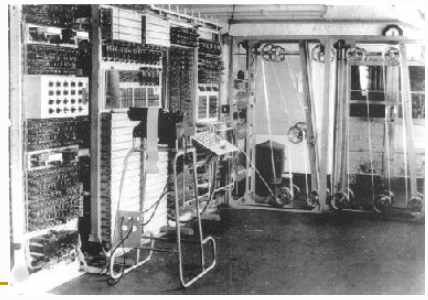
- Brute force
  - Exhaustive search along the key space until finding a suitable key
  - Usually infeasible for a large key space
    - e.g. 2^{128} random keys (or keys with 128 bits)
    - Randomness is fundamental!
- Cleaver attacks
  - Reduce the search space to a smaller set of potential candidates

Size matters!

- 2^{32}
  - IPv4 address space
  - World population
  - Years for the Sun to become a white dwarf
- 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

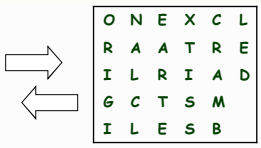
Ciphers: evolution of technology

- 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`
- 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 ! → $26! \approx 2^{88}$
- 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†52880 6*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        poemapoemapoemapoemapoemapoemapoemapoemapoemapoemapoema
cryptogram tzienpcwmbtaugedgszhdsyyarcretpbxqdpjmpaiosoocqvqtpshqfxbmpa
```

- Kasiski test
  - With text above:

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

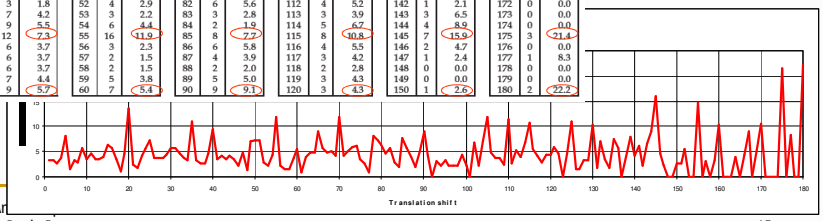
  - With the complete poem:

$175 = 5 \times\ 5 \times 7$	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	7.2	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

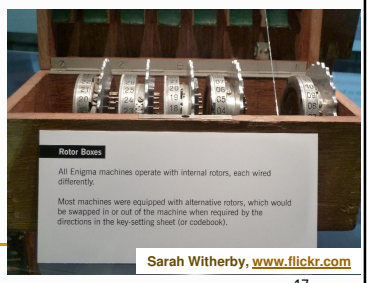


Rotor Machines (1/3)

David J Morgan, www.flickr.com

Rotor machines (2/3)

- 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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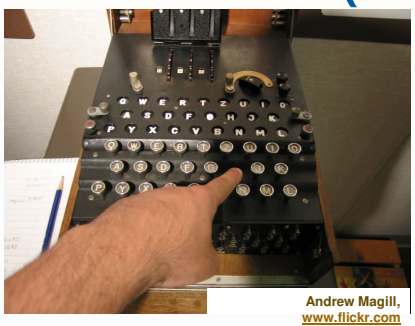
Rotor machines (3/3)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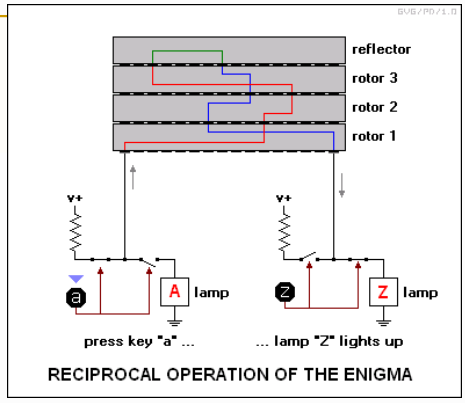
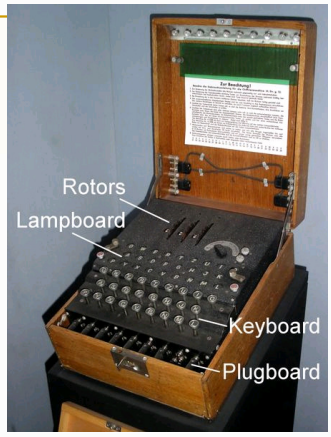


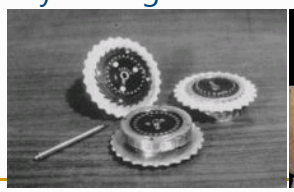
RECIPROCAL OPERATION OF THE ENIGMA

- 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

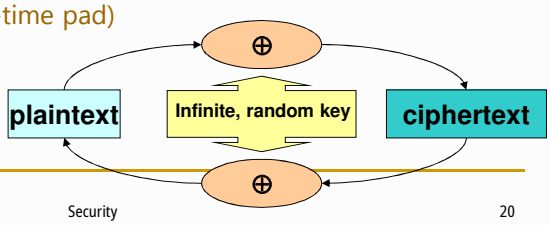
- WWII German rotor machine
  - Many models used
- Initially presented in 1919
  - Enigma I, with 3 rotors
- Several variants where used
  - With different number of rotors
  - With patch cord to permute alphabets
- Key settings distributed in codebooks





Cryptography: theoretical analysis

- 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 (information-theoretical) security
  - Given $c_j \in C$, $p(m_i, k_j) = p(m_i)$
  - $\#K \geq \#M$
  - Vernam cipher (one-time pad)



Cryptography: practical approaches (1/4)

- Theoretical security vs. practical security
  - Expected use ≠ practical exploitation
  - Defective practices can introduce vulnerabilities
    - Example: reuse of keys
- Computational security
  - Security is measured by the 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

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

Cryptography: practical approaches (4/4)

- Always assume the worst case
  - Cryptanalysts knows 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

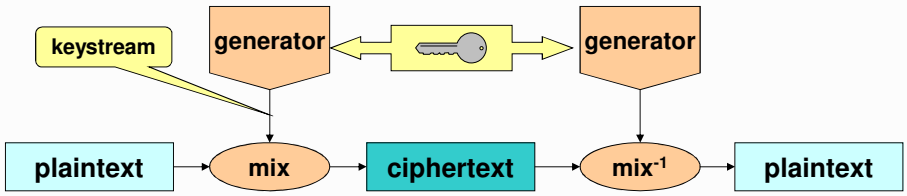
Cryptographic robustness

- 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
- Public algorithms without known attacks are likely to be more robust
  - More people looking for weaknesses
- Algorithms with longer keys are likely to be more robust
  - And usually slower …

Cryptographic guidelines

- Guideline for Using Cryptographic Standards in the Federal Government: Cryptographic Mechanisms, NIST Special Publication 800-175B, August 2016
- Cryptographic Storage Cheat Sheet, OWASP Cheat Sheets (last revision: 06/18/2018)
- Guidelines on cryptographic algorithms usage and key management, European Payments Council, EPC342-08 Version 7.0, 4 November, 2017
- Algorithms, Key Size and Protocols Report, ECRYPT – Coordination & Support Action, Deliverable D5.4, H2020-ICT-2014 Project 645421, 28 February, 2018

Stream ciphers (1/2)



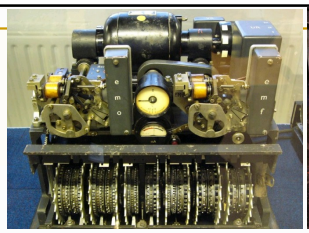
- Mixture of a keystream with the plaintext or ciphertext
  - Random keystream (Vernam's one-time pad)
  - Pseudo-random keystream (produced by generator using a finite key)
- Reversible mixture function
  - e.g. bitwise XOR
  - $C = P \oplus ks$ $P = C \oplus ks$
- Polyalphabetic cipher
  - Each keystream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

Stream ciphers (2/2)

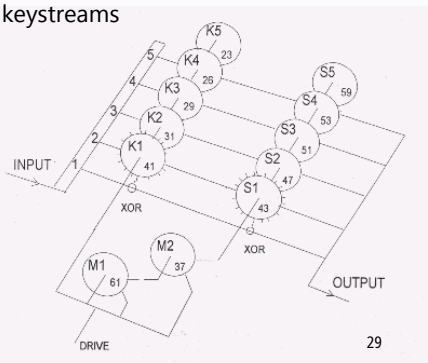
- Keystream may be infinite but with a finite period
  - The period depends on the generator
- Practical security issues
  - Each **keystream** should be used only **once**!
    - Otherwise, the sum of cryptograms yields the sum of plaintexts

      $C1 = P1 \oplus Ks, C2 = P2 \oplus Ks \rightarrow C1 \oplus C2 = P1 \oplus P2$
  - **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)

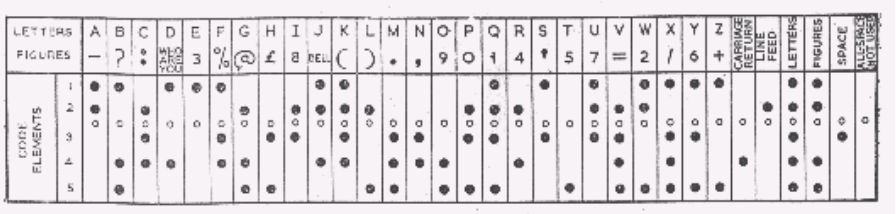


- 12-Rotor stream cipher
  - Used by the German high-command during the 2nd WW
  - Implements a stream cipher
    - Each 5-bit character is mixed with 5 keystreams
- Operation
  - 5 regularly stepped (χ) wheels
  - 5 irregularly stepped (ψ) wheels
    - All or none stepping
  - 2 motor wheels
    - For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



Cryptanalysis of Tunny in Bletchley Park (1/4)

- 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



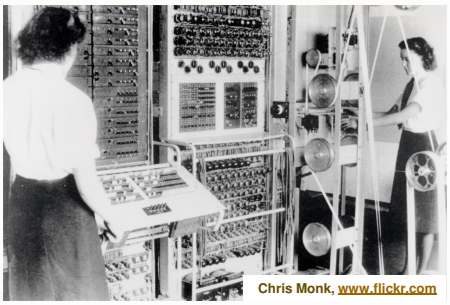
Cryptanalysis of Tunny in Bletchley Park (2/4)

- 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
    - If you know part of the initial text, you can find the variations

Cryptanalysis of Tunny in Bletchley Park (3/4)

- Breakthrough
  - Messages began with a well known SPRUCHNUMMER — "msg number"
    - The first time the operator keyed in S P R U C H N U M M E R
    - The second time he keyed in S P R U C H N R
    - Thus, immediately following the N the two texts were different!
  - Both messages were sent to John Tiltman at Bletchley Park, which was able to fully decrypt them using an additive combination of the messages (called *Depths*)
    - 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 (4/4): 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

Modern ciphers: types

- Concerning operation
  - Block ciphers (mono-alphabetic)
  - Stream ciphers (polyalphabetic)
- Concerning their key
  - Symmetric ciphers (secret key or shared key ciphers)
  - Asymmetric ciphers (or public key ciphers)
- Arrangements

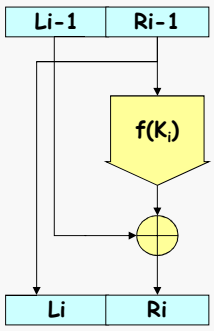
	Block ciphers	Stream ciphers
Symmetric ciphers		
Asymmetric ciphers		

Symmetric ciphers

- Secret key
  - Shared by 2 or more peers
- Allow
  - Confidentiality among the key holders
  - Limited authentication of messages
    - When block ciphers are used
- Advantages
  - Performance (usually very efficient)
- Disadvantages
  - N interacting peers, pairwise secrecy ⇒ N x (N-1)/2 keys
- Problems
  - Key distribution

Symmetric block ciphers

- Usual approaches
  - Large bit blocks
    - 64, 128, 256, etc.
  - Diffusion & confusion
    - Permutation, substitution, expansion, compression
    - Feistel Networks
      - $L_i=R_{i-1}$ $R_i=L_{i-1}\oplus f(R_{i-1},K_i)$
    - Iterations



- Most common algorithms
  - DES (Data Enc. Stand.), D=64; K=56
  - IDEA (Int. Data Enc. Alg.), D=64; K=128
  - AES (Adv. Enc. Stand., aka Rijndael), D=128, K=128, 192, 256
  - Other (Blowfish, CAST, RC5, etc.)

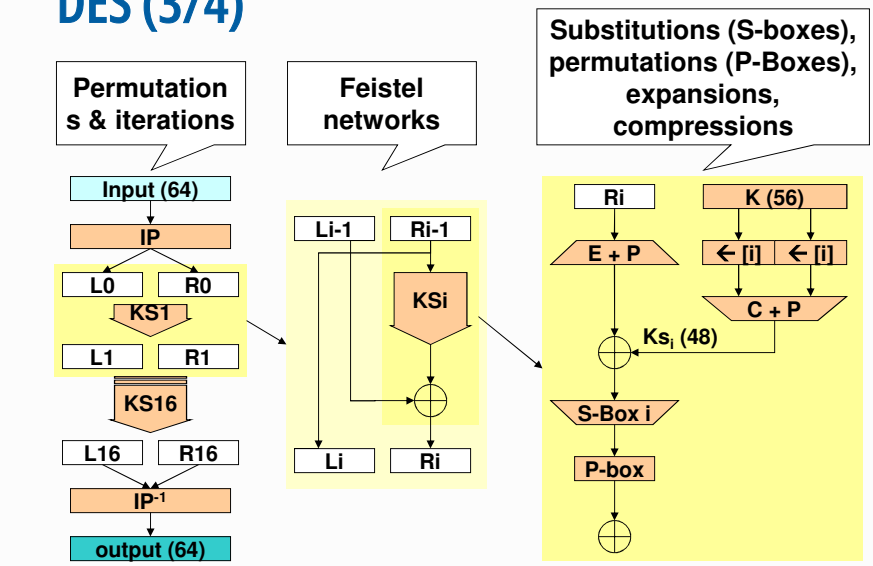
DES (Data Encryption Standard) (1/4)

- 1970: the need of a standard cipher for civilians was identified
- 1972: NBS opens a contest for a new cipher, requiring:
  - The cryptographic algorithm must be secure to a high degree
  - Algorithm details described in an easy-to-understand language
  - The details of the algorithm must be publicly available
    - So that anyone could implement it in software or hardware
  - The security of the algorithm must depend on the key
    - Not on keeping the method itself (or part of it) secret
  - The method must be adaptable for use in many applications
  - Hardware implementations of the algorithm must be practical
    - i.e. not prohibitively expensive or extremely slow
  - The method must be efficient
  - Test and validation under real-life conditions
  - The algorithm should be exportable

DES (2/4)

- 1974: new contest
  - Proposal based on Lucifer from IBM
  - 64-bit blocks
  - 56-bit keys
    - 48-bit subkeys (key schedules)
  - Diffusion & confusion
    - Feistel networks
    - Permutations, substitutions, expansions, compressions
    - 16 iterations
  - Several modes of operation
    - **ECB** (Electronic Code Book), **CBC** (Cypher Block Chaining)
    - **OFB** (Output Feedback), **CFB** (Cypher Feedback)
- 1976: adopted at US as a federal standard

DES (3/4)



DES: offered security

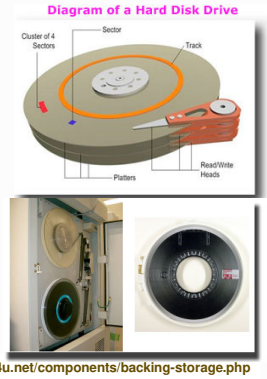
- Key selection
  - Most 56-bit values are suitable keys
  - 4 weak, 12 semi-weak keys, 48 possibly weak keys
    - Produce equal key schedules (one Ks, two Ks or four Ks)
    - Easy to spot and avoid
- Known attacks
  - Exhaustive key space search
- Key length
  - 56 bits are actually too few
    - Exhaustive search is technically possible and economically interesting
  - Solution: multiple encryption
    - Double encryption is not (theoretically) more secure
    - Triple encryption: 3DES (Triple-DES)
      - With 2 or 3 keys
      - Equivalent key length of 112 or 168 bits

(Symmetric) stream ciphers

- Approaches
  - Cryptographically secure pseudo-random generators (PRNG)
    - Using linear feedback shift registers (LFSR)
    - Using block ciphers
    - Other (families of functions, etc.)
  - Usually not self-synchronized
  - Usually without uniform random access
    - No immediate setup of generator's state for a given plaintext/cryptogram offset
- Most common algorithms
  - A5/1 (US, Europe), A5/2 (GSM)
  - RC4 (802.11 WEP/TKIP, etc.)
  - E0 (Bluetooth BR/EDR)
  - SEAL (w/ uniform random access)

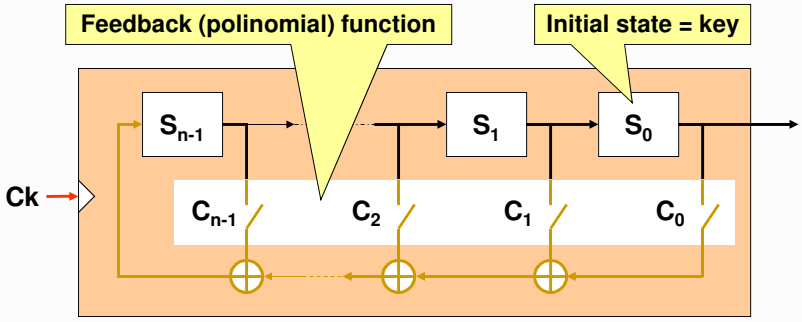
Uniform random access

- Same time to reach and process any piece of information regardeless of its position
- Uniform
  - Memory
  - Disks (magnetic, optical)
- Non-uniform
  - Tapes (audio, video, computer)



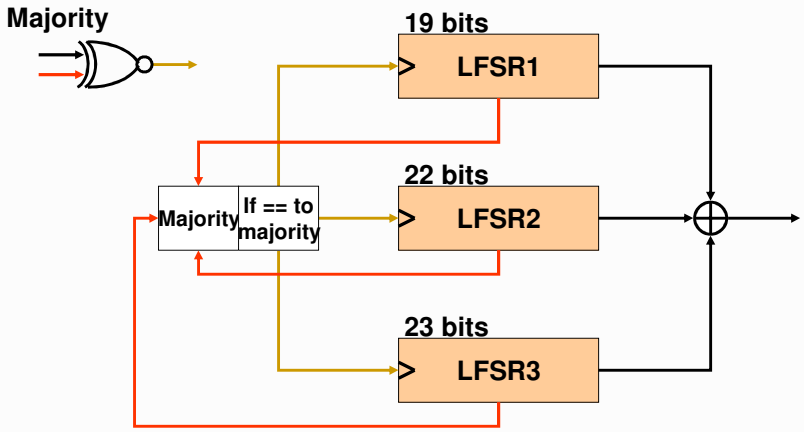
https://www.ict4u.net/components/backing-storage.php

Linear Feedback Shift Register (LFSR)



- 2^n-1 non-null sequences
  - If one of them has a 2^n-1 period length, then all have it
- Primitive feedback functions (primitive polynomials)
  - All non-null sequences have a 2^n–1 period length

Generators using many LFSR: A5/1 (GSM)



Deployment of (symmetric) block ciphers: Cipher modes

- Initially proposed for DES
  - ECB (Electronic Code Book)
  - CBC (Cipher Block Chaining)
  - OFB (Output Feeback)
  - CFB (Cipher Feedback)
- Can be used with other block ciphers
  - In principle ...
- Some other modes do exist
  - CTR (Counter Mode)
  - GCM (Galois/Counter Mode)

Block cipher modes: ECB and CBC

Electronic Code Book

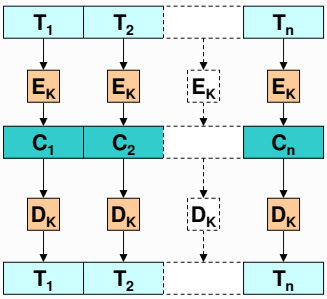
$C_i = E_K(T_i)$

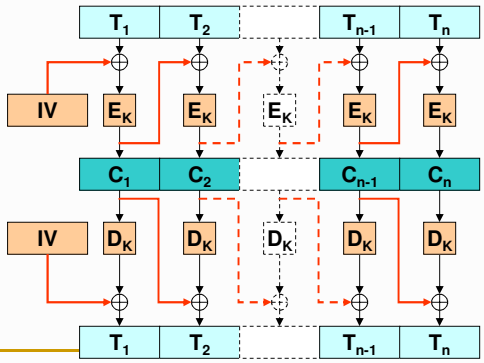
$T_i = D_K(C_i)$

Cipher Block Chaining

$C_i = E_K(T_i \oplus C_{i-1})$

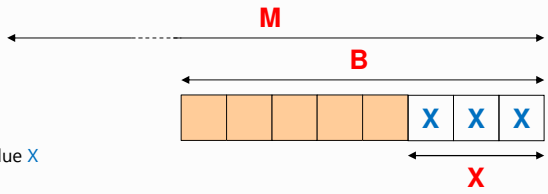
$T_i = D_K(C_i) \oplus C_{i-1}$





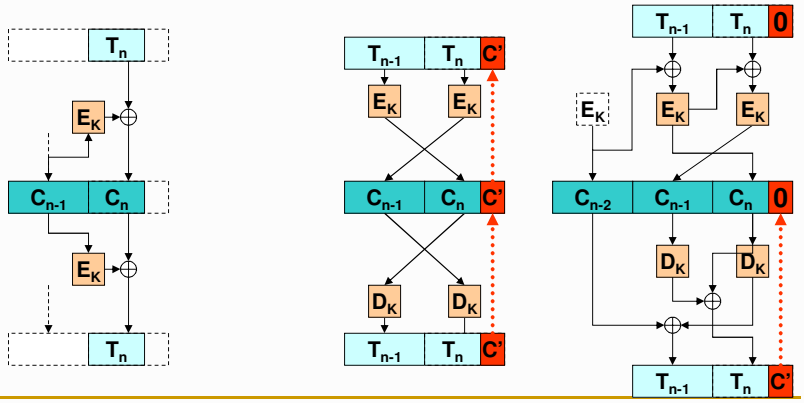
ECB/CBC cipher modes: Trailing sub-block issues

- Block cipher modes ECB and CBC require block-aligned inputs
  - Trailing sub-blocks need special treatment
- Alternatives
  - Padding
    - Of last block, identifiable
    - PKCS #7
      - X = B – (M mod B)
      - X extra bytes, with the value X
    - PKCS #5
      - Equal to PKCS #7 with B = 8
  - Different processing for the last block
    - Adds complexity



ECB/CBC cipher modes: Handling trailing sub-blocks

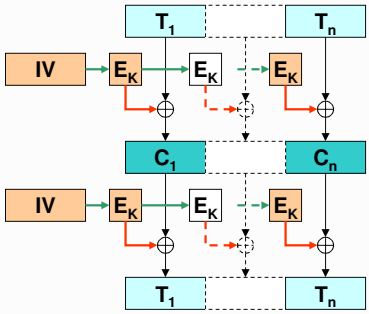
- Sort of stream cipher
- Ciphertext stealing

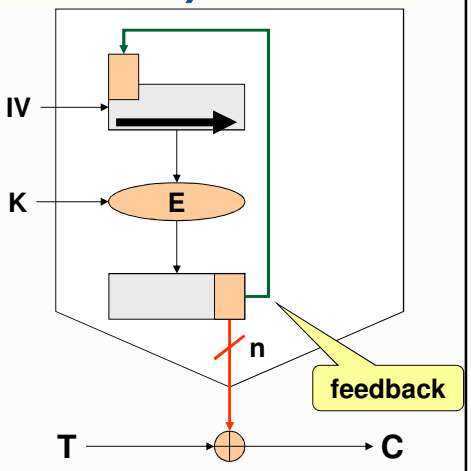


Stream cipher modes: n-bit OFB (Output Feedback)

$C_i = T_i \oplus E_K(S_i)$
$T_i = C_i \oplus E_K(S_i)$

$S_i = f(S_{i-1}, E_K(S_{i-1}))$
$S_0 = IV$

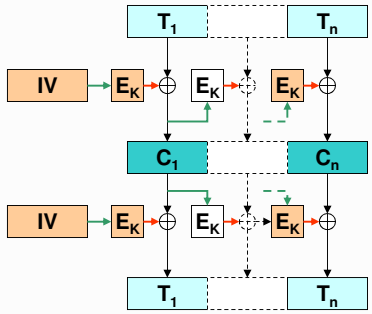


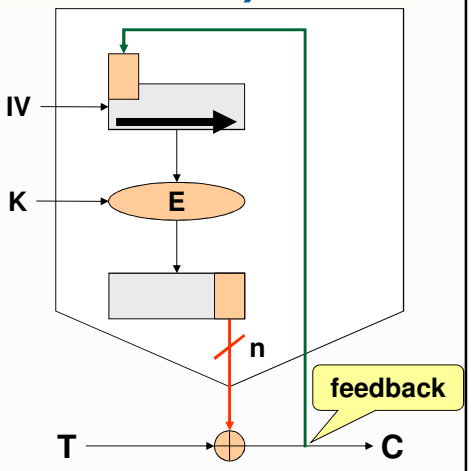


Stream cipher modes: n-bit CFB (Ciphertext Feedback)

$C_i = T_i \oplus E_K(S_i)$
$T_i = C_i \oplus E_K(S_i)$

$S_i = f(S_{i-1}, C_i)$
$S_0 = IV$

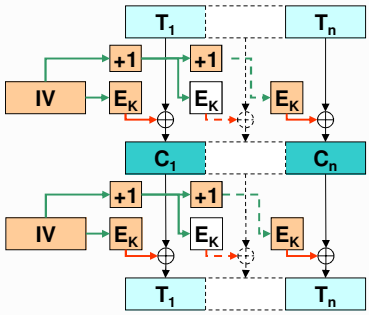


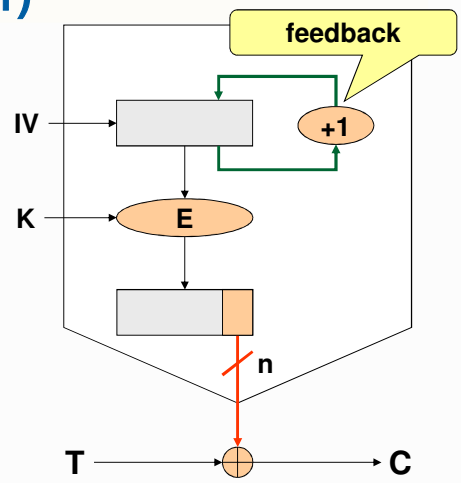


Stream cipher modes: n-bit CTR (Counter)

$C_i = T_i \oplus E_K(S_i)$
$T_i = C_i \oplus E_K(S_i)$

$S_i = S_{i-1}+1$
$S_0 = IV$



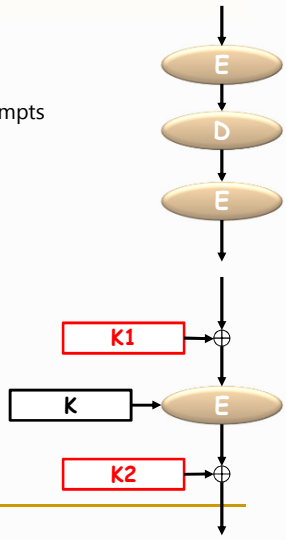


Cipher modes: Pros and cons

	Block		Stream		
	ECB	CBC	OFB	CFB	CTR
Input pattern hiding		✓	✓	✓	✓
Confusion on the cipher input		✓		✓	Secret counter
Same key for different messages	✓	✓	other IV	other IV	other IV
Tampering difficulty	✓	✓ (...)		✓	
Pre-processing			✓	...	✓
Parallel processing	✓	Decryption Only	w/ pre-processing	Decryption only	✓
Uniform random access					
Error propagation	Same block	Same block Next block		Some bits afterwards	
Capacity to recover from losses	Block Losses	Block Losses		✓	

Cipher modes: Security reinforcement

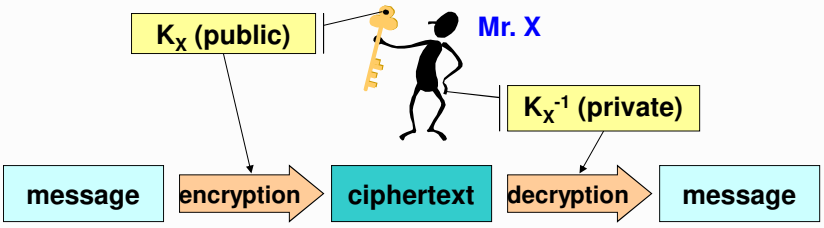
- Multiple encryption
  - Double encryption
    - Breakable with a meet-in-the-meddle attack in 2^{n+1} attempts
      - With 2 or more known plaintext blocks
      - Using 2^n blocks stored in memory ...
    - Not secure enough (theoretically)
  - Triple encryption (EDE)
    - $C_i = E_{K1}(D_{K2}(E_{K3}(T_i)))$ $\quad P_i = D_{K3}(E_{K2}(D_{K1}(C_i)))$
    - Usually $K_1 = K_3$
    - If $K_1 = K_2 = K_3$,then we get simple encryption
- Whitening (DESX)
  - Simple and efficient technique to add confusion
  - $C_i = E_K(K_1 \oplus T_i) \oplus K_2$
  - $T_i = K_1 \oplus D_K(K_2 \oplus C_i)$



Asymmetric (block) ciphers

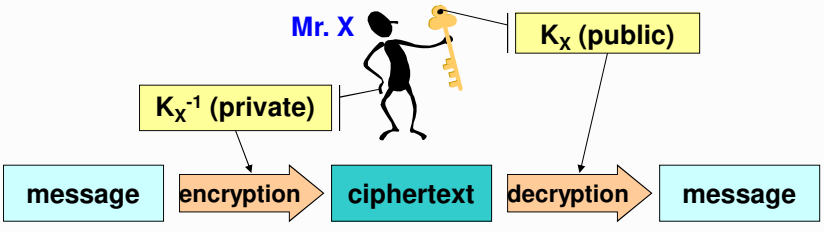
- Use key pairs
  - One private key (personal, not transmittable)
  - One public key
- Allow
  - Confidentiality without any previous exchange of secrets
  - Authentication
    - Of contents (data integrity)
    - Of origin (source authentication, or digital signature)
- Disadvantages
  - Performance (usually very inefficient and memory consuming)
- Advantages
  - N peers requiring pairwise, secret interaction ⇒ N key pairs
- Problems
  - Distribution of public keys
  - Lifetime of key pairs

Confidentiality w/ asymmetric ciphers



- Only the key pair of the recipient is involved
  - C = E(K, P) P = D(K^{-1}, C)
  - To send something with confidentiality to X is only required to know X's public key (K_X)
- There is no source authentication
  - X has no means to know who produced the ciphertext
  - If K_X is really public, then everybody can do it

Source authentication w/ asymmetric ciphers

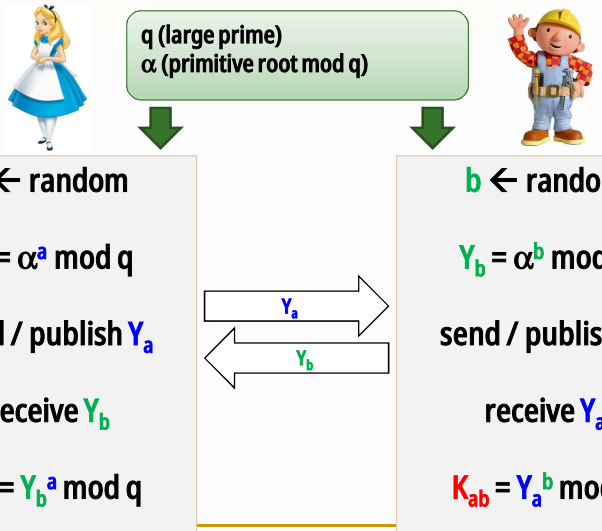


- Only the key pair of the originator is involved
  - C = E(K^{-1}, P)P = D(K, C);
  - Only X knows K_X^{-1} that produced C
- There is no confidentiality
  - Anyone knowing the public key of the originator (K_X) can decrypt C
  - If K_X is really public, then everybody can do it

Asymmetric (block) ciphers

- Approaches: complex mathematic problems
  - Discrete logarithms of large numbers
  - Integer factorization of large numbers
  - Knapsack problems
- Most common algorithms
  - RSA
  - ElGamal
  - Elliptic curves (ECC)
- Other techniques with asymmetric key pairs
  - Diffie-Hellman (key agreement)

Diffie-Hellman key agreement



Diffie-Hellman key agreement: Man-in-the-Middle (MitM) attack

$a \leftarrow$ random $Y_a = \alpha^a \bmod q$		$b \leftarrow$ random $Y_b = \alpha^b \bmod q$
send Y_a	Y_a →	
		send Y_b
	← Y_c	
receive Y_c		
	Y_b →	
		receive Y_c
$K_{ac} = Y_c^a \bmod q$	send Y_c receive Y_a, Y_b	$K_{cb} = Y_c^b \bmod q$
	$K_{ac} = Y_a^c \bmod q$ $K_{cb} = Y_b^c \bmod q$	

RSA (Rivest, Shamir, Adelman)

- Published in 1978
- Computational complexity
  - Discrete logarithm
  - Integer factoring
- Key selection
  - Large n (hundreds or thousands of bits)
  - $n = p \times q$ p and q being large (secret) prime numbers
  - Chose an e co-prime with $(p-1)\times(q-1)$
  - Compute d such that $e \times d \equiv 1 \bmod (p-1)\times(q-1)$
  - Discard p and q
  - The value of d cannot be computed out of e and n
    - Only from p and q
- Operations and keys
  - K = (e, n)
  - K^{-1} = (d, n)
  - $C = P^e \bmod n$ $P = C^d \bmod n$
  - $C = P^d \bmod n$ $P = C^e \bmod n$

RSA: example

- p = 5 q = 11 (small primes)
  - n = p x q = 55
  - $(p-1) \times (q-1) = 40$
- e = 3
  - Co-prime with 40
- d = 27
  - $e \times d \equiv 1 \bmod 40$
- P = 26 (note that P, C∈ [0, n-1])
  - $C = P^e \bmod n = 26^3 \bmod 55 = 31$
  - $P = C^d \bmod n = 31^{27} \bmod 55 = 26$

ElGamal

- Published by El Gamal in 1984
- Similar to RSA
  - But using only the discrete logarithm complexity
- A variant is used for digital signatures
  - DSA (Digital Signature Algorithm)
  - US Digital Signature Standard (DSS)
- Operations and keys (for signature handling)
  - $\beta = \alpha^x \bmod p$ $K = (\beta, \alpha, p)$ $K^{-1} = (x, \alpha, p)$
  - k random, $k \cdot k^{-1} \equiv 1 \bmod (p-1)$
  - Signature of M: (γ,δ) $\gamma = \alpha^k \bmod p$ $\delta = k^{-1} (M - x\gamma) \bmod (p-1)$
  - Validation of signature over M: $\beta^\gamma \gamma^\delta \equiv \alpha^M \pmod p$
- Problem
  - Knowing k reveals x out of δ
  - k must be randomly generated and remain secret

Elliptic curve

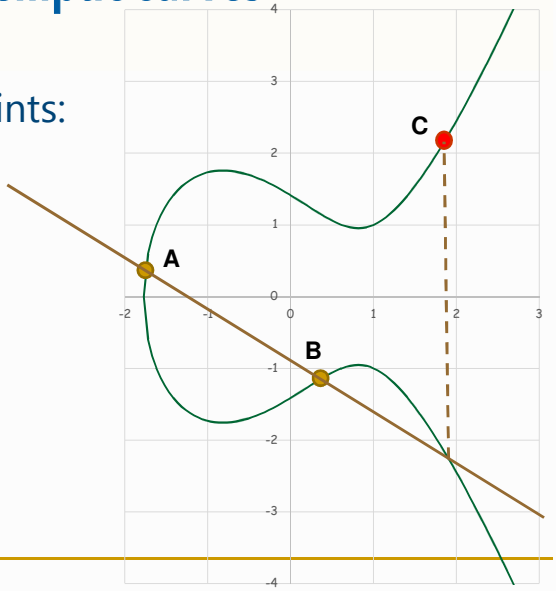
- A curve described by an equation

$$y^2 + axy + by = x^3 + cx^2 + dx + e$$

- Curves of this kind are symmetric to the X axis
  - And don't have solution for all x values

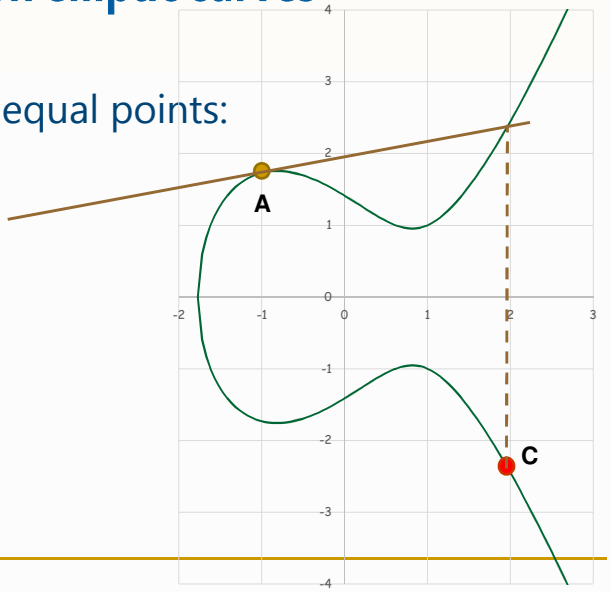
Operations on elliptic curves

- Sum of two points:
  - C = A + B



Operations on elliptic curves

- Sum of two equal points:
  - C = 2A

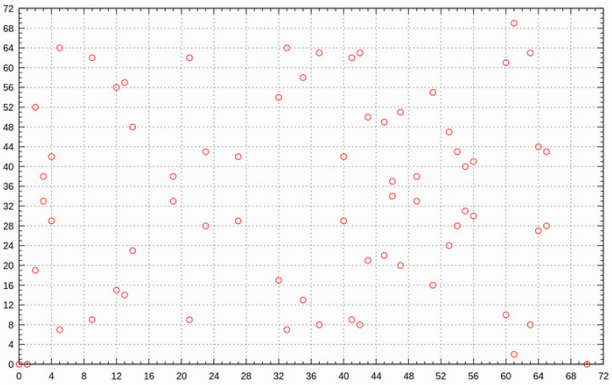


EC over finite fields

- A set of points satisfying the equation
  $$y^2 = x^3 + ax + b \ (mod\ q)$$
  - The curve also includes a point at infinity
- All x and y values must belong to $[0, q-1]$
- q must be equal to
  - p^k, for a prime p (finite field $\mathbb{F}_{p^k}$)
  - 2^m, for a prime m (finite field $\mathbb{F}_{2^m}$)
- The elliptic curve is denominated $E(\mathbb{F}_q)$

EC over finite fields: example

$$y^2 = x^3 - x \ (mod\ 71)$$



From https://en.wikipedia.org/wiki/Elliptic_curve

EC discrete logarithm problem

- Given an elliptic curve $E(\mathbb{F}_p)$,
  a point G on that curve,
  a point P which is an integer multiple of G,

  find the integer x such that
  xG = P

- For cryptographic operations, x will be the private key and P the public key

EC cryptography (ECC): curves' definition

- Prime p → (p, a, b, G, n, h)
  - Constants a and b of the EC equation
  - A generator point (or base point) G
  - The order n of G
    - Normally prime
  - A (small) co-factor h
    - Given by $\frac{1}{n}\#E(\mathbb{F}_p)$

EC Diffie-Hellman (ECDH)

- Alice and Bob agree on EC curve
  - (p, a, b, G, n, h)
- Alice chooses a random α
  - And publishes $\mathrm{A} = \alpha G$
- Bob chooses a random β
  - And publishes $\mathrm{B} = \beta G$
- Both Alice and Bob compute K
  - $K = \alpha\mathrm{B}$ $K = \beta\mathrm{A}$

Recommended curves

Length of n (bits)	p (bits)	m (bits)
161 - 223	192	163
224 - 255	224	233
256 - 383	256	283
384 - 511	384	409
≥ 512	521	571

- NIST, 1999
  - 5 P curves over prime fields $\mathbb{F}_p$
    - $y^2 = x^3 - 3x + b$
  - 5 B curves over binary fields $\mathbb{F}_{2^m}$
    - $y^2 + xy = x^3 + x^2 + b$
  - b randomly generated
    - SHA-1 hash of a seed
  - 5 K (Koblitz) curves over binary fields $\mathbb{F}_{2^m}$
    - $y^2 + xy = x^3 + ax^2 + 1$

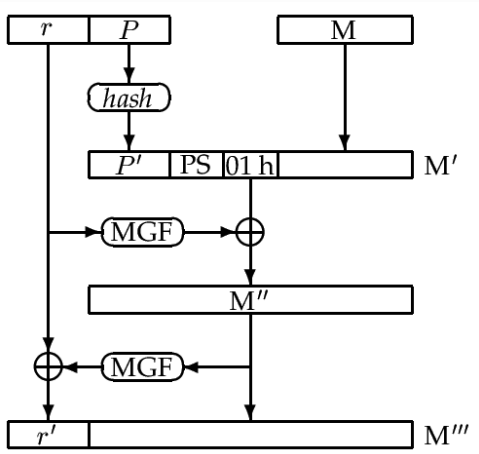
Recommended curves

- IETF
  - Daniel Bernstein's Curve25519
    - $y^2 = x^3 + 486662\,x^2 + x\ (mod\ q)$
    - $q = 2^{255} - 19$
  - Curve448
    - $y^2 = x^3 + 15632\,x^2 + x\ (mod\ q)$
    - $q = 2^{448} - 2^{224} - 1$

Randomization of asymmetric encryptions

- Non-deterministic (unpredictable) result of asymmetric encryptions
  - N encryptions of the same value, with the same key, should yield N different results
  - Goal: prevent the trial & error discovery of encrypted values
- Technics
  - Concatenation of value to encrypt with two values
    - A fixed one (for integrity control)
    - A random one (para randomization)

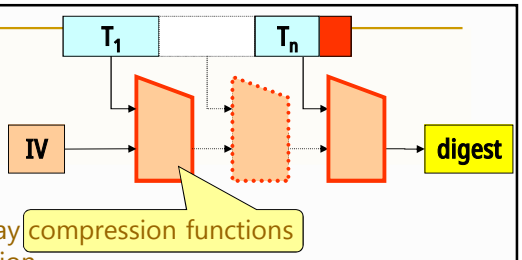
Randomization of asymmetric encryptions: OAEP (Optimal Asymmetric Encryption Padding)



Digest functions

- Give a fixed-length value from a variable-length text
  - Sort of text "fingerprint"
- Produce very different values for similar texts
  - Cryptographic one-way hash functions
- Relevant properties:
  - Preimage resistance
    - Given a digest, it is infeasible to find an original text producing it
  - 2nd-preimage resistance
    - Given a text, it is infeasible to find another one with the same digest
  - Collision resistance
    - It is infeasible to find any two texts with the same digest
    - Birthday paradox

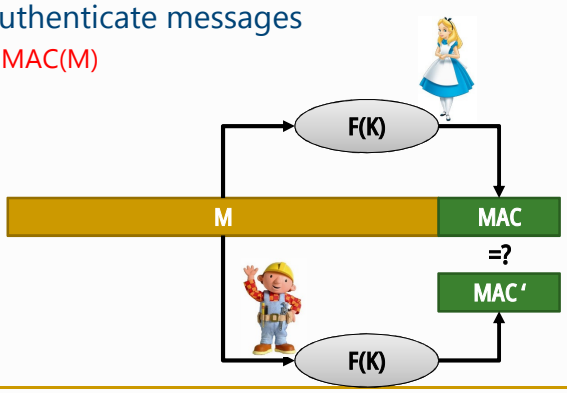
Digest functions



- Approaches
  - Collision-resistente, one-way compression functions
  - Merkle-Damgård construction
    - Iterative compression
    - Length padding
- Most common algorithms
  - MD5 (128 bits)
    - No longer secure! It's easy to find collisions!
  - SHA-1 (Secure Hash Algorithm, 160 bits)
    - Also no longer secure … (collisions found in 2017)
  - Other
    - RIPEM
    - SHA-2, aka SHA-256/SHA-512
    - SHA-3, etc.

Message Authentication Codes (MAC)

- Hash, or digest, computed with a key
  - Only key holders can generate/validate the MAC
- Used to authenticate messages
  - M' = M | MAC(M)



Message Authentication Codes (MAC): Approaches

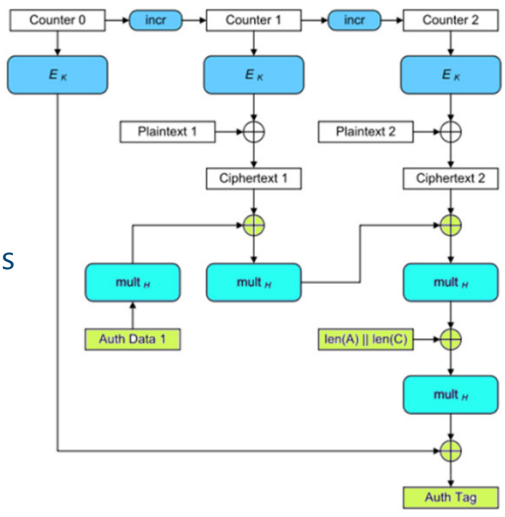
- Encryption of an ordinary digest
  - Using, for instance, a symmetric block cipher
- Using encryption with feedback & error propagation
  - ANSI X9.9 (or DES-MAC) with DES CBC (64 bits)
- Adding a key to the hashed data
  - Keyed-MD5 (128 bits)
    - MD5(K, keyfill, text, K, MD5fill)
  - HMAC (output length depends on the function H used)
    - H(K, opad, H(K, ipad, text))
    - ipad = 0x36 B times opad = 0x5C B times
    - HMAC-MD5, HMAC-SHA, etc.

Authenticated encryption

- Encryption mixed with integrity control
  - Error propagation
  - Authentication tags
- Examples
  - GCM (Galois/Counter Mode)
  - CCM (Counter with CBC-MAC)

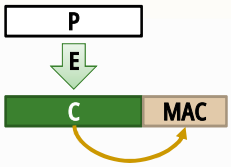
GCM

- CTR mode encryption
- Successive multiplications for integrity control
  - Multiplications in GF(2^n)
  - H = $E_k(0)$

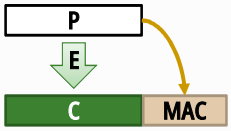


Encryption + authentication

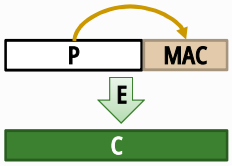
- Encrypt-then-MAC
  - MAC is computed from cryptogram



- Encrypt-and-MAC
  - MAC is computed from plaintext
  - MAC is not encrypted



- MAC-then-Encrypt
  - MAC is computed from plaintext
  - MAC is encrypted



Digital signatures

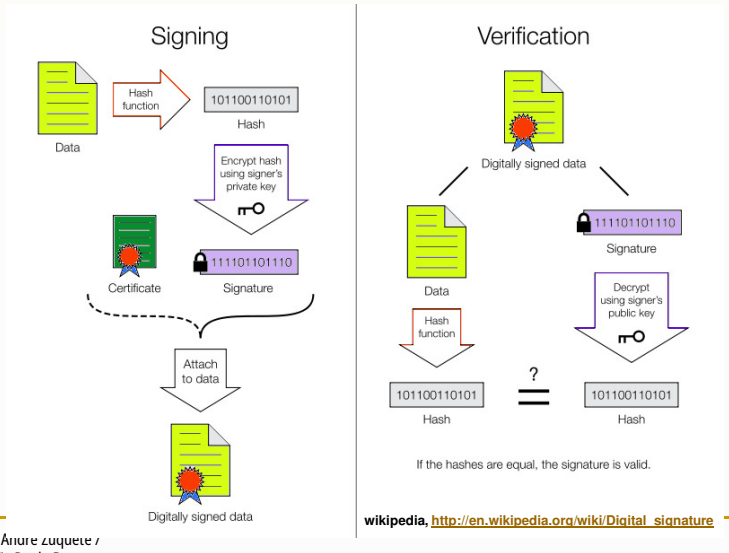
- Goal
  - Authenticate the contents of a document
    - Ensure its integrity
  - Authenticate its author
    - Ensure the identity of the creator/originator
  - Prevent origin repudiation
    - Genuine authors cannot deny authorship
- Approaches
  - Asymmetric encryption
  - Digest functions (only for performance)
- Algorithms

  Signing: $A_x(doc) = info + E(K_x^{-1}, digest(doc+info))$

  Verification: $info \rightarrow K_x$

  $D(K_x, A_x(doc)) \equiv digest(doc + info)$

Signing / verification diagrams



wikipedia, http://en.wikipedia.org/wiki/Digital_signature

Digital signature on a mail: Multipart content, signature w/ certificate

```
From - Fri Oct 02 15:37:14 2009
[…]
Date: Fri, 02 Oct 2009 15:35:55 +0100
From: =?ISO-8859-1?Q?Andr=E9_Z=FAquete?= <andre.zuquete@ua.pt>
Reply-To: andre.zuquete@ua.pt
Organization: IEETA / UA
MIME-Version: 1.0
To: =?ISO-8859-1?Q?Andr=E9_Z=FAquete?= <andre.zuquete@ua.pt>
Subject: Teste
Content-Type: multipart/signed; protocol="application/x-pkcs7-signature"; micalg=sha1; boundary="------------ms050405070101010502050101"

This is a cryptographically signed message in MIME format.

--------------ms050405070101010502050101
Content-Type: multipart/mixed;
 boundary="------------060802050708070409030504"

This is a multi-part message in MIME format.
--------------060802050708070409030504
Content-Type: text/plain; charset=ISO-8859-1
Content-Transfer-Encoding: quoted-printable

Corpo do mail

--------------060802050708070409030504--
--------------ms050405070101010502050101
Content-Type: application/x-pkcs7-signature; name="smime.p7s"
Content-Transfer-Encoding: base64
Content-Disposition: attachment; filename="smime.p7s"
Content-Description: S/MIME Cryptographic Signature

MIAGCSqGSIb3DQEHAqCAMIACAQExCzAJBgUrDgMCGgUAMIAGCSqGSIb3DQEHAQAAoIIamTCC
BUkwggSyoAMCAQICBAcnIaEwDQYJKoZIhvcNAQEFBQAwdTELMAkGA1UEBhMCVVMxGDAWBgNV
[…]
KoZIhvcNAQEBBQAEgYCofks852BV77NVuww53vSxO1XtI2JhC1Cdlu+tcTPoMDlwq5dc5v40
Tgsaw0N8dqgVLk8aC/CdGMbRBu+JLLKrcVZa+khnjjtB66HhDRLrjmEGDNttrEjbqvpd2QO2
vxB3iPTlU+vCGXo47e6GyRydqTpbq0r49Zqmx+IJ6Z7iigAAAAAAAA==
--------------ms050405070101010502050101--
```

Blind signatures

- Signatures made by a "blinded" signer
  - Signer cannot observe the signed contents
  - Similar to a handwritten signature on an envelope containing a document and a carbon-copy sheet
- They are useful for ensuring anonymity of the signed information holder, while the signed information provides some extra functionality
  - Signer X knows who requires a signature (Y)
  - X signs T_1, but Y afterwards transforms it into a signature over T_2
    - Not any T_2, a specific one linked to T_1
  - Requester Y can present T_2 signed by X
    - But it cannot change T_2
    - X cannot link T_2 to the T_1 that it observed when signing

Chaum Blind Signatures

- Implementation using RSA
  - Blinding
    - Random blinding factor K
    - $k \times k^{-1} \equiv 1 \pmod{N}$
    - $m' = k^e \times m \bmod N$
  - Ordinary signature (encryption w/ private key)
    - $A_x(m') = (m')^d \bmod N$
  - Unblinding
    - $A_x(m) = k^{-1} \times A_x(m') \bmod$