

T-79.159

Cryptography and Data Security

Lecture 2:

2.1 Classical cryptosystems

2.2. Introduction to modern cryptographic primitives

Kaufman et al: Chapter 2

Stallings: Chapter 2

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2.1 Classical Cryptosystems

Cesar Cipher, or Shift Cipher

Plain: meet me after the toga party

Cipher: PHHW PH DIWHU WKH WRJD SDUWB

Alphabets

Plain: abcdefghijklmnopqrstuvwxyz

Cipher: ABCDEFGHIJKLMNOPQRSTUVWXYZ

Or, Plain: 0123456789... 24, 25

Cipher: 0123456789... 24, 25

Substitution is a mapping from "Plain" to "Cipher"

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Caesar cipher

p = plaintext letter, $\{0,1,2,\dots,25\} \ni p$

C = ciphertext letter, $\{0,1,2,\dots,25\} \ni C$

Caesar substitution E

$$E: C = E(p) = (p + 3) \bmod 26$$

0 \rightarrow 3; 1 \rightarrow 4; ...

22 \rightarrow 25; 23 \rightarrow 0; 24 \rightarrow 1; 25 \rightarrow 2

Caesar substitution, inverse transformation D

$$D: p = D(C) = (C - 3) \bmod 26$$

0 \rightarrow 23; 1 \rightarrow 24; 2 \rightarrow 25; 3 \rightarrow 0; ... ; 25 \rightarrow 22

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Brute force cryptanalysis of shift cipher

Shift cipher: $E: C = E(p) = p + K \bmod 26$

K = key; $\{0,1,2,3,\dots,25\} \ni K$

We need only some piece of ciphertext to do exhaustive search

K	PHHW PH DIWHU WKH WRJD SDUWB
1	oggv ..
2	nffu ..
3	meet me after the toga party

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Monoalphabetic substitution

Alphabets

Plain: abcdefghijklmnopqrstuvwxyz

Cipher: ABCDEFGHIJKLMNOPQRSTUVWXYZ

Key = permutation of the 26 characters

Size of key space $26! \cong 4 \times 10^{26}$

Cryptanalysis based on statistical properties of the plaintext

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Relative Frequency of Letters in English Text

A	8.167
B	1.492
C	2.782
D	4.253
E	12.702
F	2.228
G	2.015
H	6.094
I	6.996
J	0.153
K	0.772
L	4.025
M	2.406

N	6.749
O	7.507
P	1.929
Q	0.095
R	5.987
S	6.327
T	9.056
U	2.758
V	0.978
W	2.360
X	0.150
Y	1.974
Z	0.074

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Ciphertext obtained from a Substitution Cipher

YIFQF MZRWQ FYVEC FMDZP CVMRZ
WNMDZ VEJBT XCDDU MJNDI FEFMD
ZCDMQ ZKCEY FCJMY RNCWJ CSZRE
XCHZU NMXZN ZUCDR JXYYS MRTME
YIFZW DYVZV YFZUM RZCRW NZDZJ
JXZWG CHSMR NMDHN CMFQC HZJMX
JZWIE JYUCF WDJNZ DIR

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Frequency table

A	0	N	9
B	1	O	0
C	15	P	1
D	13	Q	4
E	7	R	10
F	11	S	3
G	1	T	2
H	4	U	5
I	5	V	5
J	11	W	8
K	1	X	6
L	0	Y	10
M	16	Z	20

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Simple substitution: frequency analysis cont'd

The most frequent character: Z

The most frequent character in English: e

Guess: $D(Z) = e$

The next most frequent characters

$\{M, C, D, F, J, R, Y, N\}$

The next most frequent characters in English

$\{t, a, o, i, n, s, h, r\}$

The most frequent digrams with Z are:

DZ, ZW (4 times); NZ, ZU (3 times);

RZ, HZ, XZ, FZ, ZR, ZV, ZC, ZD (two times each)

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Using comon digrams...

NZ is common but ZN occurs only once;

guess $D(N) = h$

ZW is common and WZ not at all and W is rare;

guess $D(W) = d$

DZ (4 times) and ZD (2 times) are both common

we guess $\{r, s, t\} \ni D(D)$

ZRW and RZW occur, and RW occurs, and R is frequent we guess $D(R) = n$

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Now we have

```

end          e      ne dh e
YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
      h          e      e      nh d
XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
en      e h eh      n      n      ed
CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
      e      e      ne nd he e      ed      n h h
DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
      e      ed      d he n
CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

```

ne_ndhe suggests that $D(C) = a$

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```

end          a      e a ne dh e
YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
a      h          ea      ea      a      nhad
XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
a en      a e h eh      a n      n      ed
CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
      e      e      neand he e      ed a n h h
DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
a a e      ed      a d he n
CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

```

nh_ decrypts to RNM suggests that $D(M) = i$ or o

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We have

```

      iend      a i e a ine dhi e
YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
  a   i h      i ea i  ea   a i  nhad
XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
a en   a e hi eh   a n      in i    ed
CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
      e   e i neand he e    ed a in hi h
DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
ai a e i    ed      a d he n
CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

```

Guess $\{D, F, J, Y\} \ni E(o)$, then Y is the most likely

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```

o      iend   o a i e a ine dhi e
YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
  a   i h      i ea i  ea o  a io nhad
XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
a en   a e hi eh e a n   oo in i o ed
CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
      o e o e i neand he e    ed a in hi h
DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
ai a e i    ed      o a d he n
CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

```

Remaining $\{D, F, J\}$ possibly decrypt to $\{r, s, t\}$

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Remaining {D, F, J} possibly decrypt to {r, s, t}

o r r iend ro a rise a ine dhise t
YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
ass iths r ris easi ea rati nhadt
XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
a en a e hi eh asn t oo in i o red
CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
so e re i neand heset ed a in his h
DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
air a eti ted to ar dsthe s n
CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

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Try $D(Q) = f$ and so on ..

o rfr iendf ro a rise a ine dhise t
YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
ass iths r ris easif ea o ratio nhadt
XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
a en a e hi eh asn t oo in i o red
CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
so e ore i neand heset ed a in his h
DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
airfa eti ted to ar dsthe s n
CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

16

ourfr iendf ro a rise a ine dhise t
 YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
 ass ithsu r ris easif ea o ratio nhadt
 XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
 a en a e hi eh e asn t oo in i oured
 CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
 so e ore i neand heset t ed a in his h
 DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
 airfa eti tedu to ar dsthe sun
 CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

17

ourfr iendf rom a rise amine dhise m t
 YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
 ass ithsu r ris easif ea o ratio nhadt
 XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
 a en a e hi eh e asn t oo in i oured
 CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
 somem ore i neand heset t ed a in his h
 DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
 airfa eti tedu to ar dsthe sun
 CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

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ourfr iendf rompa risex amine dhise mptyg
 YIFQF MZRWQ FYVEC FMDZP CVMRZ WNMDZ VEJBT
 lassw ithsu rpris easif evapo ratio nhadt
 XCDDU MJNDI FEFMD ZCDMQ ZKCEY FCJMY RNCWJ
 akenp lacew hileh ewasn tlook ingip oured
 CSZRE XCHZU NMXZN ZUCDR JXYYS MRTME YIFZW
 somem orewi neand heset tledb ackin hisch
 DYVZV YFZUM RZCRW NZDZJ JXZWG CHSMR NMDHN
 airfa cetil tedup towar dsthe sun
 CMFQC HZJMX JZWIE JYUCF WDJNZ DIR

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Playfair Cipher

M	O	N	A	R
C	H	Y	B	D
E	F	G	I/J	K
L	P	Q	S	T
U	V	W	X	Z

The encryption rules

Plaintext formatting

oo -> oxo

Same row or column

ar -> RM

mu -> CM

Regular case

hs -> BP

ea -> IM

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Hill Cipher

$$\begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = \begin{pmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{pmatrix} \times \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix} \pmod{26}$$

Plain: triples of numbers in $\{0,1,2,\dots,25\}$

Cipher: triples of numbers in $\{0,1,2,\dots,25\}$

Key: 3x3 matrices with entries in $\{0,1,2,\dots,25\}$

Arithmetic as in shift cipher plus multiplication

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Polyalphabetic ciphers: Vigenère

Plain and Cipher:

finite sequences of characters in $\{0,1,2,\dots,25\}$

Key of period q : $k_1 k_2 k_3 \dots k_{q-1} k_q$

sequences of length q of characters in $\{0,1,2,\dots,25\}$

Encryption:

$$c_1 = (p_1 + k_1) \pmod{26} \quad c_{q+1} = (p_{q+1} + k_1) \pmod{26}$$

$$c_2 = (p_2 + k_2) \pmod{26} \quad c_{q+2} = (p_{q+2} + k_2) \pmod{26}$$

...

...

$$c_q = (p_q + k_q) \pmod{26} \quad c_{2q} = (p_{2q} + k_q) \pmod{26}$$

and so on..

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Polyalphabetic ciphers: Vigenère

Example

ourfr iendf rompa risex amine dhise mptyg
sprin gspri ngspr ingsp rings pring sprin
GJINE OWCUN EU... ..

Note the repetition of a two character string resulting from a repetition in the plaintext!

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Kasiski's method to determine the period

- Many strings of characters repeat themselves in natural languages.
- Assume the interval between occurrence of a string is a multiple of the period length.
- Then a repetition of a character string of the same length occurs in the ciphertext.
- By detecting repetitions of strings in the ciphertext one can find the period as the greatest common divisor (GCD) of the repetition intervals
- There may be false repetitions. The longer the repeating string the more significant it is. Repeating strings of length ≥ 3 are the most significant.

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One Time Pad

- Claude Shannon laid (1949) the information theoretic fundamentals of secrecy systems.
- Shannon's pessimistic inequality: For perfect secrecy you need as much key as you have plaintext.
- An example of a cipher which achieves perfect secrecy is the One Time Pad

$$c_i = (p_i + k_i) \bmod 26$$

where the key is a string of characters $k_1 k_2 k_3 \dots k_i$ chosen uniformly at random.

- Practical ciphers do not provide perfect secrecy

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2.2 Introduction to contemporary cryptographic primitives

- Secret key (symmetric) primitives
 - Block cipher
 - Stream cipher
 - Integrity primitives
 - Message authentication code
 - Hash functions
- Public key (asymmetric) primitives
 - Public key encryption scheme
 - Digital signature scheme

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Primitives and protocols

- Cryptographic primitives and functions are used as building blocks of cryptographic protocols
- For example,
 - 1) A stream cipher primitive is the basic building block of an encryption protocol
 - 2) A message authentication code is the basic building block of an authentication protocol

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Man-made vs. Math-made

Symmetric primitives are

- based on man-made constructions.
- Fast and easy to implement in software and hardware
- Short keys

Asymmetric (public key primitives) are

- Based on mathematical construction and their security is derived from infeasibility of some computationally hard problem.
- Slow and difficult to implement (both in software and hardware)
- Long keys and parameters

Note: it would be possible to construct symmetric primitives based on mathematics, but they are not used in practice because they are not efficient compared to symmetric primitives

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Block ciphers

(Message , Secret key) \rightarrow Ciphertext

(Ciphertext, Secret key) \rightarrow Message

Confidentiality primitive

- Threat: retrieve the plaintext from the ciphertext without the knowledge of the key.
- Security goal: protect against this threat.

Plaintext P : strings of bits of fixed length n

Ciphertext C : strings of bits of the same length n

Key K : string of bits of fixed length k

Encryption transformations: For each fixed key the encryption operation E_K is one-to-one (invertible) function from the set of plaintexts to the set of ciphertext. That is, there exist an inverse transformation, decryption transformation D_K such that for each P and K we have:
 $D_K(E_K(P)) = P$

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Block ciphers, security

- Security is measured in terms of time: How long it takes to break the cipher using available resources.
- Upperbound of security: The time complexity of exhaustive key search, which is equal to 2^k , with key length of k bits.
- A second upperbound: $2^{n/2}$, with block length n (due to Birthday paradox, to be explained later)
- If an attack leads to a break, in time 2^t , where $t < k$, then the cipher is said to be *theoretically broken*, and that the *effective key length* of the cipher is reduced to t . (This does not mean that the cipher is broken in practise unless t is very small.)

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Block ciphers, design principles

- The ultimate design goal of a block cipher is to use the secret key as efficiently as possible.
- Confusion and diffusion (Shannon)
- New design criteria are being discovered as response to new attacks.
- A state-of-the-art block cipher is constructed taking into account all known attacks and design principles.
- But no such block cipher can become provably secure, it may remain open to some new, unforeseen attacks.
- Common constructions with iterated round function
 - Substitution permutation network (SPN)
 - Feistel network

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Attack on block ciphers

- *Ciphertext only attack*: The attacker has access to some amount of ciphertext and also knows something about the nature of the plaintext, which is not perfectly random.
- *Known plaintext attack*: The attacker has access to some amount of plaintext and the corresponding ciphertext.
- *Chosen plaintext attack*: The attacker is able to choose some amount of plaintext and obtains the corresponding ciphertext.
- *Adaptively chosen plaintext attack*. The attacker is able to choose some amount of plaintext in parts, and obtain the corresponding ciphertext, where the choice of each new part of plaintext is influenced by all previously obtained ciphertext.
- *Chosen ciphertext and adaptive chosen ciphertext attacks*: Similar to the chosen plaintext attacks but now with the roles of plaintext and ciphertext reversed.

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Stream ciphers

- Stream ciphers are generally faster than block ciphers, especially when implemented in hardware.
- Stream ciphers have less hardware complexity.
- Stream ciphers can be adapted to process the plaintext bit by bit, or word by word, while block ciphers require buffering to accumulate the full plaintext block.
- Synchronous stream ciphers have no error propagation; encryption is done character by character with keys K_i that are independent of the data

$$C_i = E_{K_i}(P_i)$$

- Function E is simple, the function which computes the key sequence is complex
- Example: Vigenère cipher, One Time Pad

$$C_i = (P_i + K_i) \bmod 26$$

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Stream cipher encryption

Secret key \rightarrow Key stream

(Key stream , Message) \rightarrow Ciphertext

Secret key \rightarrow Key stream

(Ciphertext, Key stream) \rightarrow Message

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Stream ciphers: Security

- Known plaintext gives known key stream. Chosen plaintext gives the same but nothing more.
- Chosen ciphertext attack may be a useful method for analysing a self-synchronising stream cipher.
- The attacker of a stream cipher may try to find one internal state of the stream cipher to obtain a functionally equivalent algorithm without knowing the key.
- Distinguishing a key stream sequence from a truly random sequence allows also the keystream to be predicted with some accuracy. Such attack is also called prediction attack.

Requirements:

- Long period
- A fixed initialisation value the stream cipher generates a different keystream for each key.

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Stream ciphers: Designs

Linear feedback shift register (LFSR). LFSRs are often used as the running engine for a stream cipher.

Stream cipher design based on LFSRs uses a number of different LFSRs and nonlinear Boolean functions coupled in different ways. Three common LFSR-based types of stream cipher can be identified:

- *Nonlinear combination generators*: The keystream is generated as a nonlinear function of the outputs of multiple LFSRs
- *Nonlinear filter generators*: The keystream is generated as a nonlinear function of stages of a single LFSR.
- *Clock controlled generators*: In these constructions, the necessary nonlinearity is created by irregular clocking of the LFSRs. The GSM encryption algorithm A5/1 is an example of a stream cipher of this type.

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Message authentication codes (MAC)

(Secret key , Message) \rightarrow MAC

(Secret key , Message) \rightarrow MAC

- A MAC of a message P of arbitrary length is computed as a function $H_K(P)$ of P under the control of a secret key K .
- The MAC length m is fixed.
- Security requirement: it must be infeasible, without the knowledge of the secret key, to determine the correct value of $H_K(P)$ with a success probability larger than $1/2^m$. This is the probability of simply guessing the MAC value correctly at random. It should not be possible to increase this probability even if a large number of correct pairs P and $H_K(P)$ is available to the attacker.

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Message authentication codes (MAC)

- Similarly as block ciphers, MAC algorithms operate on relatively large blocks of data. Most MACs are iterated constructions. The core function in the MAC algorithm is a compression function. At each round the compression function takes a new data block and compresses it together with the compression result from the previous rounds. Hence the length of the message to be authenticated determines how many iteration rounds are required to compute the MAC value.
- Given a message X and its MAC value H , it can be verified by anybody in possession of the secret key K and the MAC computation algorithm.

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Hash functions

Message \rightarrow Hash code

Message \rightarrow Hash code

- A hash code of a message P of arbitrary length is computed as a function $H(P)$ of P . The hash length m is fixed.
- Security requirements:
 1. *Preimage resistance*: Given h it is impossible to find P such that $H(P) = h$
 2. *Second preimage resistance*: Given P it is impossible to find P' such that $H(P') = H(P)$
 3. *Collision resistance*: It is impossible to find P and P' such that $P \neq P'$ and $H(P) = H(P')$

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Hash functions

- Similarly as MAC algorithms, hash functions operate on relatively large blocks of data. Most hash functions are iterated constructions. The core function in a hash function is a compression function. At each round the compression function takes a new data block and compresses it together with the compression result from the previous rounds. Hence the length of the message to be authenticated determines how many iteration rounds are required to compute the MAC value.
- Hash function is public: Given a message P anybody can compute the hash code of P .

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Public key encryption

(Message , Public key) \rightarrow Ciphertext

(Ciphertext , Private key) \rightarrow Message

- Slow, usually used to encrypt short messages in more complex protocols than just bulk message encryption: authentication, key agreement etc.
- Because of the mathematics involved, complex message formatting rules (with hash functions) are required.
- Chosen ciphertext attacks maybe an essentially more serious threat than chosen plaintext (for symmetric block ciphers they are about the same). We will see an example later.
- RSA, ElGamal in different groups, Pairing based techniques ...

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Digital signatures

(Message , Private key) \rightarrow Signature

(Signature , Public key) \rightarrow Validity (1 bit)

- Important primitive; the only one to provide non-repudiation.
- Slow, message are signed by applying the digital signature operation on a fixed length hash of the message.
- Used for
 - message authentication protocols
 - non-repudiation protocols
 - authentication and key agreement
 - commitment schemes
 - ...
- RSA, ElGamal in different groups, Schnorr, DSA, Pairing based techniques

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