Part I

Identification, authentication, secret sharing and e-commerce

EXAMS

- December: 19.12.2019 at 8.00 in B410
- January: 03.01.2020 at 8.00 in B411
  8.01.2020 at 12.00 in B410
  15.01.2020 at 12.00 in B410
  22.01.2020 at 12.00 in B410

WISDOM

Keep in mind that a cryptosystem is as secure as its weakest part - security does not add up!

CHAPTER 9: AUTHENTICATION, SECRET SHARING and e-COMMERCE

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With all of the above problems we will deal in the first part of this chapter.

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- **Authentication** is, in particular, the act of confirmation the identity of a communicating entity (a person or a computer), and, in general, the act of confirmation the truth of an attribute, datum or entity.
- **Data integrity** refers to maintaining and ensuring the accuracy and consistency of data over its entire life cycle - the accuracy, validity and correctness of data should be ensured from hardware failures, software errors and human errors or unfriendly activities.

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An example how e-commerce can be realized, in a simplified setting, will be shown at the end of this chapter.

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Identification usually serves to control access to a resource, (often a resource should be accessed only by privileged users).

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- Each of the above conditions should remain valid even if an attacker has observed, or has even participated in, several identification processes of the same party.

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2. There should be no way to pretend, for a third party, say Charles, when communicating with Bob, that he is Alice without Bob having a large chance to find that out.

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Honest Bob, who always follows fully the protocol, would then return w to Alice and she would get this way the plaintext w.

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- Bob identifies a communicating person as Alice if she can send him back r, r_1.

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1. **To communicate a message m**, Alice sends a pair$(m, A_k(m))$ – $\{A_k(m)$ is said to be **MAC**$\}$.
2. If Bob gets (m', MAC), then he computes $A_k(m')$ and compares it with **MAC**.

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4. Verification (of the response).

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In this protocol a PKC will be used with encryption/decryption algorithms (e_U, d_U), for each user U, and a DSS with signing/verification algorithms (sig_U, ver_U).

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1. Alice chooses a random integer r_A, sets $\mathrm{t} = (I_B,\ r_A)$, signs it as $sig_A(I_A, t)$ and sends $m_1 = (t, sig_A(I_A, t))$ to Bob.

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2. Bob verifies Alice's signature, chooses a random r_B and a random session key k. He then encrypts k with Alice's public key to get $e_A(k) = c$, sets

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   and signs it as $sig_B(t_1)$.

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and signs it as $sig_B(t_1)$. Then he sends $m_2 = (t_1, sig_B(t_1))$ to Alice.

THREE-WAY AUTHENTICATION and KEY AGREEMENT II

3. Alice verifies Bob's signature $sig_{s_B}(t_1)$ with $t_1 = (I_A, r_A, r_B, c)$,, and then checks that the r_A she just got matches the one she generated in Step 1.

THREE-WAY AUTHENTICATION and KEY AGREEMENT II

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The price to pay is that communicating parties need to share a secret random key that needs to be transmitted through a secure channel.

SCHEMES for DATA AUTHENTICATION

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$$y_1 \| y_2 \| \dots \| y_l$$

is the encryption of m and

y_l can be considered as the MAC for m.

A modification of this method is to use another crypto-algorithm to encrypt the last block m_l.

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Using so called **zero-knowledge identification schemes**, discussed in the next chapter, you can identify yourself without giving to the identificator the ability to impersonate you.

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If protocol is repeated t times, Alice has a chance 2^{-t} to fool Bob if she does not know s and r.

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Completeness: If Alice knows s, and both Alice and Bob follow the protocol, then the response rs^b is the square root of xv^b.

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Eve has therefore a 50% chance to cheat.

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Fiat-Shamir IDENTIFICATION SCHEME – PARALLEL VERSION

In the following parallel version of Fiat-Shamir identification scheme the probability of a false identification is decreased.

Choose primes p, q and compute $n = pq$ and choose as security parameters integers k, t.

Choose quadratic residues $v_1, \ldots, v_k \in QR_n$.

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Alice and Bob repeat this protocol t times, until Bob is convinced that Alice knows $s_1, \ldots, s_k$.

The chance that Alice can fool Bob is 2^{-kt}, a significant decrease comparing with the chance $\frac{1}{2}$ of the previous version of the identification scheme.

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3. TA generates signature

   $$s = sig_{TA}(ID(Alice), v)$$

   and sends to Alice as her certificate: C (Alice) = (ID(Alice), v, s)

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7. This way Alice proofs her identity to Bob. Indeed,
$$\begin{aligned} \alpha^y v^r &\equiv \alpha^{k+ar} \alpha^{-ar} \mod p \\ &\equiv \alpha^k \mod p \\ &\equiv \gamma \mod p. \end{aligned}$$

Total storage needed: 512 bits for ID(Alice), 512 bits for v, 320 bits for s (if DSS is used). In total – 1344 bits.

Total communication needed from: Alice → Bob – 1996 (= 1344+512+140) bits, Bob → Alice 40 bits (to send r).

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Issuing a certificate to Alice

- TA establishes Alice's identity and issues her identification string ID(Alice).
- Alice secretly and randomly chooses $0 \leq a_1, a_2 \leq q-1$ and sends to TA
$$v = \alpha_1^{-a_1}\alpha_2^{-a_2} \mod p.$$
- TA generates a signature $s = sig_{\mathrm{TA}}(ID(Alice), v)$ and sends to Alice the certificate
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Okamoto IDENTIFICATION SCHEME – BASICS ONCE MORE

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TA chooses: a large prime $p \leq 2^{512}$,large prime $q \geq 2^{140}$ dividing p - 1; two elements $\alpha_1, \alpha_2 \in Z_p^*$ of order q. TA keep secret (also from Alice and Bob) $c = \lg_{\alpha_1} \alpha_2$.

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DATA (MESSAGE) INTEGRITY
and
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- With the use of cryptographic techniques to deal with data authentication problem we deal briefly in the next.

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Formally, an **authentication code** consists of:

- A set M of possible messages.
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- If Bob receives (w, t) he computes $t' = a_k(w)$ and if t = t', then Bob accepts the message w as authentic.

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The goal of **authentication codes**, to be discussed next, is to decrease probabilities that Mallot performs successfully impersonation or substitution.

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Let $M = T = Z_3$, $K = Z_3 \times Z_3 - -Z_3 = \{0, 1, 2\}$.
For $(i, j) \in K$ and $w \in M$, let $t_{ij}(w) = (iw + j) \mod 3$.

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The matrix key $\times$ message of authentication tags has now the form

Key	0	1	2
(0,0)	0	0	0
(0,1)	1	1	1
(0,2)	2	2	2
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Impersonation attack: Let us assume that Mallot picks a message w and tries to guess the correct authentication tag.

THE AUTHENTICATION MATRIX - EXAMPLE

Let $M = T = Z_3$, $K = Z_3 \times Z_3 - -Z_3 = \{0, 1, 2\}$.
For $(i, j) \in K$ and $w \in M$, let $t_{ij}(w) = (iw + j) \mod 3$.
The matrix key $\times$ message of authentication tags has now the form

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Substitution attack: By checking the table one can see that if Mallot observes an authenticated message (w, a), then there are exactly three possibilities for the key that was used.
Moreover, for each choice (w', a'), w $\neq$ w', there is exactly one of the three possible keys for (w',a') that can be used. Therefore $P_s = \frac{1}{3}$.

ORTHOGONAL ARRAYS

Definition: An **orthogonal array** OA(n, k, λ) is a $\lambda n^2 \times k$ array of n symbols, such that in any two columns of the array every one of the possible n^2 pairs of symbols occurs in exactly λ rows.

Example: OA(3,3,1) obtained from the authentication matrix presented before;

$$\begin{pmatrix} 0 & 0 & 0 \\ 1 & 1 & 1 \\ 2 & 2 & 2 \\ 0 & 1 & 2 \\ 1 & 2 & 0 \\ 2 & 0 & 1 \\ 0 & 2 & 1 \\ 1 & 0 & 2 \\ 2 & 1 & 0 \end{pmatrix}$$

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Theorem: Suppose we have an orthogonal array OA(n, k, λ).Then there is an authentication code with $|M| = k, |T| = n, |K| = \lambda n^2$ and $P_I = P_s = \frac{1}{n}$.

Proof: Use each row of the orthogonal array as an authentication rule (key) with equal probability. Therefore we have the following correspondence:

orthogonal array	authentication code
row	authentication rule
column	message
symbol	authentication tag

CONSTRUCTION and BOUNDS for OAs

In an orthogonal array OA(n, k, λ)

- n determines the number of authenticators/tags (security of the code);
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- Suppose that p is a prime and $d \leq 2$ an integer. Then there is an orthogonal array $OA(p, \frac{(p^d-1)}{(p-1)}, p^{d-2})$.
- Let us have an authentication code with $|A| = n$ and $P_i = P_s = \frac{1}{n}$.Then $|K| \geq n^2$. Moreover, $|K| = n^2$ if and only if there is an orthogonal array OA(n, k,1), where $|M| = k$ and $P_K(k) = \frac{1}{n^2}$ for every key $k \in K$.

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The last claim shows that there are no much better approaches to authentication codes with deception probabilities as small as possible than orthogonal arrays.

- Orthogonal arrays are a very important concept of recreational mathematics, combinatorial mathematics, coding theory.
- They were introduced by Rao in 1946.
- One of the non-trivial questions is for which parameters one can construct the corresponding Orthogonal array.
- There is a library of more than 200 Orthogonal arrays.

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For example, secret sharing is used as cryptographic primitive in several protocols for secure multiparty computation.

SECRET SHARING - PROBLEM

In some applications, it is of importance to distribute a sensitive information, called here as a secret (for example an algorithm how to open a safe or a secret key) among several parties in such a way that only a well define subsets of parties can determine the secret - if members of the parties cooperate.

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In the following we show how to solve this problem in the following "threshold" setting:

How to "partition" a number S (called here as a "secret") into n "shares" and distribute them among n parties in such a way that for a fixed (threshold) $t < n$

(1) any t, or more, of parties can create secret S,
but no $t-1$, or less, of parties can get the slightest idea how to know the secret.

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Since each degree $t-1$ polynomial p is uniquely determined by any t points on p-curve, the above distribution of points allows any t users to determine p, and so also p(0)=S, and no smaller group of parties, will have the **slightest idea** about S.

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The above scheme can be easily extended to the case of n users so that only all of them can reveal the secret.

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It is assumed that the dealer "distributes" the secret through shares to parties secretly and in such a way that no party knows shares of other parties.

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and the last participant gets, as his share $X \oplus S$, where X is xor of all remaining random shares.

By xoring all shares the secret S can be obtained.

BASIC PROPERTIES of SECURE SECRET SHARING SCHEMES

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- All secure secret sharing schemes have to use random elements.

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Theorem Let $f(x) = \sum_{i=0}^{t-1} a_i x^i \in Z_p[x]$ be a polynomial of degree t - 1 and let

$$\Omega = \{(x_i, f(x_i)) \,|\, x_i \in Z_p, i = 1, \ldots, t, x_i \neq x_j \text{ if } i \neq j\}$$

For any $Q \subseteq \Omega$, let $P_Q = \{g \in Z_p[x] | deg(g) \leq t-1, g(x) = y$ for all (x,y) $\in Q\}$. Then it holds:

- $P_\Omega = \{f(x)\}$, i.e. f is the only polynomial of degree t - 1, whose graph contains all t points in Ω.
- If Q is a proper subset of Ω and $x \neq 0$ for all $(x, y) \in Q$, then each $a \in Z_p$ appears with the same frequency as the constant coefficient of polynomials in P_Q.

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Corollary: (Lagrange formula) Let $f(x) = \sum_{i=0}^{t-1} a_i x^i \in Z_p[x]$ be a polynomial and let $P = \{(x_l, f(x_i)) \mid i = 1, \ldots, t, x_i \neq x_j, i \neq j\}$. Then

$$f(x) = \sum_{i=1}^{t} f(x_i) \prod_{1 \leq j \leq t,\quad j \neq i} \frac{x - x_j}{x_i - x_j}$$

Shamir's (n,t)-THRESHOLD SCHEME — SUMMARY

To distribute n shares of a secret S among parties $P_1, \ldots, P_n$ a dealer - a trusted authority TA - proceeds as follows:

- TA chooses a prime $p > max\{S, n\}$ and sets $a_0 = S$.
- TA selects randomly $a_1, \ldots, a_{t-1} \in Z_p$ and creates the polynomial $f(x) = \sum_{i=0}^{t-1} a_i x^i$.
- TA computes $s_i = f(i), i = 1, \ldots, n$ and transfers each (i, s_i) to the party P_i in a secure way.

Any group J of t or more parties can compute the secret. Indeed, from the previous corollary we have

$$S = a_0 = f(0) = \sum_{i \in J} f(i) \prod_{j \in J, j \neq i} \frac{j}{j - i}$$

In case $|J| < t$, then each $a_0 \in Z_p$ is equally likely to be the secret.

PROPERTIES of SHAMIR's SECRET (n, t) SHARING SCHEMES

- **Security:** The scheme is information theoretically secure.
- **Minimality:** The size of each share does not exceed the size of the secret.
- **Dynamicity:** Shares can be replaced by another ones without affecting other shares.
- **Flexibility:** Parties can obtain different number of shares according to their importance (within an organization they are in).

ORTHOGONAL ARRAYS BASED SECRET SHARING SCHEME

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General form of orthogonal arrays: An $t-(n,k,\lambda)$ orthogonal array for $t \leq k$ is a $\lambda n^t \times k$ array, whose entries are from a set X of n points such that in every subset of t columns of the array, every t-tuple of points of X appears in exactly λ rows. (Parameter t is called a **strength** of such an array.)

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SECRET SHARING – GENERAL CASE

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Let P be a set of parties. To deal with the above situation such concepts as an **authorized set of users** of P and **access structures** are used.

An 'authorized set of parties $A \subseteq P$ is a set of parties who should be able, when cooperating, to construct the secret.

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Let P be a set of parties. The **access structure** $\Gamma \subseteq 2^P$ is a set of subsets of parties such that $A \in \Gamma$ for all authorized sets A and $U \in 2^P - \Gamma$ for all unauthorized sets U.

Theorem: For any access structure there exists a secret sharing scheme realizing this access structure.

EXAMPLE of an ACCESS STRUCTURE

An access structure for the set of players

$$P = \{P_1, P_2, P_3, P_4, P_5\}$$

is the set of subsets of P that contains sets

$$\{P_2, P_5\}, \quad \{P_1, P_4\} \quad \{P_1, P_2, P_3\}$$

and all their supersets.

SECRET SHARING using CHINESE REMAINDER THEOREM

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i-th share will be $s_i = S \bmod m_i$ Recovery of the secret S from the shares $s_{i_1}, s_{i_2}, \ldots s_{i_t}$ is done by solving system of equations

$$S \equiv s_{i_j} \bmod m_{i_j}, j = 1, 2, \ldots t$$

Observe that the above condition for S implies that S is smaller than the product of any choice t of m's, but, at the same time, greater than any choice of $t - 1$ of them.

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- Two nonparallel lines in the same plane intersect at exactly one point.
- Three nonparallel planes in space intersect in exactly one point.
- In general any n nonparallel $(n-1)$-dimensional hyperplanes intersect in exactly one point.

The secret can be therefore encoded as any single coordinate of the point of the intersection of n nonparallel $(n-1)$-dimensional hyperplanes.

VISUAL SECRET SHARING

The basic idea is to create, for a visual information (a secret) S, a set of n transparencies in such a way that one can see S only if all n transparencies are overlaid.

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E-COMMERCE

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In addition to providing security and privacy, the task is also to prevent alterations of purchase orders and forgery of credit card information.

Authenticity: Participants in transactions cannot be impersonated and signatures cannot be forged.

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Additional requirement: In order to allow an efficient fighting of the organized crime a system for processing e-money has to be such that under well defined conditions it has to be possible to revoke customer's identity and flow of e-money.

HISTORICAL COMMENT

So called Secure Electronic Transaction protocol was created to standardize the exchange of credit card information.

Development of SET initiated in 1996 credit card companies MasterCard and Visa.

EXAMPLE – DUAL SIGNATURE PROTOCOL

We present a protocol to solve the following security and privacy problem in e-commerce: How to arrange e-shopping in such a way that shoppers' banks should not know what shoppers/cardholders are ordering and shops should not learn credit card numbers of shoppers.

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RSA cryptosystem will also be used and

- e_C, e_S and e_B will be public (encryption) keys of the cardholder, shop, bank and
- d_C, d_S and d_B will be their secret (decryption) keys.

CARDHOLDER and SHOP ACTIONS

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It is easy to verify that the above protocol fulfills basic requirements concerning security, privacy and integrity.

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1. One should be able to send e-money through e-networks.
2. It should not be possible to copy and reuse e-money.

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5. An e-coin could be divided into e-coins of smaller values.

Several systems of e-money have been created that satisfy all or at least some of the above requirements.

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Basic setting

Bank chooses large primes $p, q|(p-1)$ and an $g \in Z_p$ of order q.
Let $h : \{0,1\}^* \rightarrow Z_p$ be a collision-free hash function.
Bank's secret will be a randomly chosen $x \in \{0, \ldots, p-1\}$.
Public information: $(p, q, g, y = g^x)$.

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2. Transfer of the identification scheme to a signature scheme:

   Bob chooses as $c = h(m \| a)$, where m is the message to be signed.

   Signature: (c, b); Verification rule: $a = g^b y^c$; Transcript: (a, c, b).

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3. **Shnorr's blind signature scheme**
   - Bank sends to Bob $a' = g^{r'}$ with random $r' \in \{0, \ldots, q-1\}$.
   - Bob chooses random $u, v, w \in \{0, \ldots, q-1\}$, $u \neq 0$, computes $a = a'^u g^v y^w$, $c = h(m \| a)$, $c' = (c - w)u^{-1}$ and sends c' to Bank.
   - Bank sends to Bob b' = r' - c'x.

   Bob verifies whether $a' = g^{b'} y^{c'}$, computes b = ub' + v and gets blind signature σ(m) = (c, b) of m.

   Verification condition for the blind signature: $c = h(m \| g^b y^c)$.

SOME BASIC CONCEPTS Of APPLIED CRYPTOGRAPHY

In applied cryptography literature the following concepts are often used:

- random string - a string obtained by tossing coins.
- nonce - a random number that is used only once (in a use of a protocol).
- salt - a short random string.
- salting (padding) - attaching a short random string - a salt

A use of such concepts will be illustrated in the next.