Distributed Systems
Lecture 12

Professor Louise E. Moser

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Security

- Introduction
- Secure channels
- Access control
- Security management

Dependability Revisited

- **Basics:** A **component** provides **services** to **clients**
- To provide services, a component might require services of other components and, thus, it might **depend** on other components
- Properties of dependability

Availability	Readiness for usage
Reliability	Continuity of service delivery
Safety	Very low probability of catastrophes
Maintainability	Ease with which a failed system be repaired
Confidentiality	No unauthorized disclosure of information
Integrity	No accidental or malicious alterations of information (even by authorized entities)

- **Note:** In distributed systems, **security** is the combination of **confidentiality** and **integrity**. A **dependable** distributed system is thus **fault-tolerant** and **secure**

Security Threats

- **Subject:** Entity capable of issuing a request for a service provided by an object
- **Channel:** The carrier of requests and replies for services
- **Object:** Entity providing services to subjects
- Channels and objects are subject to **Security Threats**

Threat	Channel	Object
Interruption	Preventing message transfer	Denial of service
Inspection	Reading contents of a message being transferred	Reading data contained in an object
Modification	Changing message content	Changing data in an object
Fabrication	Inserting messages	Spoofing an object

Security Mechanisms

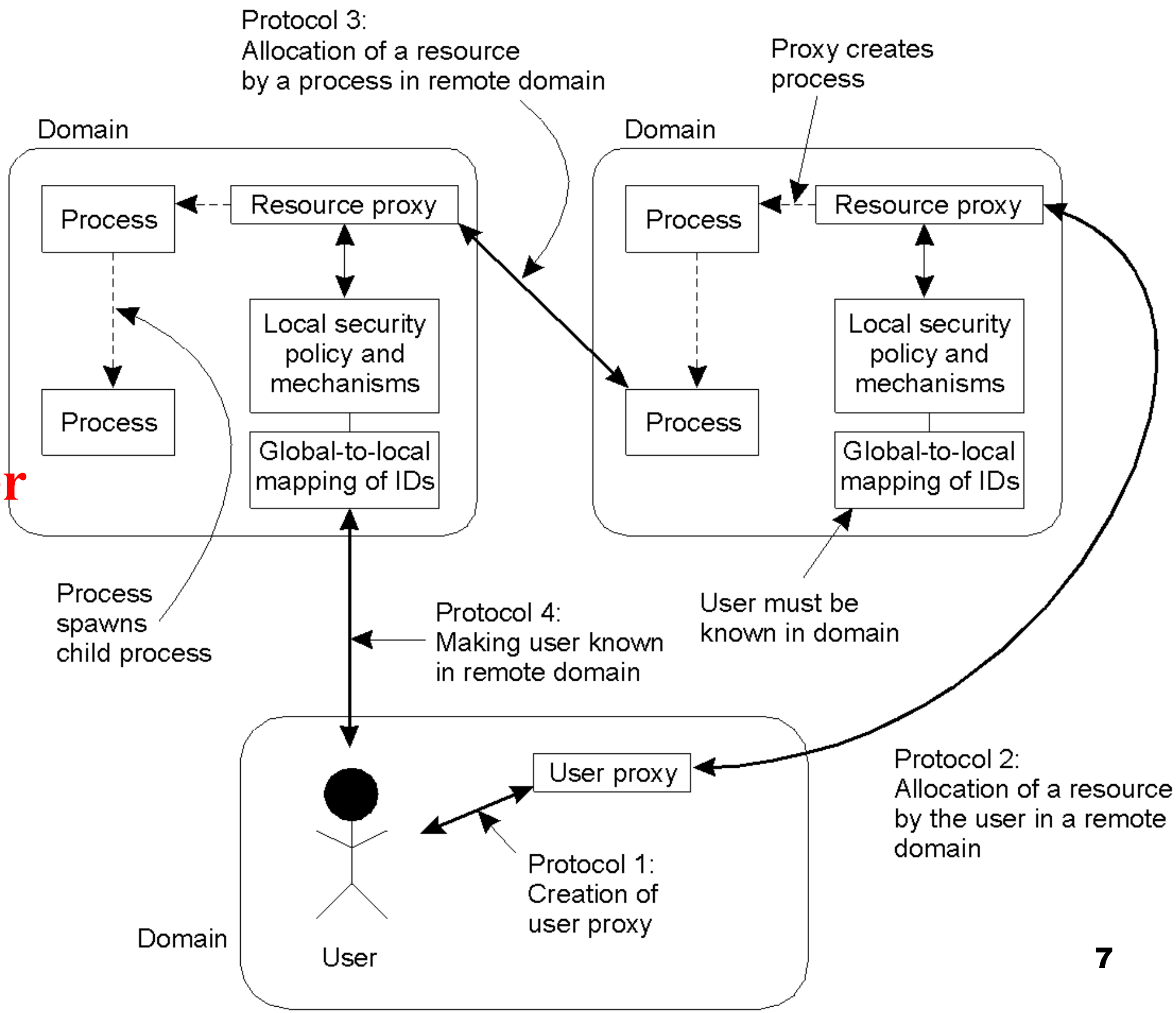
- **Security Mechanism:** Protects against security threats. Some security mechanisms are:
  - **Encryption:** Transform data into other data that an attacker cannot understand (confidentiality). Also used to check whether data have been modified (integrity)
  - **Authentication:** Verify that a subject is who he/she claims to be, i.e., verify the identity of a subject
  - **Authorization:** Determine whether a subject is permitted to use certain services
  - **Auditing:** Trace the data that subjects accessed, and how they did so. Useful only if it can help catch an attacker
- **Note:** Authorization makes sense only if the requesting subject has been authenticated

Security Policies

- **Security Policy:** Prescribes how to use mechanisms to protect against attacks. Requires that a model of possible attacks is described, i.e., a **Security Architecture**
- **Example: Globus Security Architecture**
  - **There are multiple administrative domains**
  - **Local operations are subject to local security policies**
  - **Global operations require requesters to be globally known**
  - **Inter-domain operations require mutual authentication**
  - **Global authentication replaces local authentication**
  - **Users can delegate privileges to processes**
  - **Processes in the same domain can share credentials**

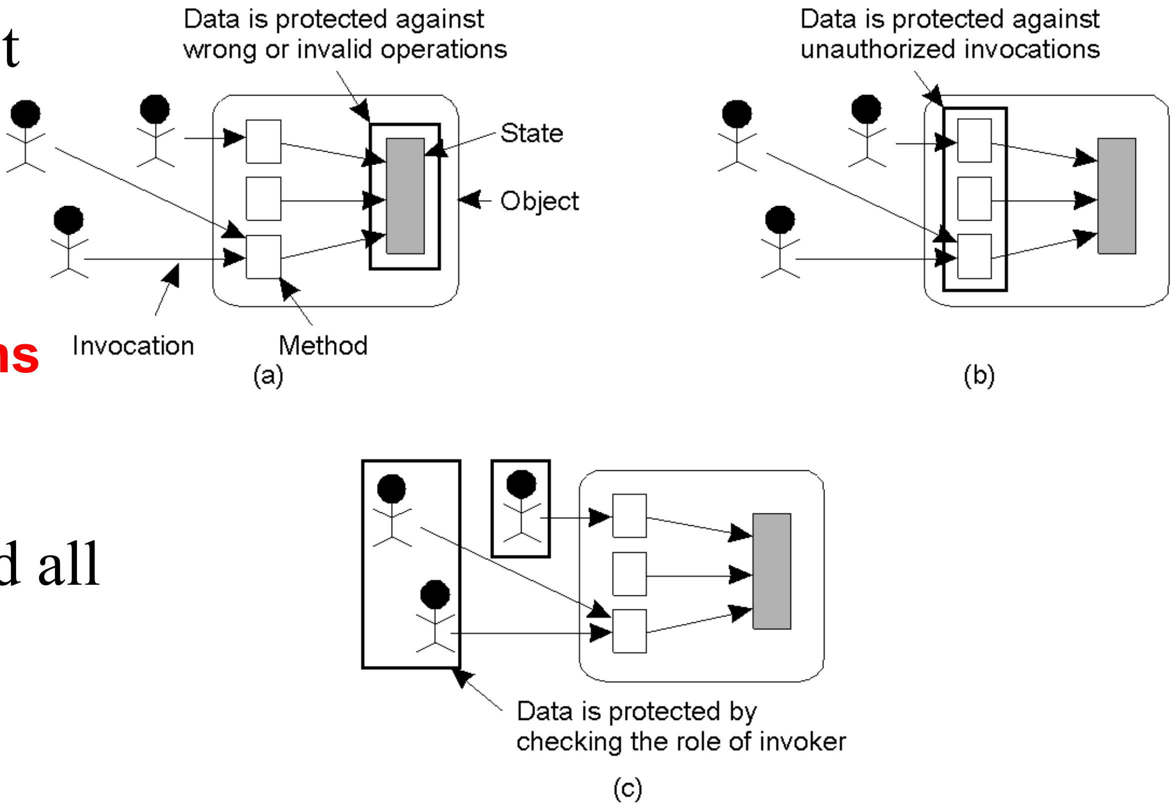
Globus Security Architecture

- Policies lead to mechanisms for cross-domain authentication and users who are globally known => **user proxies** and **resource proxies**



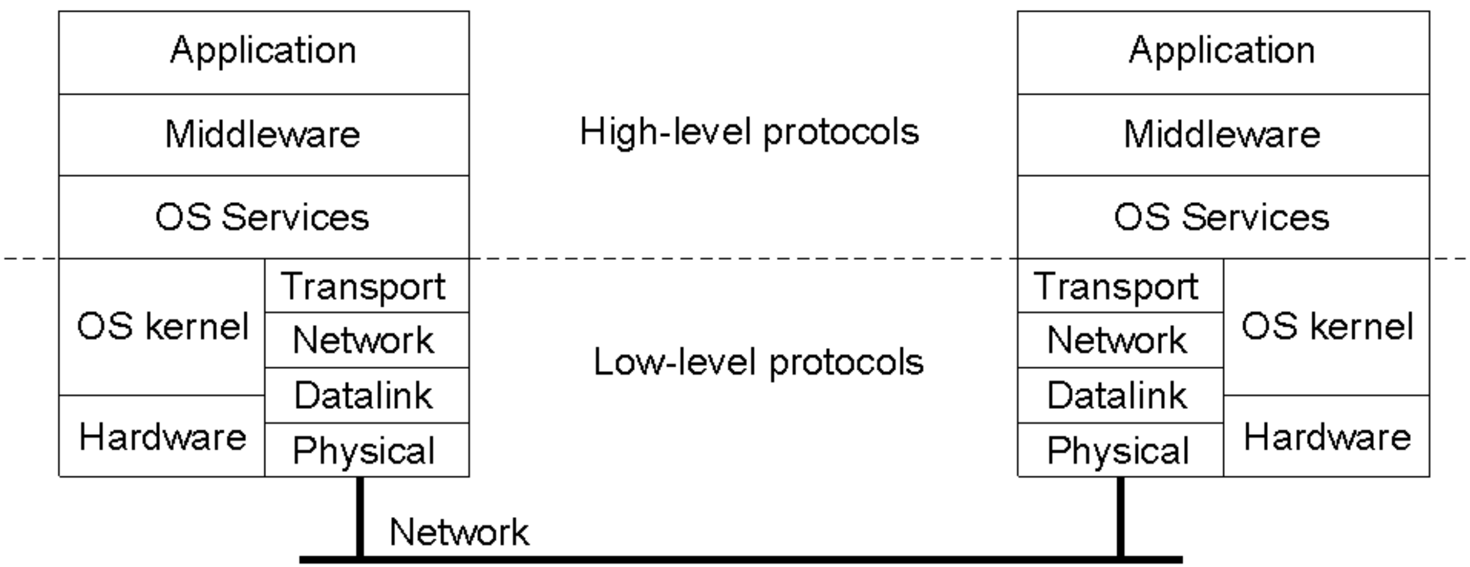
Protection of Data

- Three approaches for protection of data against security threats
  - **(a) Protection against** **invalid operations**
  - **(b) Protection against** **unauthorized invocations**
  - **(c) Protection against** **unauthorized users**
- Note: Generally, we need all three, but each requires different mechanisms



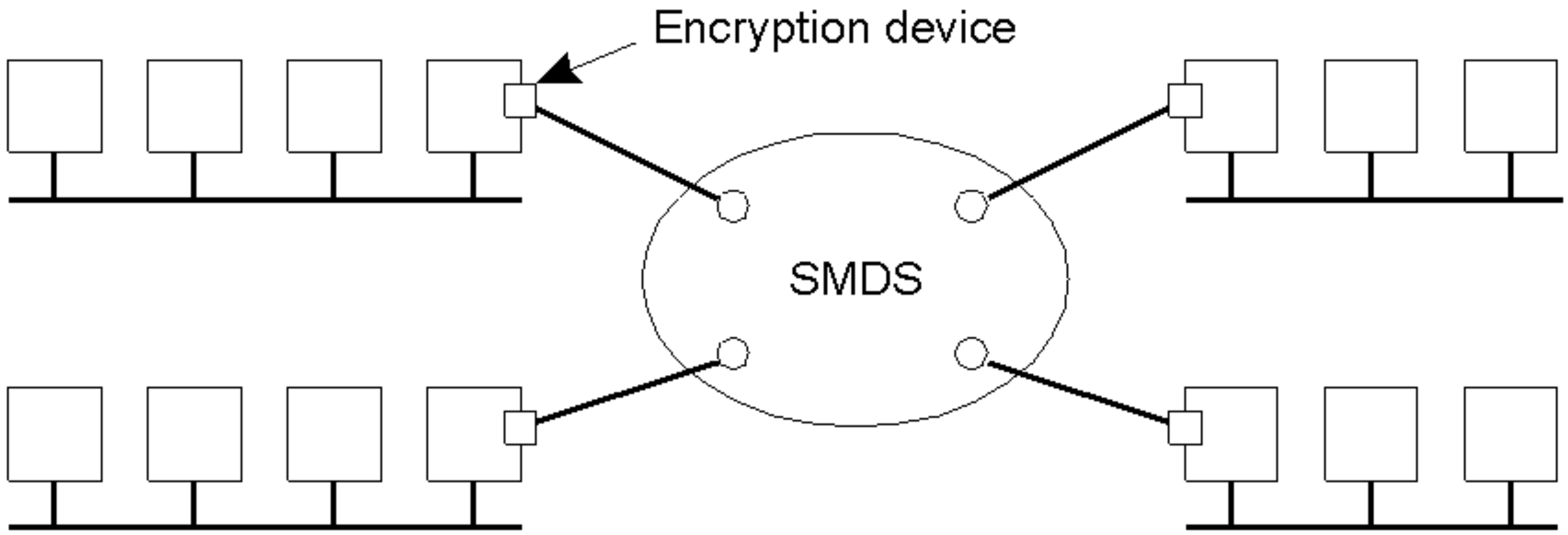
Layering of Security Mechanisms

- The logical organization of a distributed system into several layers. At which logical level should we implement security mechanisms?
- Whether security mechanisms are actually used is related to the **trust** a user has in those mechanisms. No trust => implement your own
- **Trusted Computing Base (TCB):** The set of mechanisms needed to enforce a security policy. The smaller, the better



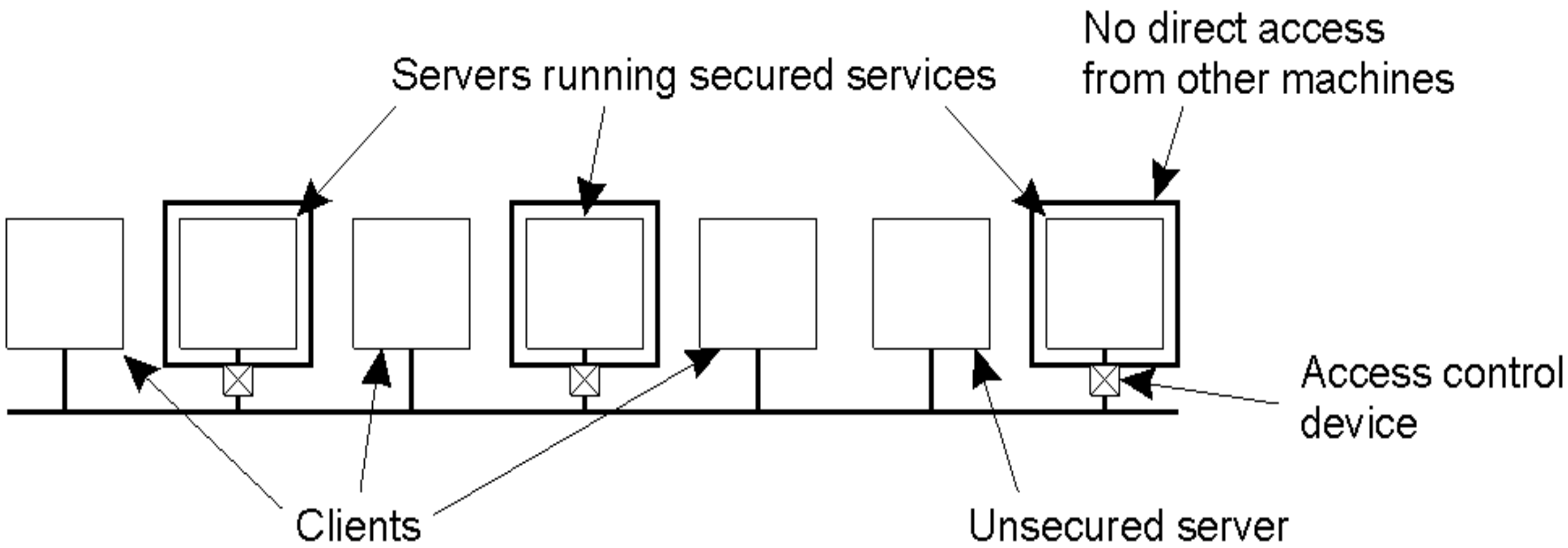
Layering of Security Mechanisms

- **Encryption devices** for local-area networks of computers connected through a wide-area backbone service, called the Switched Multi-Megabit Data Service (SMDS)



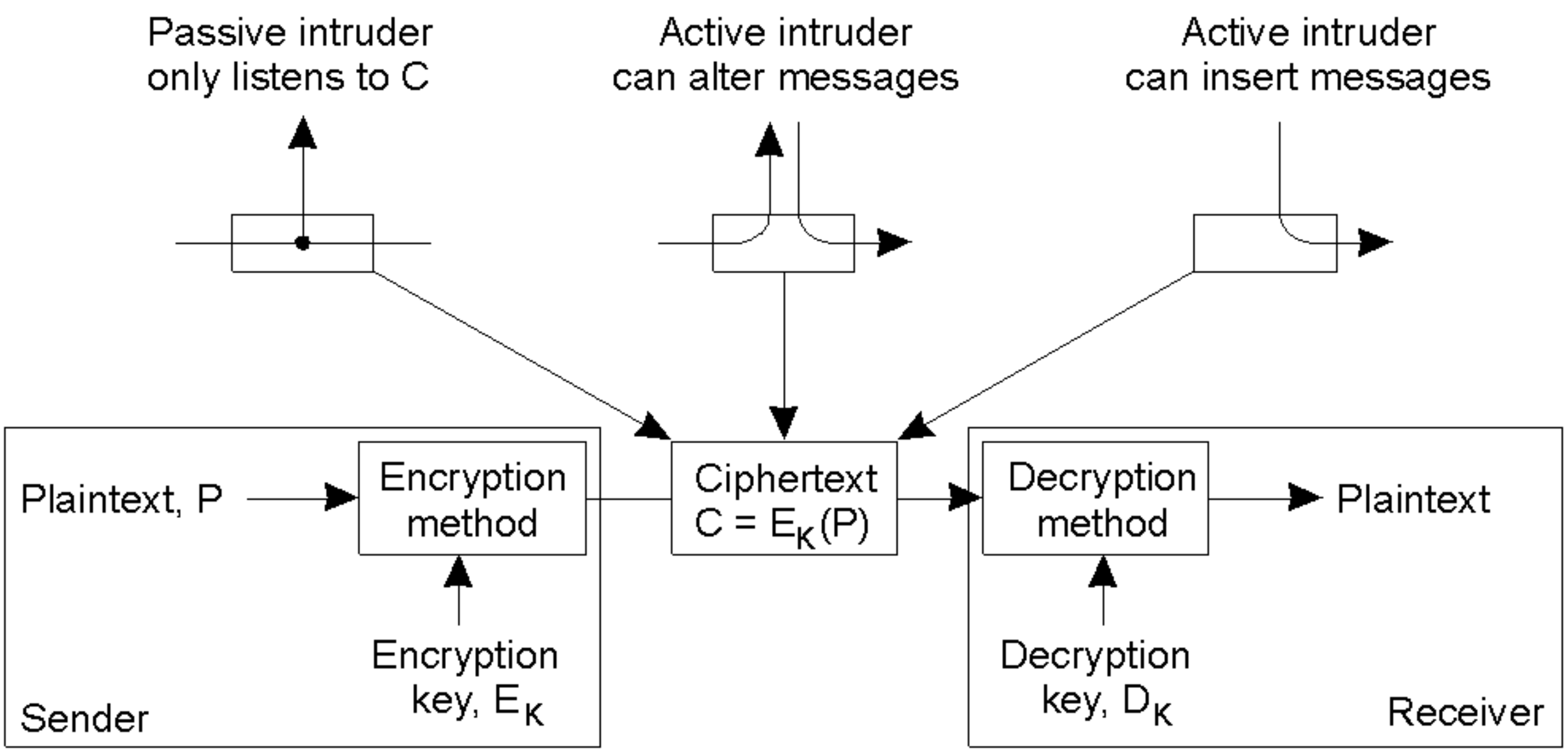
Layering of Security Mechanisms

- **Access control devices** on several computers that provide Reduced Interfaces for Secure System Component (RISSC)



Cryptography

- The use of **encryption** and **decryption** to protect against intruders and eavesdroppers in communication

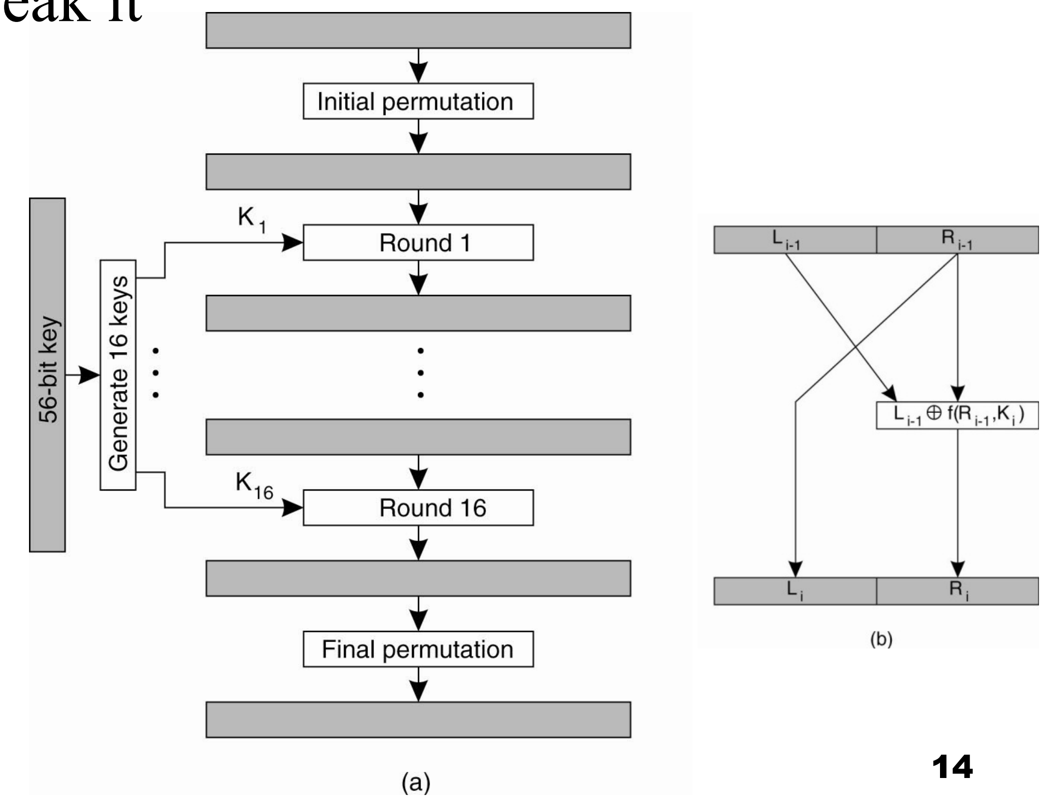


Cryptography

- **Different kinds of Cryptographic Systems**
  - **Symmetric System:** Use a **single key** to encrypt the plaintext and to decrypt the ciphertext. The sender and the receiver **share** a **secret key**
  - **Asymmetric System (Public Key Cryptosystem):** Use **different keys** for encryption and decryption, one **public** and one **private.** The sender and the receiver each has its own public key and private key
  - **Hashing System:** Encrypt the data and produce a fixed-length **digest**. No decryption; only comparison (like checksums)

Symmetric Cryptosystem

- **Data Encryption Standard (DES) Algorithm**. U.S. standard for unclassified information, developed by IBM (1974)
- **Aim:** To make the encryption algorithm so complicated that not even a computer can break it
- Same key for encryption and decryption
- Encrypts in 64-bit blocks
- Uses 56-bit "master" key
- Has 19 stages, each of the 16 stages uses a different key K_i as the parameter of the "mangler" function f

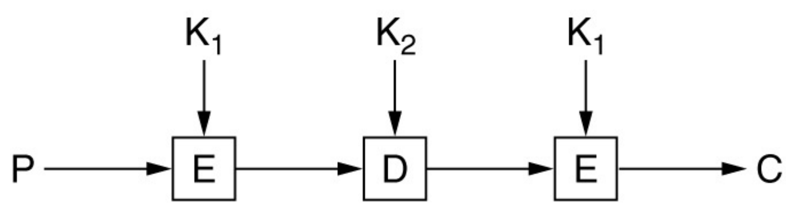


Symmetric Cryptosystem

- **DES Algorithm**
  - **Each iteration i of the 16 iterations uses a different key K_i**
    1. Before the 16 iterations start, apply a 56-bit transposition of the key
    2. Before each iteration i, partition the key into two 28-bit numbers, and rotate the left half by the number of bits determined by the iteration number i
    3. Obtain the key K_i from the rotated key by applying another 56-bit transposition
  - **The "mangler" function f involves 4 steps**
    1. Expand the 32-bit number R_{i-1} into a 48-bit number E
    2. Take the exclusive or (XOR) of E and K_i
    3. a. Partition the output into 8 chunks of 6 bits each
       b. Input each chunk to a different substitution box
       c. Substitution box produces 4 output bits
       d. Result is 8 4-bit numbers
    4. Pass the 32-bit result through a permutation box

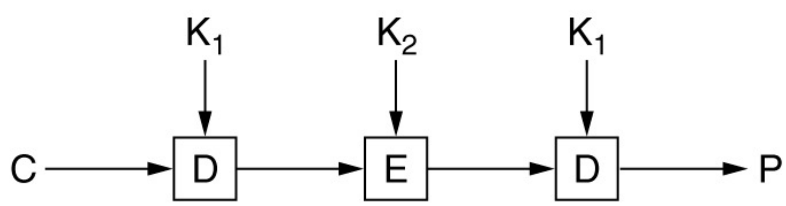
Symmetric Cryptosystem

- **Triple DES** – Effectively increases the key length, uses two keys K_1 and K_2 and three stages
  - **In the first stage, encrypt the plaintext using DES in the usual way with the key K_1**
  - **In the second stage, run DES in decryption mode, using the key K_2**
  - **In the third stage, encrypt again using DES with the key K_1**



(a)

Triple DES Encryption



(b)

Triple DES Decryption

Asymmetric Cryptosystem

- **Diffie Hellman Algorithm** (1976) – Radically different from a symmetric cryptosystem; uses *different keys* (rather than the same key) for encryption and decryption
- Uses an encryption algorithm E and a decryption algorithm D, such that even if you know E you can't determine D
- Three requirements:
  - **D(E(P)) = P**
  - **Can't deduce D (private) from E (public)**
  - **Can't break D by a plaintext attack**
- User A makes public its encryption algorithm and key E_A
  User B makes public its encryption algorithm and key E_B
- A encrypts A's message P using B's public key E_B to obtain $E_B(P)$
  B decrypts A's message using B's private key D_B to obtain $D_B(E_B(P)) =$ P (and vice versa with A and B interchanged)

Asymmetric Cryptosystem

- **RSA Algorithm** - named after Rivest, Shamir, Adelman (1978)
- Four steps:
  1. **Choose two large primes p and q (typically 1024 bits)**
  2. **Compute $n = p \times q$ and $z = (p-1) \times (q-1)$**
  3. **Find a number d relatively prime to z**
  4. **Find a number e such that $e \times d \equiv 1 \bmod z$**
- Divide the plaintext into blocks P of k bits each, where k is the largest integer such that $2^k < n$ => $0 \leq P < n$
- The **public** key consists of the pair (e, n)
  The **private** key consists of the pair (d, n)
- To **encrypt** P, compute $C = P^e \bmod n$
  To **decrypt** C, compute $P = C^d \bmod n$
- RSA algorithm is based on the difficulty of factoring large numbers
  - **If you can factor n, then you know p and q, and also z**
  - **If you know z and e, you can find d**

Asymmetric Cryptosystem

- A simple example of the RSA algorithm
  - **$p = 3$, $q = 11$ => $n = p \times q = 33$ and $z = (p-1) \times (q-1) = 20$**
  - **Find d relatively prime to z, e.g., $d = 7$**
  - **Find e by solving $7 \times e \equiv 1 \bmod 20$, e.g., $e = 3$**
  - **$C \equiv P^3 \bmod 33$, $P \equiv C^7 \bmod 33$**

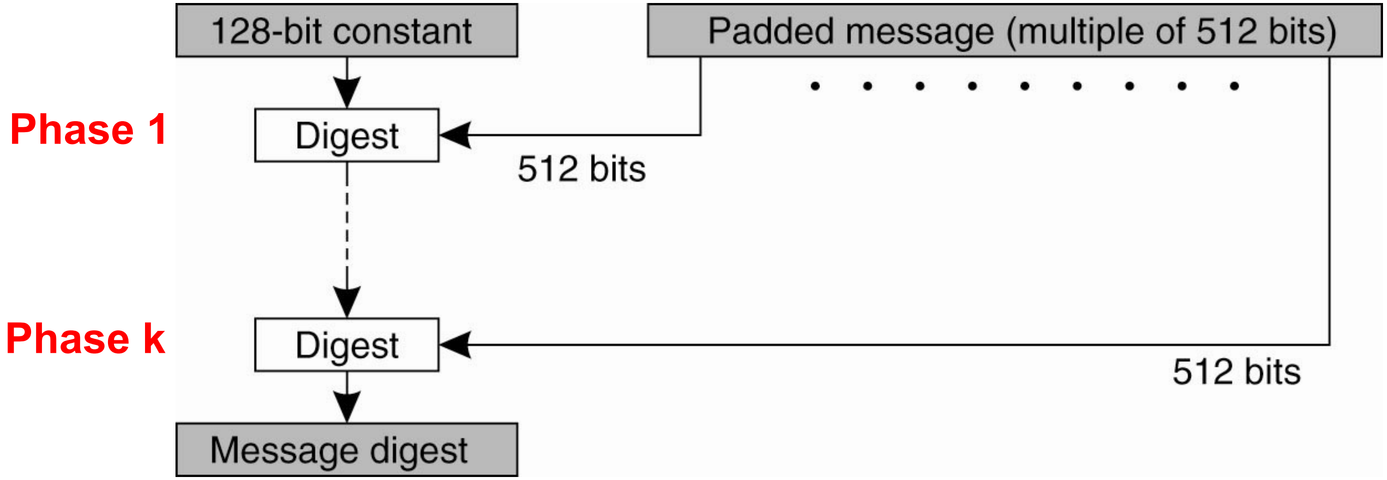
Plaintext (P)			Ciphertext (C)		After decryption	
Symbolic	Numeric	P^3	P^3 (mod 33)	C^7	C^7 (mod 33)	Symbolic
S	19	6859	28	13492928512	19	S
U	21	9261	21	1801088541	21	U
Z	26	17576	20	1280000000	26	Z
A	01	1	1	1	01	A
N	14	2744	5	78125	14	N
N	14	2744	5	78125	14	N
E	05	125	26	8031810176	05	E
Sender's computation				Receiver's computation		

Hash Function

- **MD5** – A hash function for computing a 128-bit fixed-length **message digest** from an arbitrary-length binary input string
  - **Convert the input string to a sequence of k 512-bit blocks**

    (a) Pad the input string to a total length of 448 bits mod 512

    (b) Add the length of the original bit string as a 64-bit integer



Hash Function

- **MD5** (continued)
  - **The algorithm then proceeds in k phases**
    During each phase, a 128-bit digest is computed from the 512-bit block and the 128-bit digest in the preceding phase
  - **A phase consists of four rounds of computation**
    Each round uses one of the following four functions:
    F(x,y,z) = (x AND y) OR ((NOT x) AND z)
    G(x,y,z) = (x AND z) OR (y AND (NOT z))
    H(x,y,z) = x XOR y XOR z
    I(x,y,z) =y XOR (x OR (NOT z))
  - **Note: MD5 uses only AND, OR, NOT, XOR, and can be implemented in hardware, but is still quite complex (see the text p. 396 for an example)**

Cryptographic Functions

- **Essence:** Make the encryption method E public, but let the encryption as a whole be parameterized by means of a key K (same for decryption)
- **One-way function:** Given an output message m_{out} of E_K, it is *computationally infeasible* to find an input message m_{in} such that $E_K(m_{\text{in}}) = m_{\text{out}}$
- **Weak collision resistance:** Given a pair m, $E_K(m)$, it is *computationally infeasible* to find a different input message $m^* \neq m$ such that $E_K(m^*) = E_K(m)$
- **Strong collision resistance:** It is *computationally infeasible* to find two different input messages $m \neq m^*$ such that $E_K(m) = E_K(m^*)$

Cryptographic Functions

- **One-way *key*:** Given an encrypted message m_{out}, a message m_{in} and an encryption function E, it is *computationally infeasible* to find a key K such that $m_{out} = E_K(m_{in})$
- **Weak *key* collision resistance:** Given a triple m, K, E, it is *computationally infeasible* to find a different key $K^* \neq K$ such that $E_{K^*}(m) = E_K(m)$
- **Strong *key* collision resistance:** It is *computationally infeasible* to find two different keys $K \neq K^*$ such that for all messages m $E_K(m) = E_{K^*}(m)$
- **Note:** Not all cryptographic functions have keys, for example, hash functions do not keys

Secure Channels

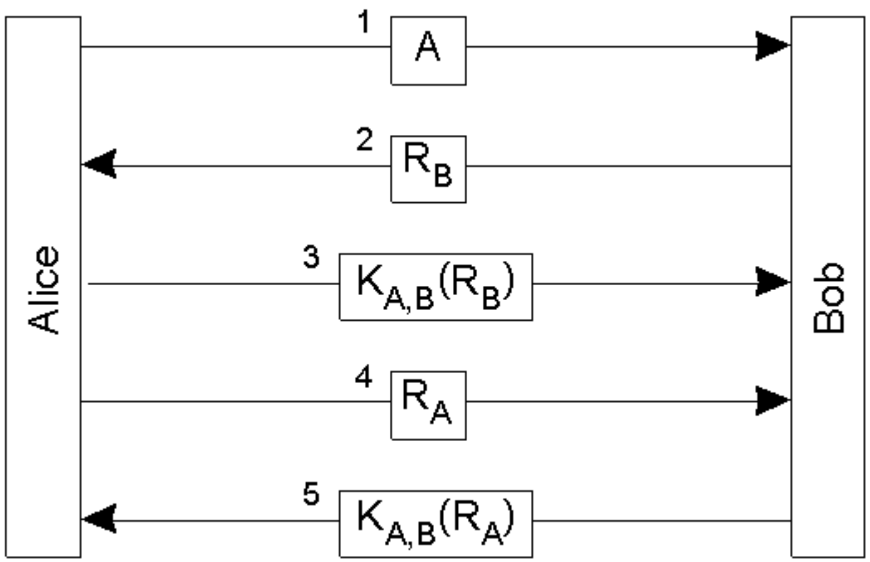
- **Goal:** Set up a channel for secure communication between two processes with the properties:
  - **Authentication:** **Both processes know who is at the other end of the channel**
  - **Integrity:** **Both processes know that messages cannot be tampered with**
  - **Confidentiality:** **Both processes know that messages cannot be leaked**

Authentication vs. Integrity

- **Note:** Authentication and integrity rely on each other
- Consider an active attack by Trudy on the communication from Alice to Bob
- **Authentication without integrity:** Alice's message is authenticated, but it is intercepted by Trudy, who tampers with its contents, but leaves the authentication part in tact
  - **Authentication has become meaningless**
- **Integrity without authentication:** Trudy intercepts a message from Alice, and then makes Bob believe that the contents were really sent by Trudy
  - **Integrity has become meaningless**
- **Question:** What can we say about authentication and integrity vs. confidentiality?

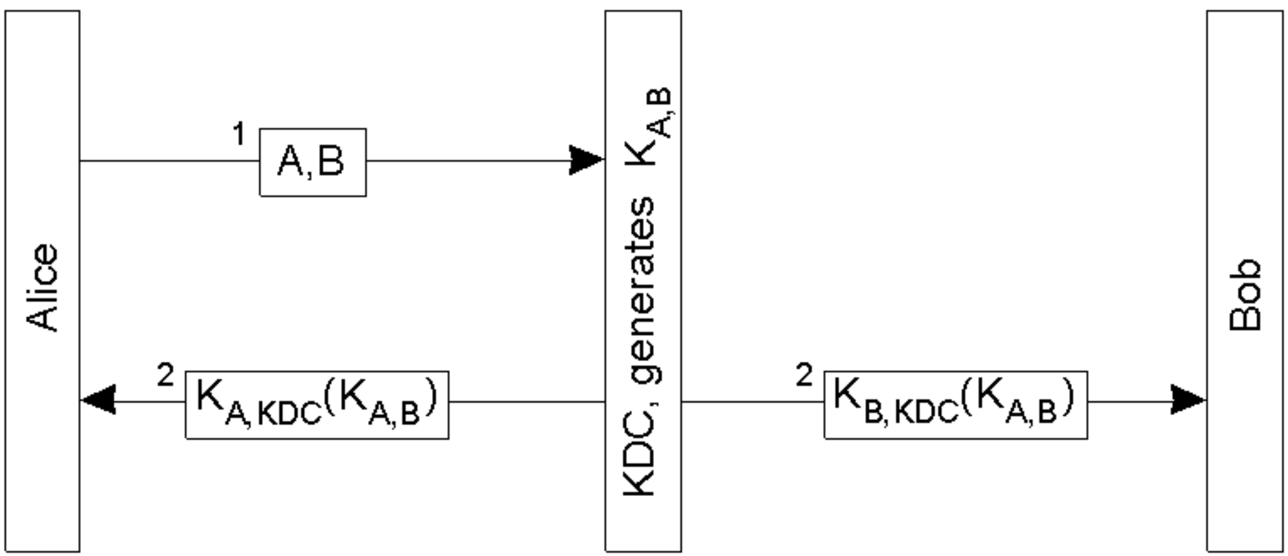
Authentication

- Authentication based on a **shared secret key** $K_{A,B}$ with a **nonce** R_A for Alice and a **nonce** R_B for Bob
  - A nonce is a *number* used only *once*, such as a timestamp, that is used to relate two (or more) messages to each other and to ensure that the response is not a replay of an old message



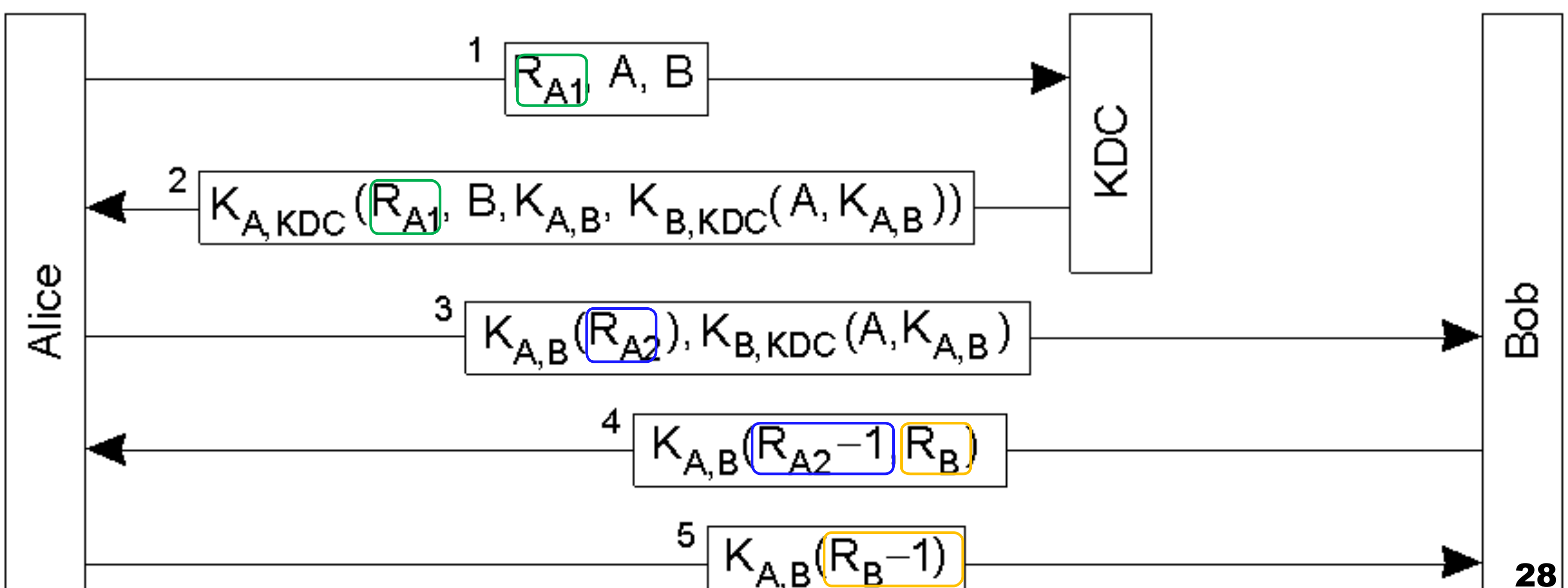
Authentication Using a Key Distribution Center

- **Problem:** With N subjects, we need to manage $\boldsymbol{N(N-1)/2}$ shared keys, each subject knowing N-1 keys
- **Solution:** To reduce the number of keys, use a **trusted Key Distribution Center (KDC)** that generates a **shared session key** $K_{A,B}$ when necessary
  - Then we need only ***N*** keys: $K_{A,KDC}$ for Alice, $K_{B,KDC}$ for Bob, etc.



Authentication Using a Key Distribution Center

- **Needham-Schroeder Authentication Protocol** that uses:
  - **Shared session key** $K_{A,B}$
  - **Ticket** $K_{B,KDC}(A, K_{A,B})$ that enables Alice to tell Bob what the shared secret key is
  - **Nonce** R_{A1} for Alice with the KDC
  - **Nonce** R_{A2} for Alice with Bob
  - **Nonce** R_B for Bob with Alice

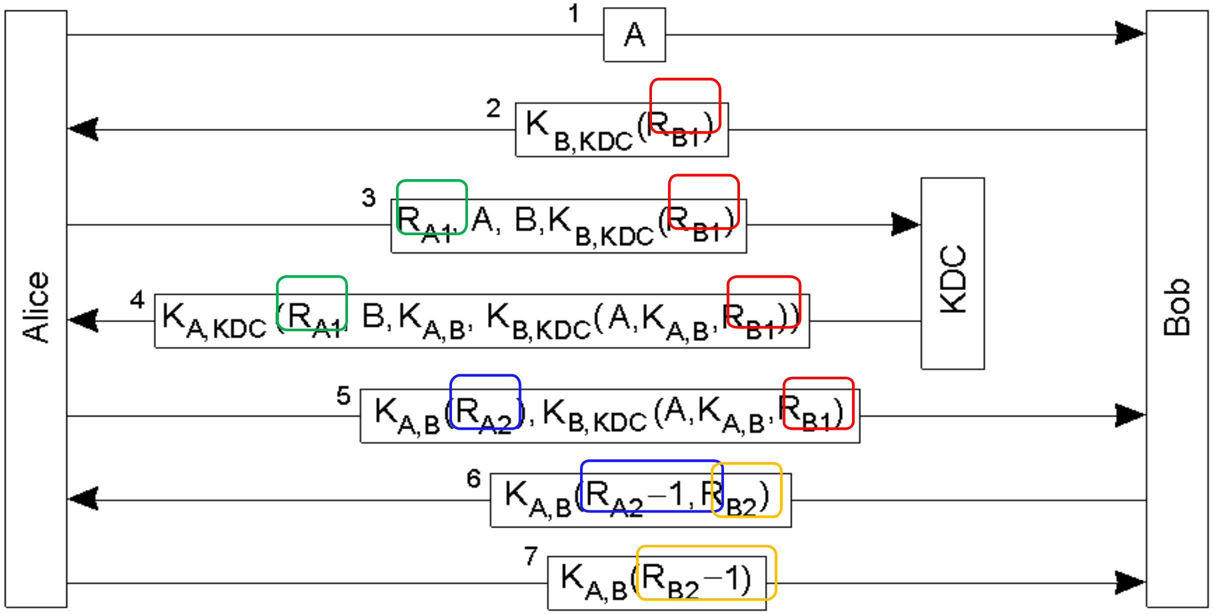


Needham-Schroeder: Subtleties

- **Question 1:** Why does the KDC put B (Bob) into its reply message, and put A (Alice) into the ticket?
- **Question 2:** The reply message that the KDC sent to Alice is encrypted with Alice's key. Is this necessary?
- **Security flaw:** Suppose Chuck discovers Alice's private key $K_{A,KDC}$ He can use that key anytime to impersonate Alice, even if Alice changes her private key at the KDC
- **Reasoning:** Once Chuck discovers Alice's private key $K_{A,KDC}$, he can use it to decrypt a (possibly old) ticket for a session with Bob, and convince Bob to talk to him using the old session key
- **Solution:** Have Alice get an encrypted nonce from Bob first, and put the encrypted nonce in the ticket provided by the KDC, thus ensuring that every session is known by the KDC

Authentication Using a Key Distribution Center

- Fixing the security flaw in the Needham-Schroeder protocol to protect against malicious reuse of a previous session key
  - Bob communicates with Alice providing a (new) **nonce R_{B1}** for Bob with Alice, encrypted with Bob's secret key, which prevents Chuck from using Alice's secret key
  - The nonce R_{B1} is included in four messages, so Chuck can't replay an old message sequence



Authentication Using Public Key Cryptography

- Mutual authentication in a public key cryptosystem, using:
  - **Bob's public key K_B^+**
  - **Alice's public key K_A^+**
  - **Alice's nonce R_A**
  - **Bob's nonce R_B**
  - Bob sends a **session key $K_{A,B}$** to Alice, encrypted with Alice's public key K_A^+
  - Alice decrypts it with her private key K_A^-