Distributed Systems
Principles and Paradigms

Chapter 08
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Overview

- Introduction
- Secure channels
- Access control
- Security management

Security: Dependability Revisited

Basics: A *component* provides *services* to *clients*. To provide services, the component may require the services from other components ⇒ a component may **depend** on some other component.

Property	Description
Availability	Accessible and usable upon demand for authorized entities
Reliability	Continuity of service delivery
Safety	Very low probability of catastrophes
Confidentiality	No unauthorized disclosure of information
Integrity	No accidental or malicious alterations of information have been performed (even by authorized entities)

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

Security Threats

Subject: Entity capable of issuing a request for a service as provided by objects

Channel: The carrier of requests and replies for services offered to subjects

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 the content of transferred messages	Reading the data contained in an object
Modification	Changing message content	Changing an object's encapsulated data
Fabrication	Inserting messages	Spoofing an object

Security Mechanisms

Issue: To protect against security threats, we have a number of **security mechanisms** at our disposal:

Encryption: Transform data into something that an attacker cannot understand (confidentiality). It is also used to check whether something has been modified (integrity).

Authentication: Verify the claim that a subject says it is S: verifying the **identity** of a subject.

Authorization: Determining whether a subject is permitted to make use of certain services.

Auditing: Trace which subjects accessed what, and in which way. Useful only if it can help catch an attacker.

Note: authorization makes sense only if the requesting subject has been authenticated

Security Policies (1/2)

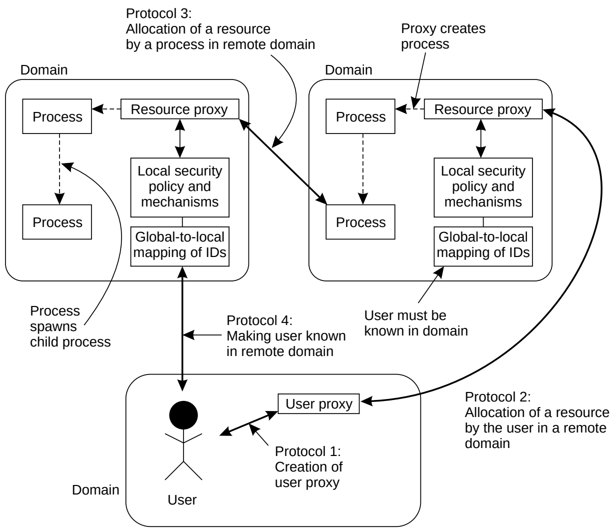
Policy: Prescribes how to use mechanisms to protect against attacks. Requires that a model of possible attacks is described (i.e., **security architecture**).

Example: Globus security architecture

- There are multiple administrative domains
- Local operations subject to local security policies
- Global operations require requester to be globally known
- Interdomain operations require mutual authentication
- Global authentication replaces local authentication
- Users can delegate privileges to processes
- Credentials can be shared between processes in the same domain

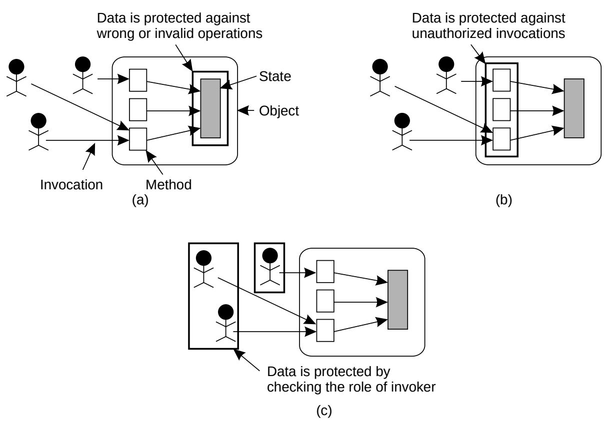
Security Policies (2/2)

Policy statements leads to the introduction of mechanisms for cross-domain authentication and making users globally known ⇒ **user proxies** and **resource proxies**



Design Issue: Focus of Control

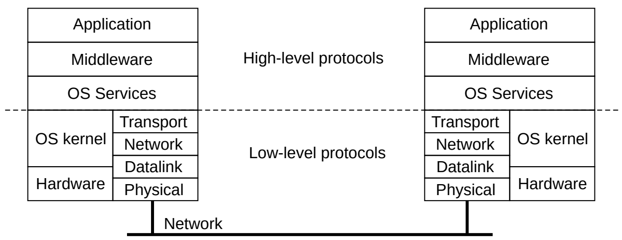
Essence: What is our focus when talking about protection: (a) data, (b) invalid operations, (c) unauthorized users



Note: We generally need all three, but each requires different mechanisms

Design Issue: Layering of Mechanisms and TCB

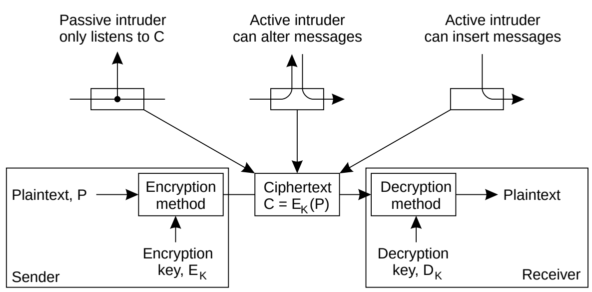
Essence: At which logical level are we going to implement security mechanisms?



Important: Whether security mechanisms are actually used is related to the **trust** a user has in those mechanisms. No trust ⇒ implement your own mechanisms.

Trusted Computing Base: What is the set of mechanisms needed to enforce a policy. The smaller, the better.

Cryptography



Symmetric system: Use a single key to (1) encrypt the plaintext and (2) decrypt the ciphertext. Requires that sender and receiver **share** the secret key.

Asymmetric system: Use different keys for encryption and decryption, of which one is **private**, and the other **public**.

Hashing system: Only encrypt data and produce a fixed-length digest. There is no decryption; only comparison is possible.

Cryptographic Functions (1/2)

Essence: Make the encryption method E public, but let the encryption as a whole be parameterized by means of a **key** S (Same for decryption)

One-way function: Given some output m_{out} of E_S, it is (analytically or) computationally infeasible to find $m_{\text{in}} : E_S(m_{\text{in}}) = m_{\text{out}}$

Weak collision resistance: Given a pair $\langle m, E_S(m) \rangle$, it is computationally infeasible to find an $m^* \neq m$ such that $E_S(m^*) = E_S(m)$

Strong collision resistance: It is computationally infeasible to find any two different inputs m and m^* such that $E_S(m) = E_S(m^*)$

Cryptographic Functions (2/2)

One-way key: Given an encrypted message m_{out}, message m_{in}, and encryption function E, it is analytically and computationally infeasible to find a key K such that $m_{\text{out}} = E_K(m_{\text{in}})$

Weak key collision resistance: Given a triplet $\langle m, S, E \rangle$, it is computationally infeasible to find an $K^* \neq K$ such that $E_{K^*}(m) = E_K(m)$

Strong key collision resistance: It is computationally infeasible to find any two different keys K and K^* such that for all m: $E_K(m) = E_{K^*}(m)$

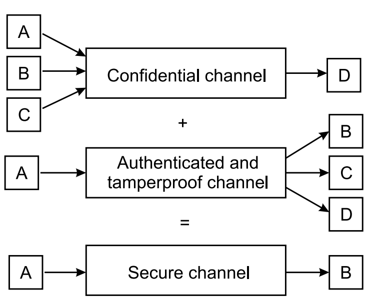
Note: Not all cryptographic functions have keys (such as hash functions)

Secure Channels

- Authentication
- Message Integrity and confidentiality
- Secure group communication

Secure Channels

Goal: Set up a channel allowing for secure communication between two processes:



- They both know who is on the other side (authenticated).
- They both know that messages cannot be tampered with (integrity).
- They both know messages cannot leak away (confidentiality).

Authentication versus Integrity

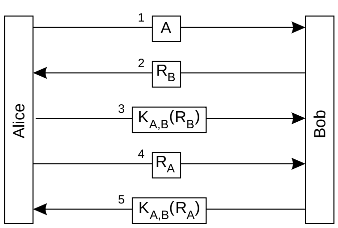
Note: Authentication and data integrity rely on each other: Consider an active attack by Trudy on the communication from Alice to Bob.

Authentication without integrity: Alice's message is authenticated, and intercepted by Trudy, who tampers with its content, but leaves the authentication part as is. Authentication has become meaningless.

Integrity without authentication: Trudy intercepts a message from Alice, and then makes Bob believe that the content was really sent by Trudy. Integrity has become meaningless.

Question: What can we say about confidentiality versus authentication and integrity?

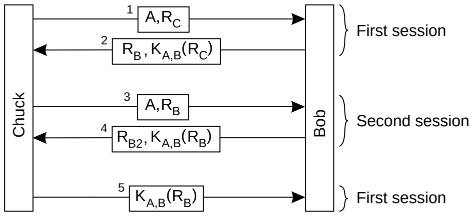
Authentication: Secret Keys



1: Alice sends ID to Bob
2: Bob sends challenge R_B (i.e. a random number) to Alice
3: Alice encrypts R_B with shared key $K_{A,B}$. Now Bob knows he's talking to Alice
4: Alice send challenge R_A to Bob
5: Bob encrypts R_A with $K_{A,B}$. Now Alice knows she's talking to Bob

Note: We can "improve" the protocol by combining steps 1&4, and 2&3. This costs only the correctness.

Authentication: Secret Keys Reflection Attack



1: Chuck claims he's Alice, and sends challenge R_C

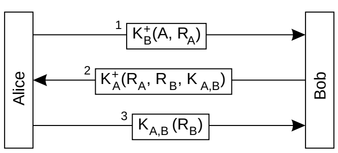
2: Bob returns a challenge R_B and the encrypted R_C

3: Chuck starts a second session, claiming he is Alice, but uses challenge R_B

4: Bob sends back a challenge, plus $K_{A,B}(R_B)$

5: Chuck sends back $K_{A,B}(R_B)$ for the first session to prove he is Alice

Authentication: Public Key



1: Alice sends a challenge R_A to Bob, encrypted with Bob's public key K_B^+.

2: Bob decrypts the message, generates a secret key $K_{A,B}$, proves he's Bob (by sending R_A back), and sends a challenge R_B to Alice. Everything's encrypted with Alice's public key K_A^+.

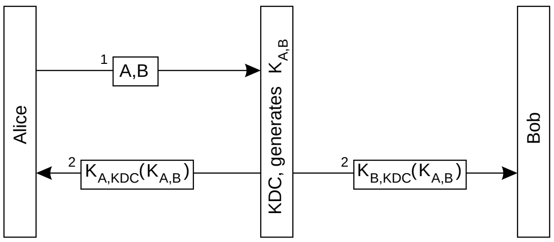
3: Alice proves she's Alice by sending back the decrypted challenge, encrypted with generated secret key $K_{A,B}$

Note: $K_{A,B}$ is also known as a **session key** (we'll come back to these keys later on).

Authentication: KDC (1/2)

Problem: With N subjects, we need to manage $N(N-1)/2$ keys, each subject knowing $N-1$ keys.

Essence: Use a trusted **Key Distribution Center** that generates keys when necessary.

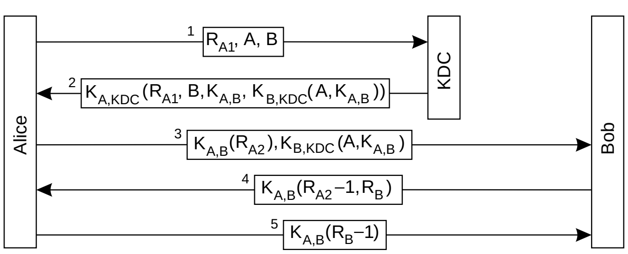


Question: How many keys do we need to manage?

Authentication: KDC (2/2)

Inconvenient: We need to ensure that Bob knows about $K_{A,B}$ before Alice gets in touch.

Solution: Let Alice do the work and pass her a **ticket** to set up a secure channel with Bob



Note: This is also known as the **Needham-Schroeder** authentication protocol, and is widely applied (in different forms).

Needham-Schroeder: Subtleties

Q1: Why does the KDC put Bob into its reply message, and Alice into the ticket?

Q2: The ticket sent back to Alice by the KDC is encrypted with Alice's key. Is this necessary?

Security flaw: Suppose Chuck finds out Alice's key $\Rightarrow$ he can use that key anytime to impersonate Alice, even if Alice changes her private key at the KDC.

Reasoning: Once Chuck finds out Alice's key, 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 number from Bob first, and put that number in the ticket provided by the KDC $\Rightarrow$ we're now ensuring that every session is known at the KDC.

Confidentiality (1/2)

Secret key: Use a shared secret key to encrypt and decrypt all messages sent between Alice and Bob

Public key: If Alice sends a message m to Bob, she encrypts it with Bob's public key: $K_B^+(m)$

There are a number of problems with keys:

Keys wear out: The more data is encrypted by a single key, the easier it becomes to find that key $\Rightarrow$ *don't use keys too often*

Danger of replay: Using the same key for different communication sessions, permits old messages to be inserted in the current session $\Rightarrow$ *don't use keys for different sessions*

Confidentiality (2/2)

Compromised keys: If a key is compromised, you can never use it again. Really bad if *all* communication between Alice and Bob is based on the same key over and over again ⇒ *don't use the same key for different things*

Temporary keys: Untrusted components may play along perhaps just once, but you would never want them to have knowledge about your really good key for all times ⇒ *make keys disposable*

Essence: Don't use valuable and expensive keys for all communication, but only for authentication purposes.

Solution: Introduce a "cheap" **session key** that is used only during one single conversation or connection ("cheap" also means efficient in encryption and decryption)

Digital Signatures

Harder requirements:

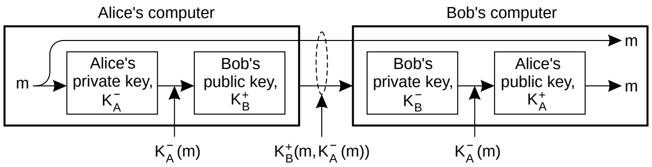
Authentication: Receiver can verify the claimed identity of the sender

Nonrepudiation: The sender can later not deny that he/she sent the message

Integrity: The message cannot be maliciously altered during, or after receipt

Solution: Let a sender sign all transmitted messages, in such a way that (1) the signature can be verified and (2) message and signature are uniquely associated

Public Key Signatures



1: Alice encrypts her message m with her private key $K_A^- \Rightarrow m' = K_A^-(m)$

2: She then encrypts m' with Bob's public key, along with the original message m $\Rightarrow m'' = K_B^+(m, K_A^-(m))$, and sends m'' to Bob.

3: Bob decrypts the incoming message with his private key K_B^-. We know for sure that no one else has been able to read m, nor m' during their transmission.

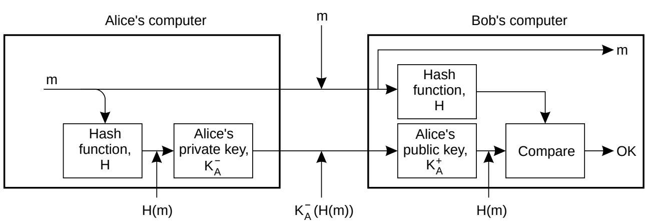
4: Bob decrypts m' with Alice's public key K_A^+. Bob now knows the message came from Alice.

Question: Is this good enough against nonrepudiation?

Message Digests

Basic idea: Don't mix authentication and secrecy. Instead, it should also be possible to send a message in the clear, but have it signed as well.

Solution: take a message digest, and sign that:



Recall: Message digests are computed using a hash function, which produces a fixed-length message from arbitrary-length data.

Secure Group Communication

Design issue: How can you share secret information between multiple members without losing everything when one member turns bad.

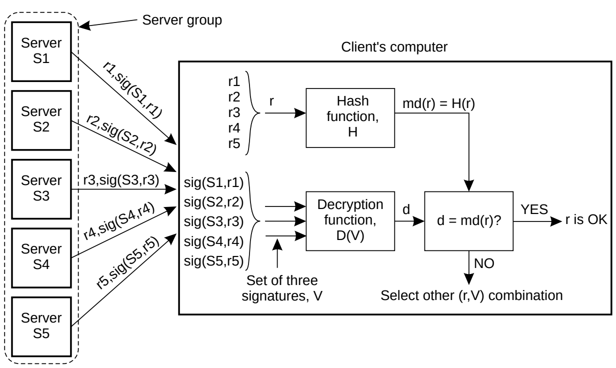
Confidentiality: Follow a simple (hard-to-scale) approach by maintaining a separate secret key between each pair of members.

Replication: You also want to provide replication transparency. Apply **secret sharing**:

- No process knows the entire secret; it can be revealed only through joint cooperation
- Assumption: at most k out of N processes can produce an incorrect answer
- At most $c \leq k$ processes have been corrupted

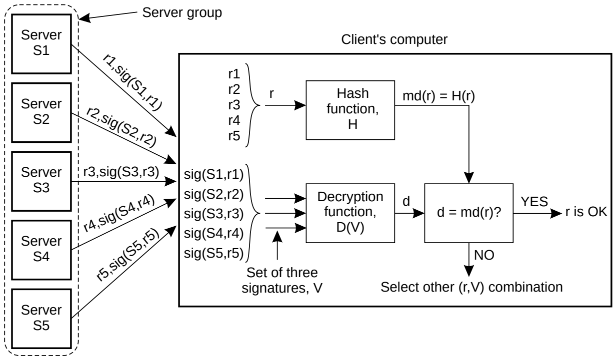
Note: We are dealing with a k fault tolerant process group.

Secure Replicated Group (1/2)



- Let $N = 5, c = 2$
- Each server S_i gets to see each request and responds with r_i
- Response r_i is sent along with digest $md(r_i)$, and signed with private key K_i^-. Signature is denoted as $sig(S_i, r_i) = K_i^-(md(r_i))$.

Secure Replicated Group (2/2)



- Client uses special decryption function D that computes a single digest d from *three* signatures:

$$d = D(sig(S,r), sig(S',r'), sig(S'',r''))$$

- If $d = md(r_i)$ for some r_i, r_i is considered correct
- Also known as **(m,n)-threshold scheme** (with $m = c+1, n = N$)

Access Control

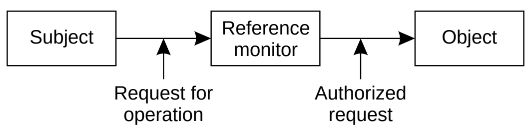
- General issues
- Firewalls
- Secure mobile code

Authorization versus Authentication

Authentication: Verify the claim that a subject says it is S: verifying the **identity** of a subject

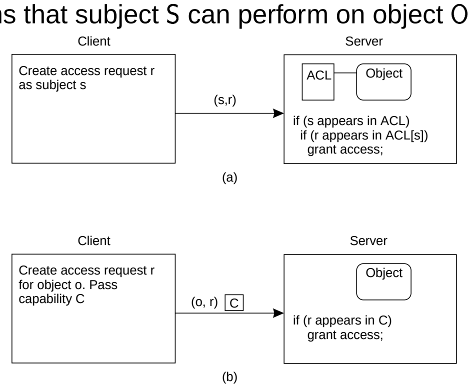
Authorization: Determining whether a subject is permitted certain services from an object

Note: authorization makes sense only if the requesting subject has been authenticated



Access Control Matrix

Essence: Maintain an **access control matrix** ACM in which entry ACM[S,O] contains the permissible operations that subject S can perform on object O



Implementation (a): Each object O maintains an **access control list (ACL)**: ACM[*,O] describing the permissible operations per subject (or group of subjects)

Implementation (b): Each subject S has a **capability**: ACM[S,*] describing the permissible operations per object (or category of objects)

Protection Domains

Issue: ACLs or capability lists can be very large. Reduce information by means of **protection domains**:

- Set of *(object, access rights)* pairs
- Each pair is associated with a protection domain
- For each incoming request the reference monitor first looks up the appropriate protection domain

Common implementation of protection domains:

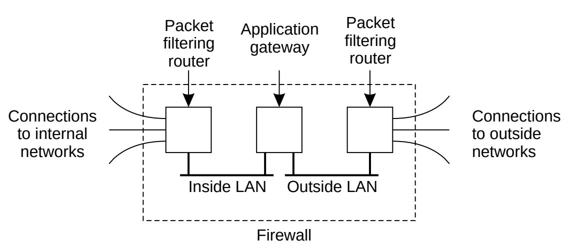
Groups: Users belong to a specific group; each group has associated access rights

Roles: Don't differentiate between users, but only the roles they can play. Your role is determined at login time. Role changes are allowed.

Firewalls

Essence: Sometimes it's better to select service requests at the lowest level: network packets. Packets that do not fit certain requirements are simply removed from the channel

Solution: Protect your company by a firewall: it implements access control



Question: What do you think would be the biggest breach in firewalls?

Secure Mobile Code

Problem: Mobile code is great for balancing communication and computation, but is hard to implement a general-purpose mechanism that allows different security policies for local-resource access. In addition, we may need to protect the mobile code (e.g., agents) against malicious hosts.

Protecting an Agent

Ajanta: Detect that an agent has been tampered with while it was on the move. Most important: **append-only logs**:

- Data can only be appended, not removed
- There is always an associated checksum. Initially, $C_{\text{init}} = K^{+}_{\text{owner}}(N)$, with N a nonce.
- Adding data X by server S:

$$C_{\text{new}} = K^{+}_{\text{owner}}(C_{\text{old}}, sig(S,X), S)$$

- Removing data from the log:

$$K^{-}_{\text{owner}}(C) \rightarrow C_{\text{prev}}, sig(S,X), S$$

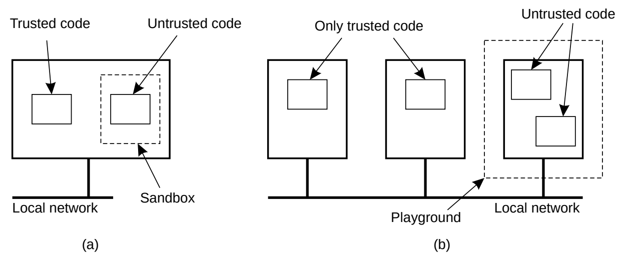
  allowing the owner to check integrity of X

Protecting a Host (1/2)

Simple solution: Enforce a (very strict) single policy, and implement that by means of a few simple mechanisms

Sandbox model: Policy: Remote code is allowed access to only a pre-defined collection of resources and services. Mechanism: Check instructions for illegal memory access and service access

Playground model: Same policy, but mechanism is to run code on separate “unprotected” machine.



Protecting a Host (2/2)

Observation: We need to be able to distinguish local from remote code before being able to do anything

Refinement 1: We need to be able to assign a set of permissions to mobile code before its execution and check operations against those permissions at all times

Refinement 2: We need to be able to assign different sets of permissions to different units of mobile code $\Rightarrow$ authenticate mobile code (e.g. through signatures)

Question: What would be a very simple policy to follow (Microsoft’s approach)?

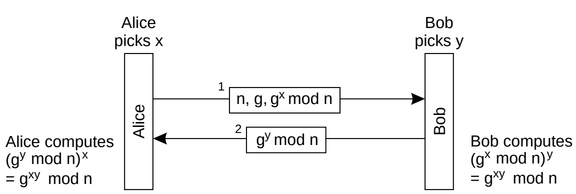
Security Management

- Key establishment and distribution
- Secure group management
- Authorization management

Key Establishment: Diffie-Hellman

Observation: We can construct secret keys in a safe way without having to trust a third party (i.e. a KDC):

- Alice and Bob have to agree on two large numbers, n and g. Both numbers may be public.
- Alice chooses large number x, and keeps it to herself. Bob does the same, say y.



1: Alice sends $(n, g, g^x \bmod n)$ to Bob
2: Bob sends $(g^y \bmod n)$ to Alice
3: Alice computes $K_{A,B} = (g^y \bmod n)^x = g^{xy} \bmod n$
4: Bob computes $K_{A,B} = (g^x \bmod n)^y = g^{xy} \bmod n$

Key Distribution (1/2)

Essence: If authentication is based on cryptographic protocols, and we need session keys to establish secure channels, who's responsible for handing out keys?

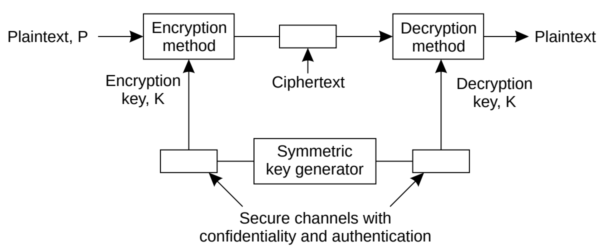
Secret keys: Alice and Bob will have to get a shared key. They can invent their own and use it for data exchange. Alternatively, they can trust a **key distribution center** (KDC) and ask it for a key.

Public keys: Alice will need Bob's public key to decrypt (signed) messages from Bob, or to send private messages to Bob. But she'll have to be sure about actually having Bob's public key, or she may be in big trouble. Use a trusted **certification authority** (CA) to hand out public keys.

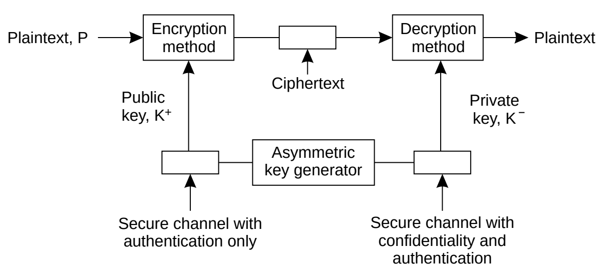
A public key is put in a **certificate**, signed by a CA.

Key Distribution (2/2)

Another problem: How do we get the secret keys to their new owners?



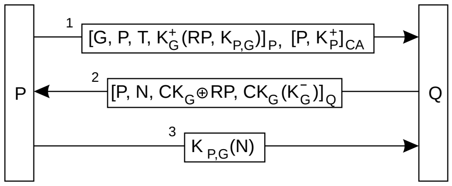
(a)



(b)

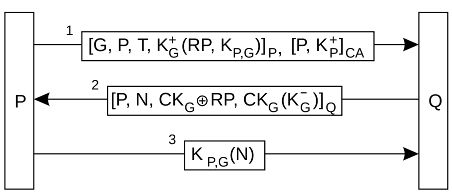
Secure Group Management (1/2)

Structure: Group uses a key pair (K_G^+, K_G^-) for communication with nongroup members. There is a separate shared secret key CK_G for internal communication. Assume process P wants to join the group and contacts Q.



1: P generates a one-time *reply pad* RP, and a secret key $K_{P,G}$. It sends a join request to Q, signed by itself (notation: $[JR]_P$), along with a certificate containing its public key K_P^+.

Secure Group Management (2/2)



2: Q authenticates P, checks whether it can be allowed as member. It returns the group key CK_G, encrypted with the one-time pad, as well as the group's private key, encrypted as $CK_G(K_G^-)$.

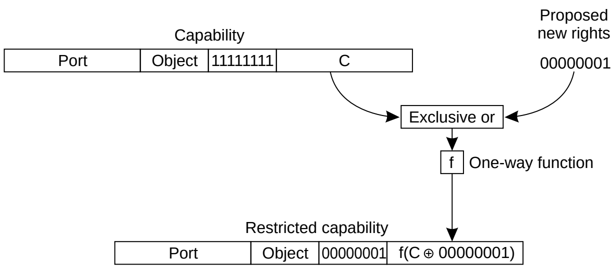
3: Q authenticates P and sends back $K_{P,G}(N)$ letting Q know that it has all the necessary keys.

Question: Why didn't we send $K_P^+(CK_G)$ instead of using RP?

Authorization Management

Issue: To avoid that each machine needs to know about all users, we use capabilities and attribute certificates to express the access rights that the holder has.

In Amoeba, restricted access rights are encoded in a capability, along with data for an integrity check to protect against tampering:



Delegation (1/2)

Observation: A subject sometimes wants to delegate its privileges to an object O1, to allow that object to request services from another object O2

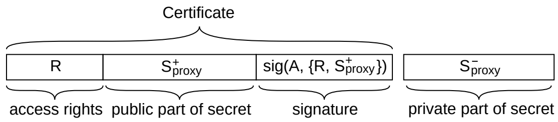
Example: A client tells the print server PS to fetch a file F from the file server FS to make a hard copy ⇒ the client delegates its read privileges on F to PS

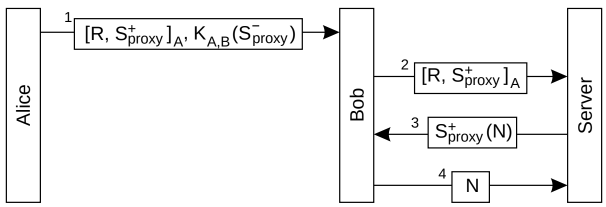
Nonsolution: Simply hand over your attribute certificate to a delegate (which may pass it on to the next one, etc.)

Problem: To what extent can the object trust a certificate to have originated at the initiator of the service request, without forcing the initiator to sign every certificate?

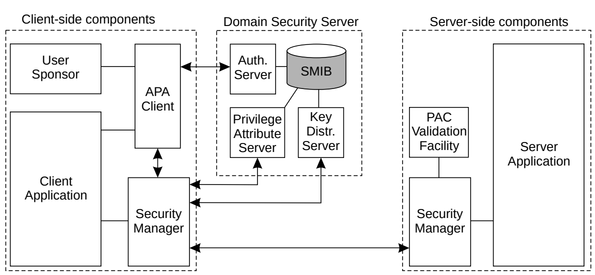
Delegate Privileges (2/2)

Solution: Ensure that delegation proceeds through a secure channel, and let a delegate prove it got the certificate through such a path of channels originating at the initiator.





Putting it all together: SESAME



SMIB: Database holding shared secret keys, basic access rights, and so on

AS: Authenticates a user, and returns a ticket

PAS: Hands out attribute certificates

KDS: Generates session keys for authenticated users

Security Manager: Handles setting up and communicating over a secure channel

PVF: Validates access rights contained in attribute certificates