Kerberos Authentication Service

- Developed at MIT under Project Athena in mid 1980s
  - Versions 1-3 were for internal use; versions 4 and 5 are being used externally
  - Version 4 has a larger installed base, is simpler, and has better performance, but works only with TCP/IP networks
  - Version 5 developed in mid 90’s (RFC-1510) corrects some of the security deficiencies of Version 4
- Kerberos (intended) Services:
  - Authentication
  - Accounting
  - Audit
- The last two were never implemented
Objective

- To provide a trusted third-party service (based on the Needham/Schroeder authentication protocol), named Kerberos, that can perform authentication between any pair of entities in TCP/IP networks
- primarily used to authenticate user-at-workstation to server
- Authentication is two-way
- Not meant for high risk operations (e.g., bank transactions, classified government data, student grades)

Needham-Schroeder Protocol

- original third-party key distribution protocol, for session between A and B mediated by KDC
- protocol overview is:
  1. A→KDC: $ID_A || ID_B || N_I$
  2. KDC→A: $E_{K_s}[K_s || ID_B || N_I || E_{K_b}[K_s||ID_A]]$
  3. A→B: $E_{K_b}[K_s||ID_A]$
  4. B→A: $E_{K_b}[N_2]$
  5. A→B: $E_{K_s}[f(N_2)]$
Physical Security

- CLIENT WORKSTATIONS
  - None, so cannot be trusted

- SERVERS
  - Moderately secure rooms, with moderately diligent system administration

- KERBEROS
  - Highly secure room, with extremely diligent system administration

Design Goals

- Impeccability
  - No cleartext passwords on the network
  - No client passwords on servers (server must store secret server key)
  - Minimum exposure of client key on workstation (smartcard solution would eliminate this need)

- Containment
  - Compromise affects only one client (or server)
  - Limited authentication lifetime (8 hours, 24 hours, more)

- Transparency
  - Password required only at login
  - Minimum modification to existing applications
Kerberos model

- Network consists of clients and servers
  - clients may be users, or
  - programs that can, e.g., download files, send messages, access databases and access printers
- Kerberos keeps a database of clients and servers with a secret key for each one (selected at the time of registration)
  - $O(n+m)$ keyspace, instead of $O(nm)$ keyspace with $n$ clients and $m$ servers
- Kerberos provides authentication of one entity to another and issues session key
- Issues tickets for access rights
  - temporary rights issued by authentication server
  - tickets time-stamped to reduce replay attacks

Where To Start

- Every principal has a master (secret) key
  - Human user's master key is derived from the password
  - Other resources must have their keys configured in
- Every principal is registered with the Kerberos server AS
- All principals' master keys are stored in the AS database (encrypted using the AS master key)
Encryption and clocks

- **Note:**
  - Each user has a password which is converted to a DES key
  - Client and server do not initially share an encryption key
  - Any symmetric key system would work

- **Clocks**
  - All machines that use Kerberos are loosely synchronized (within a few minutes) to prevent replays

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Kerberos Components

- **Key Distribution Center (KDC)** - consists of two logical components:
  - **Kerberos Database** — with secret key for each principal (user or service)
  - **Authentication Service (AS)** — uses the Kerberos database to verify the identity of users requesting the use of network services

- **Ticket Granting Server (TGS)** — issues tickets to clients for communicating with network servers after the AS has verified the identity of the client
Kerberos Operation

- The Kerberos protocol is simple and straightforward.
- First, the Client requests a ticket for a Ticket-Granting Service (TGS) from Kerberos (Msg 1).
- This ticket is sent to the client encrypted using the client’s secret key (Msg 2).
- To use a particular server, the client requests a ticket for that server from the TGS (Msg 3).

Kerberos Operation

- If everything is in order, the TGS sends back a ticket to the client for the server (Msg 4).
- At this point the client presents this ticket to the server along with an authenticator (Msg 5).
- If there is nothing wrong with the client’s credentials, the server permits access to the service.
Getting an Initial Ticket

- When Bob logs into a workstation (WS), WS sends Bob’s user id to AS in the clear
- AS returns to the WS, encrypted with Bob’s secret key $K_{Bob}$:
  - A session key $K_{Bob,TGS}$ (a secret key to be used during the current session)
  - A ticket-granting ticket (TGT) containing the session key, the user id, and an expiration time, encrypted with $K_{TGS}$

After receiving the message from AS, WS prompts Bob for his password and uses it to derive Bob’s secret key $K_{Bob}$:

- Bob’s secret key is then used to decipher the session key $K_{Bob,TGS}$ and the TGT
- WS discards both Bob’s password and his secret key

Note that:
- When Bob requires access to a service (Alice), WS will need to send the TGT to TGS.
- Bob cannot read the contents of the TGT encrypted with TGS secret key.
- Since TGT contains all the information TGS needs about the initial login session, Kerberos can be stateless.
**Getting a Server Ticket**

- When Bob wants to access a service (Alice), WS sends to TGS the name Alice, and an authenticator which proves that WS knows the session key.
- Authenticator consists of the time of day encrypted with the session key (in this case $K_{Bob, TGS}$).
- TGS decrypts the TGT to obtain $K_{Bob, TGS}$, and verifies the timestamp (times can be off by some amount). If so, TGS generates a new session key $K_{Bob, Alice}$ (session key to be shared by Bob and Alice), finds Alice’s master key, and sends to WS a “ticket for Alice” and $K_{Bob, Alice}$, encrypted with the session key $K_{Bob, TGS}$.
- The “ticket for Alice” consists of Bob’s identity, an expiration time, and $K_{Bob, Alice}$ encrypted using Alice’s master key.

**Requesting a Service**

- Upon receiving the message from TGS, WS decrypts the message using $K_{Bob, TGS}$.
- WS sends the “ticket for Alice” (that it cannot read) and an authenticator to Alice.
- Alice uses $K_{Alice}$ to decrypt the ticket to obtain $K_{Bob, Alice}$ and decrypts the authenticator using $K_{Bob, Alice}$ to verify the timestamp.
- If everything checks out, Alice knows that the message is from Bob.
Use of session key

- Kerberos establishes a session key $K_{Bob,Alice}$ to be used by the applications for
  - client to server authentication (no additional step required in the protocol)
  - mutual authentication (requires the additional step of sending another message from server to client $f(A_{Bob,Alice}) \cdot K_{Bob,Alice}$, using some known (hash) function $f$)
- message confidentiality using $K_{Bob,Alice}$
- message integrity using $K_{Bob,Alice}$

Kerberos Version 4

- Terms:
  - $C =$ Client
  - $AS =$ authentication server
  - $V =$ server
  - $ID_c =$ identifier of user on $C$
  - $ID_v =$ identifier of $V$
  - $AD_c =$ network address of $C$
  - $K_v =$ secret encryption key shared by $AS$ and $V$
  - $K_{C,V} =$ secret encryption key shared by $C$ and $V$
  - $TS =$ timestamp
  - $|| =$ concatenation
How Kerberos works

- Kerberos uses two types of credentials
  - tickets (to convey keys and identity)
  - authenticators (to verify identity)

\[\text{Ticket}_{tg} = E_{Ktg} [K_{c,tg} || ID_c || AD_c || ID_{tg} || TS || \text{Life}]\]

\[\text{Authenticator}_c = E_{Kc,tg} [ID_c || AD_c || TS]\]

- A client uses a ticket (that he/she cannot read or modify) to access a server
  - It can be used multiple times until it expires
- A client generates an authenticator to use a service on the server (once only)

V4 Authentication Dialogue

Authentication Service Exchange: To obtain Ticket-Granting Ticket

1. \(C \rightarrow AS:\)
   \[ID_c || ID_{tg} || TS1\]

2. \(AS \rightarrow C:\)
   \[E_{Kc} [K_{c,tg} || ID_{tg} || TS_2 || \text{Lifetime}_2 || \text{Ticket}_{tg}]\]
V4 Authentication Dialogue

Ticket-Granting Service Exchange: To obtain Service-Granting Ticket

- (3) $C \rightarrow TGS$:  
  $ID_v \ || Ticket_{tgs} \ || Authenticator_c$
- (4) $TGS \rightarrow C$:  
  $E_{K_{c,tgs}}[K_{c,v} \ || ID_v \ || TS4 \ || Ticket_v]$

V4 Authentication Dialogue

Client/Server Authentication Exchange: To Obtain Service

- (5) $C \rightarrow V$:  
  $Ticket_v \ || Authenticator_c$
- (6) $V \rightarrow C$:  
  $E_{K_{c,v}}[TS5 +1]$
Replicated Kerberos Servers

- To avoid single point of failure and performance bottleneck, it is possible to replicate Kerberos server
- Mutual consistency of copies of password database could be maintained as follows:
  - All updates are made to a primary (master) copy
  - Other (slave) copies are read only; these copies are replaced periodically by downloading the master copy
  - The database (with encrypted keys) is transferred in the clear
  - To ensure that an attacker has not rearranged data in transit, a cryptographic checksum is also exchanged
  - To ensure that an attacker does not replace a copy by an older copy, a timestamp is also sent

Kerberos V4 Realm

- A full-service Kerberos environment consists of the following entities:
  - A Kerberos server
  - A set of one, or more, clients
  - A set of one, or more, application servers

- This environment is known as a realm.
  - Networks of clients and servers under different administrative organizations typically constitute different realms.
Cross-Realm Operation

- The Kerberos protocol is designed to operate across organizational boundaries: a client in one organization can be authenticated to a server in another.
- Each organization wishing to run a Kerberos server establishes its own "realm".
- The name of the realm in which a client is registered is part of the client’s name, and can be used by the end-service to decide whether to honor a request.

Cross-Realm Operation

- By establishing "inter-realm" keys, the administrators of two realms can allow a client authenticated in the local realm to use its authentication remotely.
- With appropriate permissions, a client could arrange registration of a separately-named principal in a remote realm, and engage in normal exchanges with that realm’s services.
Cross-Realm Operation: Message Exchange

- Typically, cross-realm message exchange operates as follows:
  
  \[ C \rightarrow AS: \]
  
  \[ \text{ID}_C \ || \ \text{ID}_{tgs} \ || \ \text{TS}_1 \]
  
  \[ AS \rightarrow C: \]
  
  \[ E_{KC} [\text{KC}, \text{tgs} || \text{ID}_{tgs} || \text{TS}_2 || \text{Lifetime}_2 || \text{Ticket}_{tgs}] \]
  
  \[ C \rightarrow TGS: \]
  
  \[ \text{ID}_{tgsrem} || \text{Ticket}_{tgs} || \text{Authenticator}_C \]

TGS \rightarrow C:

\[ E_{K_{C,tgs}} [K_{C,tgsrem} || \text{ID}_{tgsrem} || \text{TS}_4 || \text{Ticket}_{tgsrem}] \]

\[ C \rightarrow TGS_{rem}: \]

\[ \text{ID}_{vrem} || \text{Ticket}_{tgsrem} || \text{Authenticator}_C \]

TGS_{rem} \rightarrow C:

\[ E_{K_{C,tgsrem}} [K_{C,vrem} || \text{ID}_{vrem} || \text{TS}_6 || \text{Ticket}_{vrem}] \]

\[ C \rightarrow V_{rem}: \]

\[ \text{Ticket}_{vrem} || \text{Authenticator}_C \]
Kerberos V5 vs. V4

- addresses environmental shortcomings
  - encryption system dependence (only DES)
  - internet protocol dependence (only IP addresses)
  - byte order (sender's choosing + tag)
  - ticket lifetime (only 8bit of 5 min units = 21 hrs)
  - authentication forwarding (not allowed)
  - Inter-realm authentication ($n^2$ relationships in V4, fewer in V5)

Kerberos V5 vs. V4

- and technical deficiencies
  - double encryption (of ticket= not necessary)
  - non-std mode of DES Propagating CBC (now CBC DES for encryption and separate integrity checks)
  - session keys (used too often: now subsession keys)
  - password attacks (still possible)
### Kerberos V5 Realm

- For a realm to function, it requires the following:
  - The Kerberos server must have the user ID (UID) and hashed password of all participating users in its database.
  - All users are registered with the Kerberos server.
  - The Kerberos server must share a secret key with each server.
  - All servers are registered with the Kerberos server.

### Kerberos V5 Multiple Realms

- Kerberos provides a mechanism for support multiple realms and inter-realm authentication.
- Inter-realm authentication adds the following third requirement:
  - The Kerberos server in each inter-operating realm share a secret key with the server in the other realm.
  - The two Kerberos servers are registered with each other.
- This inter-realm scheme requires that the Kerberos server in one realm trust the Kerberos server in the other realm to authenticate its users.
  - In a similar fashion, the participating servers in the second realm must also be willing to trust the Kerberos server in the first realm.
Realms: Hierarchical Organization

- Realms are typically organized hierarchically.
  - Each realm shares a key with its parent and a different key with each child.
- If an inter-realm key is not directly shared by two realms, the hierarchical organization allows an authentication path to be easily constructed.
- If a hierarchical organization is not used, it may be necessary to consult some database in order to construct an authentication path between realms.

Kerberos V5 Credentials: Ticket

- A Kerberos ticket used to pass to server identity of client for whom the ticket was issued.
  - also contains information that server uses to ensure that client using ticket is same client to whom ticket was issued.
- Some of the information, encrypted using the server's secret key, in a ticket include
  - Client's name
  - Client's network address
  - Timestamp
  - Session key
- A ticket is good for a single server and a single client; it can, however, be used multiple times to access a server — until the ticket expires.
- Ticket security is assured since its critical elements are encrypted using the server's secret key.
Kerberos V5 Tickets

- Kerberos version 5 tickets are renewable, so service can be maintained beyond maximum ticket lifetime.
- Ticket can be renewed until minimum of:
  - requested end time
  - start time + requesting principal’s max renewable lifetime
  - start time + requested server’s max renewable lifetime
  - start time + max renewable lifetime of realm

Kerberos V5 Authenticator

- A Kerberos authenticator is generated each time a client wishes to use a service on a server.
- Some of the information, encrypted using the key between the client and the server, in an authenticator includes:
  - Client’s name
  - Timestamp
  - Session key
- Unlike a ticket, an authenticator can be used only once.
- However, a client can create authenticators as needed.
Kerberos V5 Message Types

- Kerberos uses six message types:
  - Client to Kerberos Authentication Server (AS)
  - Kerberos Authentication Server (AS) to Client
  - Client to Ticket-Granting Server
  - Ticket-Granting Server to Client
  - Client to Server
  - Server to Client

Getting the Initial Ticket

- The client has one piece of information to prove client’s identity - the password.
  - However, sending the password over the network is not advisable.

- Instead, the client sends a message containing its name and the name of the TGS to the Kerberos Authentication Server (AS).
  - A network may have multiple TGS servers.
In Kerberos V5 the initial message from the client to the Kerberos Authentication Server would look as follows:

\[ C \rightarrow AS: \]

\[ \text{Options} \ || \ ID_C \ || \ Realm \ || \ ID_{tgs} \ || \ \text{Times} \ || \ \text{Nonce}_1 \]

- **Options**: Used to request that certain flags be set in the returned ticket.
- **ID_C**: The identifier of the client C.
- **Realm**: Indicates the realm of the user.
- **ID_{tgs}**: Used to represent the identifier of the Ticket-Granting Server.

**Times**: Used by the client to request the following time settings in the ticket:

- **from**: desired start time for requested ticket.
- **till**: requested expiration time for the requested ticket.
- **rtime**: requested renew-till time.

**Nonce**: A random number to be repeated in the message back to the client to assure that the response is fresh and has not been replayed by an attacker.
Authentication Server to Client

- The Kerberos Authentication Server (AS) looks up the client in its database.
- If the client exists in the database, Kerberos generates a session key to be used between the client and the TGS known as the Ticket Granting Ticket (TGT).
- In Kerberos V5 the message from the Authentication Server to the client would look as follows:
  \[ \text{AS} \rightarrow C: \]
  \[ \text{Realm}_C || \text{ID}_C || \text{Ticket}_{tgs} || \]
  \[ E_{KC} [K_{C,tgs} || \text{Times} || \text{Nonce}_1 || \text{Realm}_{tgs} || \text{ID}_{tgs}] \]

Ticket Granting Ticket Format

- The format for the TGT ticket is as follows:
  \[ \text{TGT}_{tgs} = \]
  \[ E_{ktgs}[\text{Flags} || K_{C,tgs} || \text{Realm}_C || \text{ID}_C || \text{AD}_C || \text{Times}] \]

- What is encrypted using the TGS’s encryption key:
  - Flags
  - Encryption key Client C to TGS
  - Realm and ID for C
  - (optional) Addresses for which ticket valid
  - Time setting information
Getting Server Tickets

- A client has to obtain a separate ticket for each service it wants to use.

- When a client needs a ticket that it does not already have, it sends a request to the Ticket-Granting Server (TGS).
- In reality, in most cases the program would do this automatically and it would be invisible to the user.

Client to TGS

- The format for the this message is as follows:
  
  \[ C \rightarrow TGS: \]

  \[ \text{Options}|| \text{ID}_V || \text{Times}|| \text{Nonce}_2 || \text{Ticket}_{tgS}|| \text{Authenticator}_C \]

- **Options**: Used to request that certain flags be set in the return ticket.
- **ID$_V$**: The ID of the server for which the ticket is being requested.
- **Nonce$_2$**: A different random number between the client and the TGS.
- **Ticket$_{tgS}$**: The ticket provided by the Ticket-Granting Ticket Server.
- **Authenticator$_C$**: An authenticator created by Client $C$ to validate it to the TGS.
Client: Authenticator Format

- The format for the client authenticator is as follows:
  Authenticator\(_C\) = \(K_{KC,tgs} [ID_C \mid \text{Realm}_C \mid TS_1]\)

- Notice that the following information is encrypted using the secret key between Client \(C\) and the TGS:
  - \(ID_C\): ID of Client \(C\)
  - \(\text{Realm}_C\): Realm of Client \(C\)
  - \(TS_1\): Timestamp when the authenticator was created.

Getting Server Tickets

- When TGS receives the request, it decrypts the Ticket Granting Ticket (TGT) with the secret key and uses the session key in the TGT to decrypt the authenticator.
- It compares the information in the authenticator with the information in the ticket:
  - Client's network address
  - Timestamp [Clocks must be in close synchronization]
- If all is correct, the TGS returns a valid ticket for the client to present to the requested server.
- TGS creates new session key for client and server encrypted with the session key shared by the client and the TGS.
- Information is sent back to client via a message.
TGS to Client

- The format for this message is as follows:
  \[ TGS \rightarrow C: \]
  \[ \text{Realm}_C \ || \ ID_C \ || \ Ticket_V \ || \]
  \[ E_{K_{KC, TGS}} [K_{C,V} \ || \ Times \ || \ Nonce_2 \ || \ \text{Realm}_V \ || \ ID_V] \]

- The message from the TGS to C, encrypted using the secret key shared by Client and the TGS, contains the following information:
  - ID and Realm information for Server V
  - Session key to be used by Client C and Server V
  - Time setting information
  - Return nonce

Requested Server: Ticket Format

- The format for the TGT ticket is as follows:
  \[ \text{Ticket}_V = \]
  \[ E_{K_V}[\text{Flags} \ || \ K_{C,V} \ || \ \text{Realm}_C \ || \ ID_C \ || \ AD_C \ || \ \text{Times}] \]

- Notice what is encrypted using the secret key between the TGS and Server V:
  - Flags
  - Encryption key from Client C to Server V
  - Realm and ID for C
  - (optional) Addresses for which ticket valid
  - Time setting information
Client to Server

- Now, the client is able to authenticate itself to the server that will provide the requested service.

- The format for the message from the client to a server to request the service is as follows:

  \[ C \rightarrow V: \text{Options} || \text{Ticket}_V || \text{Authenticator}_C \]

Client to Server: Ticket Formats

- The format for the ticket between the client and the server is:

  \[ \text{Ticket}_V = E_{KV} \left[ \text{Flags} || K_{C,V} || \text{Realm}_C || ID_C || AD_C || \text{Times} \right] \]
**Client to Server: Authenticator Format**

- The authenticator sent by client to sever is:
  \[
  \text{Authenticator}_C = \text{E}_{K_{V,C}} [\text{ID}_C || \text{Realm}_C || \text{TS}_2 || \text{Subkey} || \text{Seq} \#] 
  \]

  - The **subkey** field is a client's choice for an encryption key to be used to protect this specific application session.
  - If omitted, session key from the ticket \(K_{C,V}\) is used.
  - The **Seq#** field is an optional field that specifies the starting sequence number to used by server for messages sent to the client during this session.
  - Messages may be sequenced numbered to detect replays.

**Message: Server to Client**

- The server decrypts and check the ticket, the authenticator, and the client's address and timestamp.
- If everything checks out, server is assured by the Kerberos protocol that the client is who it says it is.
- For applications that require mutual authentication, the server sends the client back a message consisting of the timestamp encrypted with the session key.
  - This demonstrates that the server knew the secret key and could decrypt the ticket and authenticator.
- Now, the client and serve can encrypt future messages with the shared key.
**Message: Server to Client**

- The format for the message from the server back to the client to provide mutual authentication is:

  \[ V \rightarrow C: E_{KC, V} [TS_2 || Subkey || Seq#] \]

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**Kerberos V5 Ticket Flags**

- The flags field was added in Kerberos V5.
  - The standard defines 11 flags (see Table 4.4 on Page 104 of text for the complete lists).

  - **INITIAL**: This flag indicates that a ticket was issued using the AS protocol and not issued based on a ticket-granting ticket.
  - **INVALID**: This flag indicates that a ticket is invalid, which means that application servers must reject tickets which have this flag set.
Kerberos V5 Ticket Flags

- **RENEWABLE**: This flag is normally only interpreted by the ticket-granting service, not by application servers, and can be used to obtain a replacement ticket that expires at a later date.

- **POSTDATED**: The POSTDATED flag indicates that a ticket has been postdated.
  - The application server can check the auth-time field in the ticket to see when the original authentication occurred.
  - Some services may choose to reject postdated tickets, or they may only accept them within a certain period after the original authentication.

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Kerberos V5 Ticket Flags

- **PROXIABLE**: normally interpreted by the ticket-granting service and ignored by application servers.
  - When set, this flag tells the ticket-granting server that it is OK to issue a new (proxy) 'client' ticket with a different network address based on this ticket.

- **PROXY**: This flag is set in a ticket by the TGS when it issues a proxy ticket.

- **FORWARDABLE**: This flag has an interpretation similar to that of the PROXIABLE flag, except ticket-granting tickets may also be issued with different network addresses (to be used with remote TGS)
Limitations of Kerberos

- It is possible to cache and replay old authenticators during the lifetime (typically 8 hours) of the ticket.
- If a server can be fooled about the correct time, old tickets can be reused.
- Vulnerable to password guessing attacks (attacker collects tickets and does trial decryptions with guessed passwords).
- Active intruder on the network can cause denial of service by impersonation of Kerberos IP address.

Not Addressed by Kerberos V5

- "Denial of service" attacks are not solved with Kerberos.
- There are places in these protocols where an intruder can prevent an application from participating in the proper authentication steps.
- Principals must keep their secret keys secret.
- If an intruder steals a principal’s key, can masquerade as that principal or impersonate any server to the legitimate principal.
Not Addressed by Kerberos V5

- "Password guessing" attacks are not solved by Kerberos.
- If a user chooses a poor password, it is possible for an attacker to successfully mount an offline dictionary attack by repeatedly attempting to decrypt, with successive entries from a dictionary, messages obtained which are encrypted under a key derived from the user's password.

Kerberos V5 availability

- Kerberos is not in the public domain, but MIT freely distributes the code.
- Integrating it into the UNIX environment is another story.
- A number of companies sell versions of Kerberos

Additional references