KERBEROS

T16.2 Herakles, Kerberos, Hekate

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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

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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)

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Needham-Schroeder Protocol

- original third-party key distribution protocol, for session between A and B mediated by KDC
- protocol overview is:

1. A→KDC: $ID_A \,||\, ID_B \,||\, N_1$
2. KDC→A: $E_{Ka}[Ks \,||\, ID_B \,||\, N_1 \,||\, E_{Kb}[Ks||ID_A]]$
3. A→B: $E_{Kb}[Ks||ID_A]$
4. B→A: $E_{Ks}[N_2]$
5. A→B: $E_{Ks}[f(N_2)]$

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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

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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

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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

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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)

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Encryption and clocks

- Note:
  - Each user has a password which is converted to a DES key
  - Client and server do <u>not</u> 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

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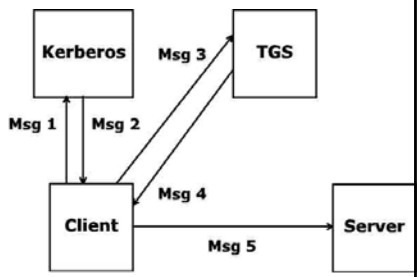
Kerberos Operation

- 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**).



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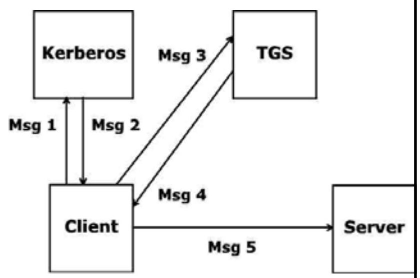
Kerberos Operation

- 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.



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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}

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Getting an Initial Ticket

- 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.

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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

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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

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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($A_{Bob, Alice}$) } $K_{Bob, Alice}$, using some known (hash) function f)
  - message confidentiality using $K_{Bob, Alice}$
  - message integrity using $K_{Bob, Alice}$

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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

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How Kerberos works

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

$Ticket_{tgs} = E_{Ktgs} [K_{c,tgs} || ID_c || AD_c || ID_{tgs} || TS || Life]$

$Authenticator_c = E_{Kc,tgs} [ID_c || AD_c || TS]$

- 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)

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V4 Authentication Dialogue

Authentication Service Exhange: To obtain Ticket-Granting Ticket

- (1) C → AS:

  $ID_c || ID_{tgs} || TS1$

- (2) AS → C:

$E_{Kc} [K_{c,tgs} || ID_{tgs} || TS_2 || Lifetime_2 || Ticket_{tgs}]$

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V4 Authentication Dialogue

Ticket-Granting Service Echange: To obtain Service-Granting Ticket

- (3) C → TGS:

  ID_v || $Ticket_{tgs}$ || $Authenticator_c$

- (4) TGS → C:

  $E_{Kc,tgs}$ [$K_{c,v}$ || ID_v || TS4 || $Ticket_v$]

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V4 Authentication Dialogue

Client/Server Authentication Exhange: To Obtain Service

- (5) C → V:

  $Ticket_v$ || $Authenticator_c$

- (6) V → C:

  $E_{Kc,v}$[TS5 +1]

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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

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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.

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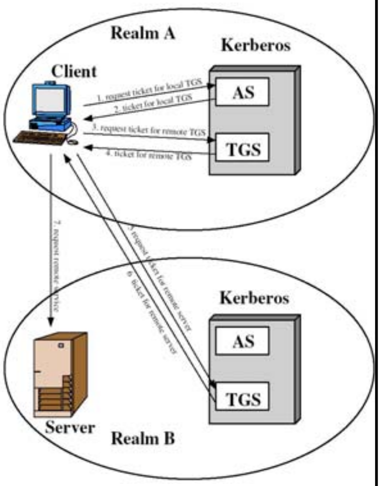
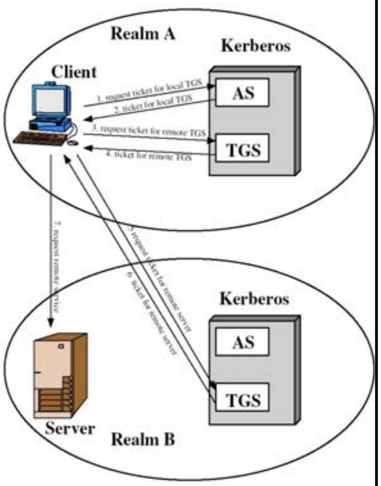
Cross-Realm Operation

- 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:

  $C \rightarrow AS$:

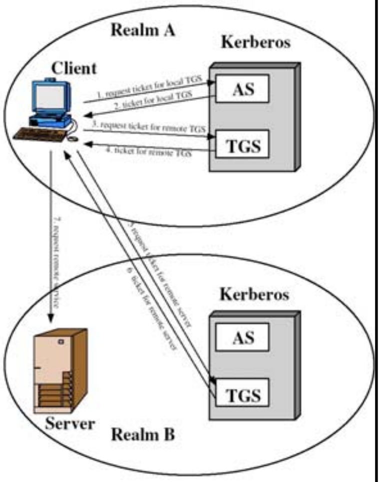
$ID_C \,||\, ID_{tgs} \,||\, TS_1$

  $AS \rightarrow C$:

$E_{KC}\,[K_{C,\,tgs} \,||\, ID_{tgs} \,||$
  $TS_2 \,||\, Lifetime_2 \,||\, Ticket_{tgs}]$

  $C \rightarrow TGS$:

$ID_{tgsrem} \,||\, Ticket_{tgs} \,||\, Authenticator_C$



Cross-Realm Operation: Message Exchange

$TGS \rightarrow C$:

$E_{\,Kc,tgs}\,[K_{C,\,tgsrem} \,||$
  $ID_{tgsrem} \,||\, TS_4 \,||\, Ticket_{tgsrem}]$

$C \rightarrow TGS_{rem}$:

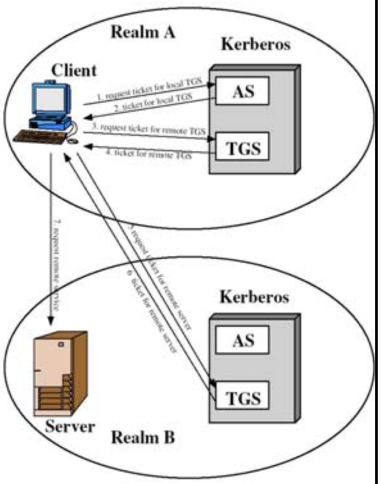
$ID_{vrem} \,||\, Ticket_{tgsrem} \,||\, Authenticator_C$

$TGS_{rem} \rightarrow C$:

$E_{\,Kc,tgsrem}\,[K_{c,\,vrem} \,||$
  $ID_{vrem} \,||\, TS_6 \,||\, Ticket_{vrem}\,]$

$C \rightarrow V_{rem}$:

$Ticket_{vrem} \,||\, Authenticator_C$



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)

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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)

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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.

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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.

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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.

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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.

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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

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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.

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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

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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.

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Client to Authentication Server

- In Kerberos V5 the initial message from the client to the Kerberos Authentication Server would look as follows:

C → AS:

Options || ID_C || Realm || ID_{tgs} || Times || $Nonce_1$

  - 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.

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Client to Authentication 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.

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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 AS to the client would look as follows:

  AS → C:

  $Realm_C$ || ID_C || $Ticket_{tgs}$ ||
  E_{KC} [$K_{C,tgs}$ || Times || $Nonce_1$ || $Realm_{tgs}$ || ID_{tgs}]

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Ticket Granting Ticket Format

- The format for the TGT ticket is as follows:

  $Ticket_{tgs}$ =
  E_{ktgs}[Flags || $K_{C,tgs}$ || $Realm_C$ || ID_C || AD_C || 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

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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.

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Client to TGS

- The format for the this message is as follows:

C → TGS:

Options|| ID_V || Times|| $Nonce_2$ || $Ticket_{tgs}$|| $Authenticator_C$

- 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.

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Client: Authenticator Format

- The format for the client authenticator is as follows:

  $Authenticator_C = K_{KC,tgs} [ID_C || Realm_C || TS_1]$

- Notice that the following information is encrypted using the secret key between Client C and the TGS:
  - ID_C: ID of Client C
  - $Realm_C$: Realm of Client C
  - TS1: Timestamp when the authenticator was created.

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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.

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TGS to Client

- The format for the this message is as follows:

TGS → C:

$Realm_C$ || ID_C || $Ticket_V$ ||

$E_{KC,\ tgs}$ [$K_{C,V}$ || Times || $Nonce_2$ || $Realm_V$ || ID_V]

- The message from the TGS to C, encrypted using 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

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Requested Server: Ticket Format

- The format for the TGT ticket is as follows:

$Ticket_V$ =

E_{KV}[Flags || $K_{C,V}$ || $Realm_C$ || ID_C || AD_C || 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

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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 → V: Options || Ticket_V || Authenticator_C

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Client to Server: Ticket Formats

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

Ticket_V =
E_{KV} [Flags || $K_{C,V}$ || Realm_C || ID_C || AD_C || Times]

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Client to Server: Authenticator Format

- The authenticator sent by client to sever is:

$Authenticator_C$ =

$$E_{KV,C}\ [ID_C \ || \ Realm_C \ || \ TS_2 \ || \ Subkey \ || \ Seq\ \#]$$

- 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.

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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.

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Message: Server to Client

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

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

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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.

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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)

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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

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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.

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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
- Microsoft has incorporated it into the Windows 2000 Server product line. (http://www.sans.org/rr/win2000/kerberos.php)

Additional references

- S. M. Bellovin and M. Merritt, "Limitations of the Kerberos Authentication System," Proc. USENIX, Winter 1991.
- B. C. Neuman and T. Ts'o, "Kerberos: An authentication service for computer networks," IEEE Communications, September 1994, pp. 33-38.