Kerberos and Mediated Key Exchange

Lecture 05

Software Security Engineering

Winter 2023
Thompson Rivers University

Kerberos, the three headed dogs that guard hades,

as protocol to key exchange.

Establishing a session key between two entities.

Kerberos is an old idea in computer science,

and is in significant use today.

A TIME-TESTED TOOL

Imagine we have printers and some employees.
It’s not reasonable to give everyone a single username for each printer and expect to type password for every use.

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Kerberos abstract away authentication from delivery of the service.

The core idea is

Key Distribution Center (KDC)

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- a central trusted party
- knows all the nodes in the network
- has authentic channel with all the nodes
- allows for mediated key exchange

what can go wrong?

what can go wrong?

Availability

(Single point of failure)

KDC Operation (in principle)

- Alice ⟶ KDC: “I want to talk to Bob”
- KDC invents a random key K_{AB}
- KDC ⟶ Alice: {use K_{AB} for Bob}$_{KA}$
- KDC ⟶ Bob: {use K_{AB} for Alice}$_{KB}$
- what can go wrong? (rather than KDC’s availability)

{Message}$_{key}$ means the content of the message is protected with the key

KDC Operation (in principle)

- Alice → KDC: “I want to talk to Bob”
- KDC invents a random key K_{AB}
- KDC → Alice: $\{\text{use } K_{AB} \text{ for Bob}\}_{KA}$
- KDC → Bob: $\{\text{use } K_{AB} \text{ for Alice}\}_{KB}$
- what can go wrong? (rather than KDC’s availability)
  - Bob should be online

KA = Alice’s Key
KB = Bob’s Key

Only KDC and the particular user know the key

KDC Operation (in practice)

- Alice → KDC: “I want to talk to Bob”
- KDC invents a random key K_{AB}
- KDC → Alice:
  - {use K_{AB} for Bob}$_{KA}$
  - {use K_{AB} for Alice}$_{KB}$
    - this is called a ticket
- Alice → Bob: “Hi I’m Alice! ticket = {use K_{AB} for Alice}$_{KB}$

KDC Operation (in practice)

- Alice → KDC: "I want to talk to Bob"
- KDC invents a random key K_{AB}
- KDC → Alice:
  - {use K_{AB} for Bob}$_{KA}$
  - {use K_{AB} for Alice}$_{KB}$
    - this is called a **ticket**
- Alice → Bob: "Hi I'm Alice! ticket = {use K_{AB} for Alice}$_{KB}$
- what can go wrong?

This ticket does not have any notion of time.

Alice can uses the ticket years later.

Needham-Schroeder Protocol

- goal is key transport on insecure networks (like the Internet)
  - e.g., you print a document at TRU
- use of a trusted third party to mediate keys for people
  - you don't need to do key exchange with everyone before communicating
- two types
  - symmetric key
    - goal: establish a session key between Alice and Bob
  - public key
    - goal: provide mutual authentication between Alice and Bob
- both protocols insecure as proposed!
  - because crypto is hard

N-S Symmetric

- Notation:
  - (A)lice, (B)ob, (S)erver (trusted by both A and B)
  - K_{xy} symmetric key known only by X and Y
  - N_x a random nonce generated by X
  - $\{data\}_{Kxy}$ data is encrypted with K_{xy}
- Protocol:
  - $A \rightarrow S : A, B, N_A$
  - $S \rightarrow A : \{N_A, K_{AB}, B, \{K_{AB}, A\}_{KBS}\}_{KAS}$
  - $A \rightarrow b : \{K_{AB}, A\}_{KBS}$
  - $B \rightarrow A : \{N_B\}_{KAB}$
  - $A \rightarrow B : \{N_B - 1\}_{KAB}$
- where is the flaw?

N-S Symmetric

- Protocol:
  - $A \rightarrow S : A, B, N_A$
  - $S \rightarrow A : \{N_A, K_{AB}, B, \{K_{AB}, A\}_{KBS}\}_{KAS}$
  - $A \rightarrow b : \{K_{AB}, A\}_{KBS}$
  - $B \rightarrow A : \{N_B\}_{KAB}$
  - $A \rightarrow B : \{N_B - 1\}_{KAB}$
- where is the flaw?
  - replay attack. if Eve learns one single key only once (by compromising the system), Eve can start with line 3
  - Thus is secure under assumption that Eve never learn the key. But is vulnerable in a way that if Eve only learn the key once, the protocol is broken forever.

One fix

- amend the first two line to:
  - $A \longrightarrow B : A$
  - $B \longrightarrow A : \{A, N'_B\}_{KBS}$
  - $A \longrightarrow S : \{A, B, N_A, \{A, N'_B\}_{KBS}\}_{KAS}$
  - $S \longrightarrow A : \{N_A, K_{AB}, B, \{K_{AB}, A, N'_B\}_{KBS}\}_{KAS}$
- why does this fix the flaw?

N-S Public Key

- Notation:
  - A, B, S the same
  - K_{PX} - public key for X (= A, B, or S)
  - K_X- private key for X (paired with K_{PX})
  - $\{message\}_{PX}$ - encrypted for X
  - $\{message\}_X$ - signed by X
- Protocol:
  - $A \longrightarrow S : A, B$
  - $S \longrightarrow A : \{K_{PB}, B\}_{KS}$
  - $A \longrightarrow B : \{N_A, A\}_{KPB}$
  - $B \longrightarrow S : B, A$
  - $S \longrightarrow B : \{K_{PA}, A\}_{KS}$
  - $B \longrightarrow A : \{N_A, N_B\}_{KPA}$
  - $A \longrightarrow B : \{N_B\}_{KPB}$
- where is the flaw?

N-S Mafia Fraud

- $A \longrightarrow S : A, E$
- $S \longrightarrow A : \{K_{PE}, E\}_{KS}$
- $A \longrightarrow E : \{N_A, A\}_{KPE}$
- $E \longrightarrow B : \{N_A, A\}_{KPB}$
    - E can decrypt this ans so know N_A
- $B \longrightarrow E : \{N_A, N_B\}_{KPA}$
    - E cannot decrypt this so does not learn N_B
- $E \longrightarrow A : \{N_A, N_B\}_{KPA}$
    - E can just reply it verbatim
- $A \longrightarrow E : \{N_B\}_{KPE}$
    - E learns N_B by design
- $E \longrightarrow E : \{N_B\}_{KPB}$
    - success

Lowe fixed this flaw

N-S-Lowe

- Notation:
  - A, B, S the same
  - K_{PX} - public key for X (= A, B, or S)
  - K_X- private key for X (paired with K_{PX})
  - $\{message\}_{PX}$ - encrypted for X
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  - $B \longrightarrow S : B, A$
  - $S \longrightarrow B : \{K_{PA}, A\}_{KS}$
  - $B \longrightarrow A : \{N_A, N_B, \mathbf{B}\}_{KPA}$
  - $A \longrightarrow B : \{N_B\}_{KPB}$

Now for Kerberos, based on symmetric N-S

Many-to-Many Authentication

- how to prove identity when requesting services on Network (e.g., the Internet)
  - many users, many services (mail, printer, servers, etc.)
  - “single sign-on” (SSO)
- naive solution: every server knows every user password
  - insecure: break into one server, compromise all users
  - inefficient: to change password, user must contact all servers

Enter Kerberos

Requirements

- security
  - against attacks by passive eavesdroppers
  - against attacks by actively malicious users
- transparency
  - users shouldn’t notice authentications taking place
  - password entering fine, as long as not all the time
- scalability
  - lots of users, lots of servers

Threats

- user impersonation
  - malicious user with access to a workstation pretended to be another user from same workstation
- network address impersonation
  - malicious user changes network address of their workstation to impersonate another workstation
- eavesdropping, tampering, replay
  - malicious user eavesdrops, tampers, or replay other users' conversations to gain unauthorized access

Solution: Trusted Third Party (TTP)

- user proves identity to trusted third party (TTP), requests a ticket for service
- TTP knows all users and services, can grant access
- user gets a ticket
- ticket is used to access service
- TTP is **authentication service** on the network
  - convenient (but also single point of failure!)
  - requires high level of physical security

Ticket Requirements

- ticket gives holder access to a network service
- ticket proves that a user has authenticated
- user should not be able to create a ticket
- user should not be able to delegate tickets

Ticket Logistics

- authentication service encrypts some information with a key known to the server
  - e.g., the printer can decrypt it, but not the user
- the user simply forwards the ticket to the printer, but cannot
- create one or read it
- server decrypts the ticket and verifies the information

Ticket Contents

- ticket must include everything to prevent abuse
  - user using tickets to other servers
  - user using tickets after they lose access
    - e.g., they've been fired
  - user giving tickets to other users to use
- ticket includes:
  - user name
  - server name
  - address of user's workstation
  - ticket lifetime

Naive Authentication

- protocol:
  - user sends password to authentication server
  - server provides an encrypted ticket
- problems:
  - insecure: eavesdropper sees the password and can impersonate
  - inconvenient: need to send the password each time to get the ticket
    - separate authentication for email, printing, etc.

Two-Step Authentication

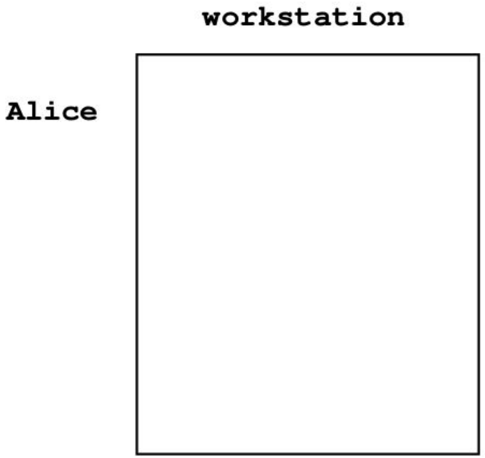
- protocol:
  - user authenticates to the key distribution centre (KDC)
  - gets a special ticket granting service (TGS) ticket
  - user gives TGS ticket to TGS server when needed
  - gets encrypted service ticket (e.g., for printer)
  - user gives ticket to printer

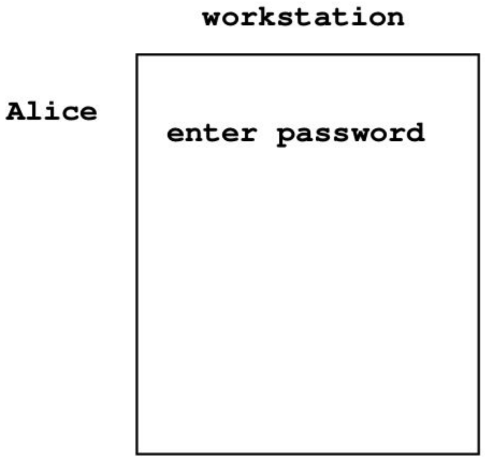
Threats to Two Step

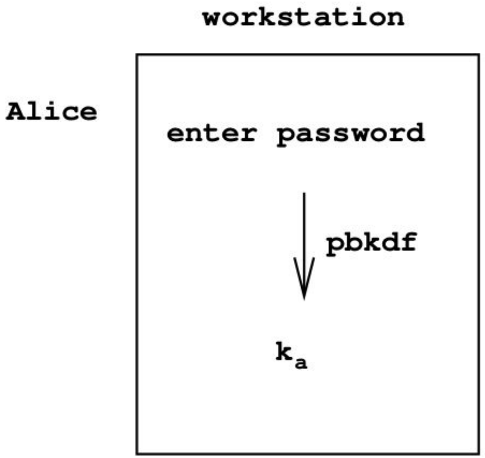
- ticket hijacking
  - malicious user steals service ticket
  - uses it on the same workstation
    - network address verification doesn’t help
  - server must verify that the user who gives the ticket is the same who was issued
- no server authentication
  - attacker may misconfigure the network so they receive messages sent to server
  - deny service or capture private information

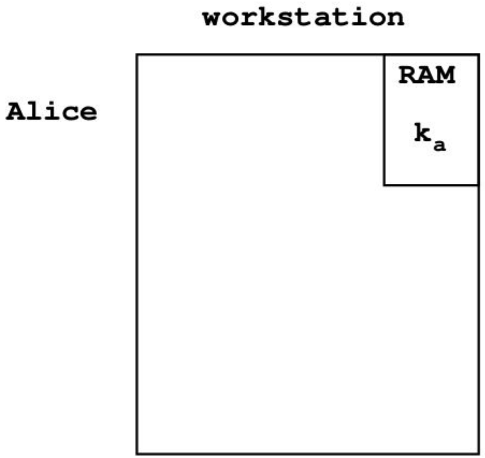
Kerberos

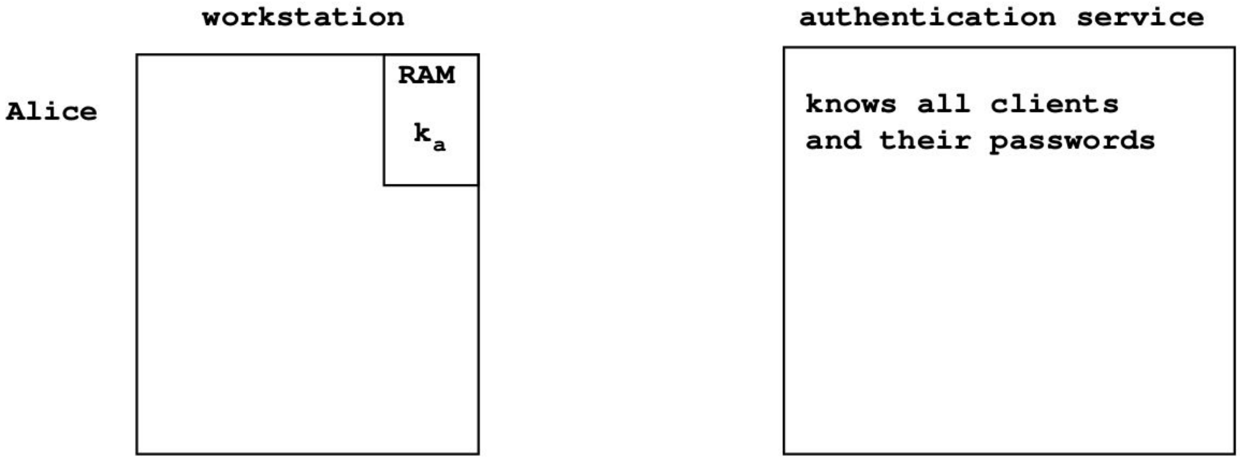
- K_C is a long-term key of client C
  - derived from the user's password
- K_{TGS} is a long-term key of the TGS
  - known by KDC and TGS
- K_V is a long-term key of network service V
  - known to V and TGS; each V has its own key
- $K_{C,TGS}$ is a short-term session key b/w C and TGS
  - created by KDC, known to C and TGS
- $K_{C,V}$ is a short-term session key b/w C and V
  - created by TGS, known to C and TGS

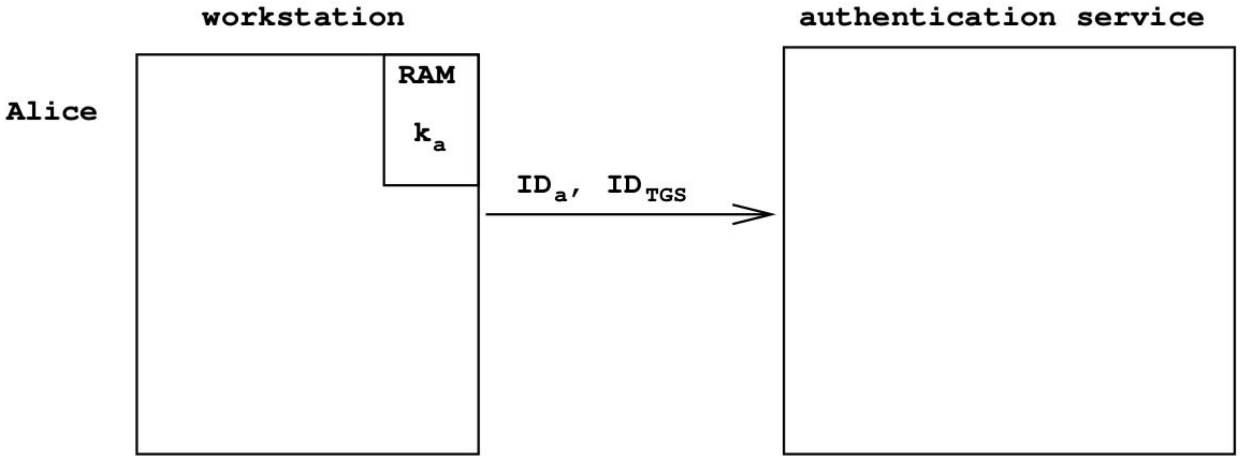

workstation
Alice

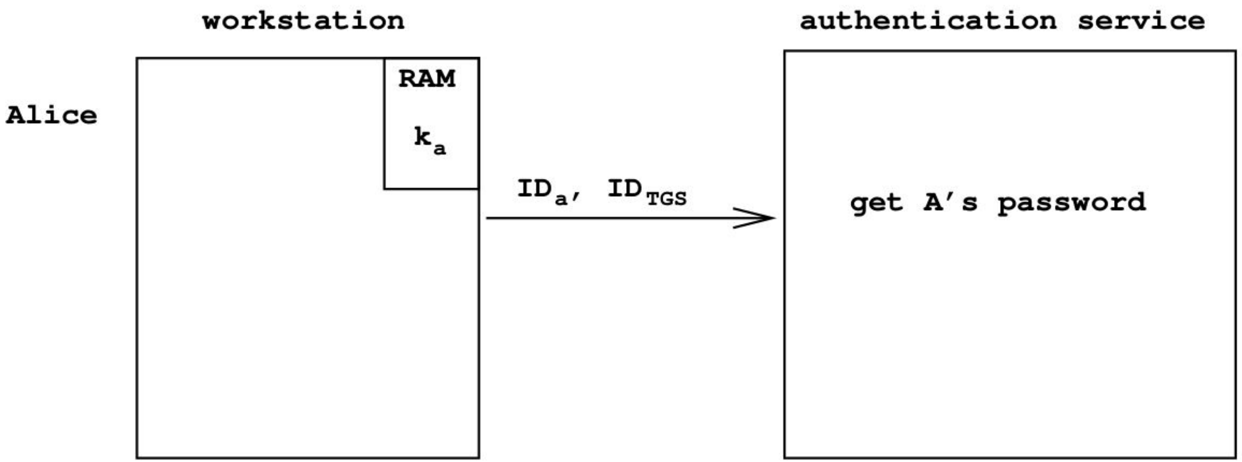

workstation
Alice
enter password

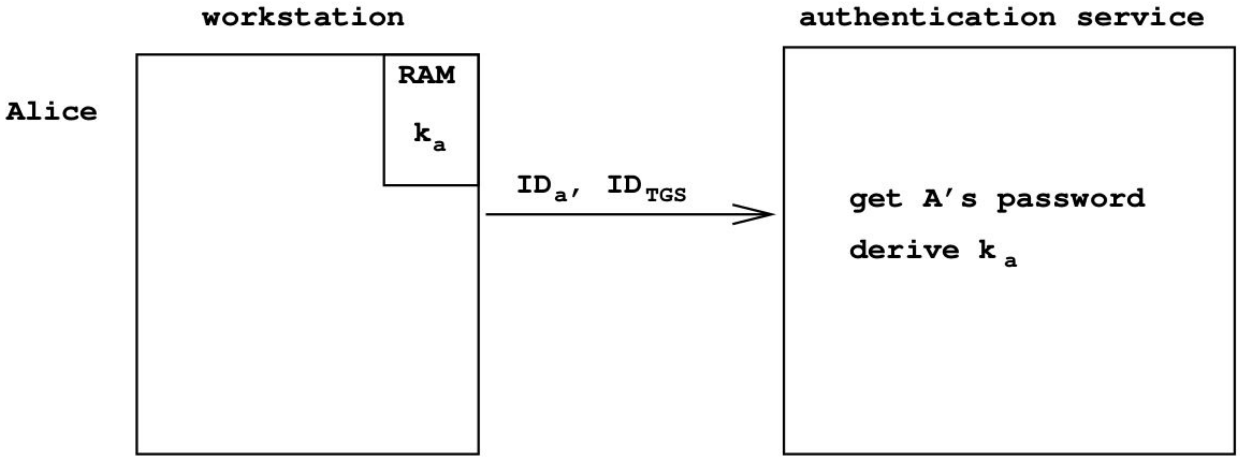

workstation
Alice
enter password
pbkdf
k_a

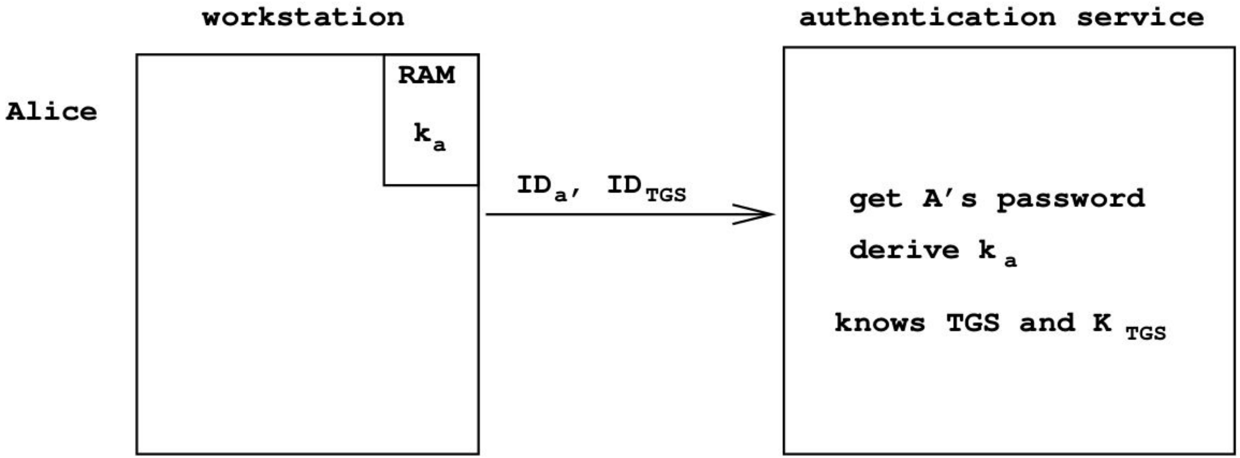

workstation
Alice
RAM
k_a

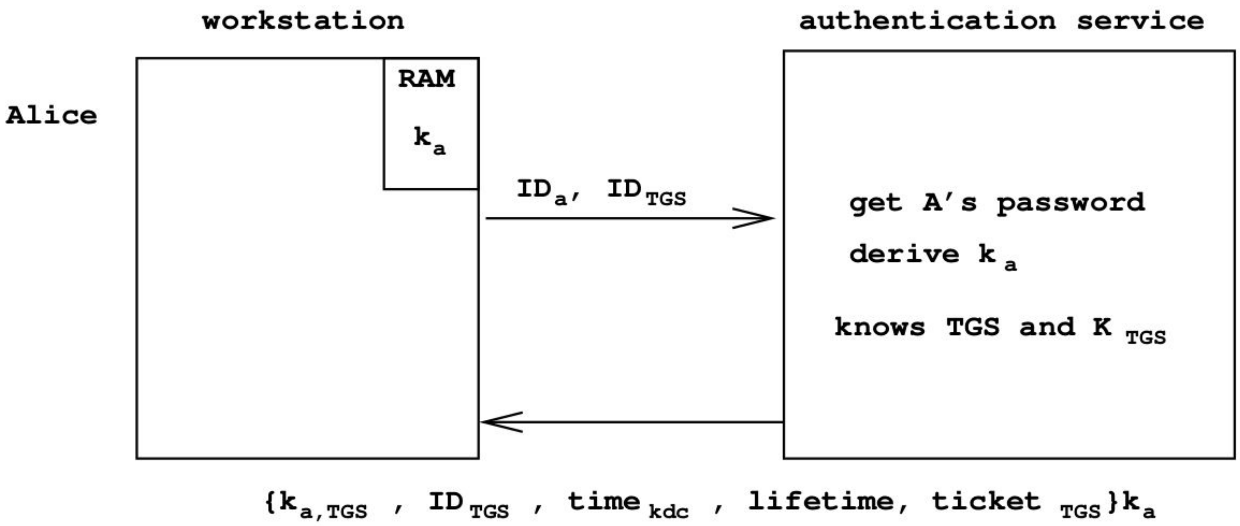

workstation
authentication service
RAM
Alice
k_a
knows all clients
and their passwords

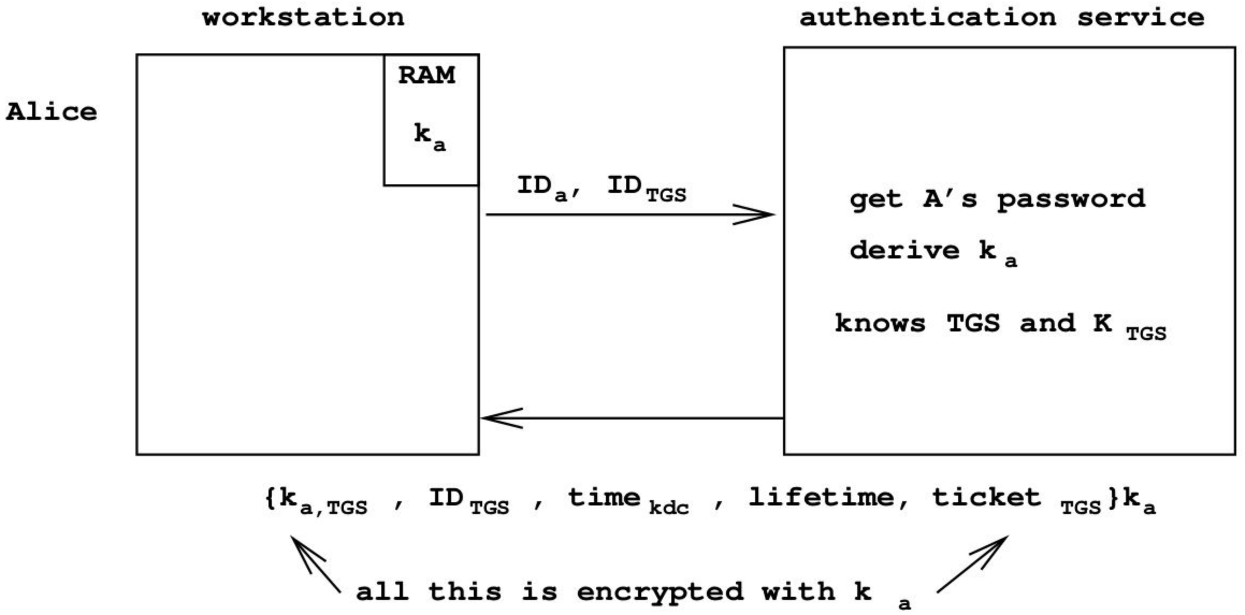

workstation
authentication service
Alice
RAM
k_a
ID_a, ID_{TGS}

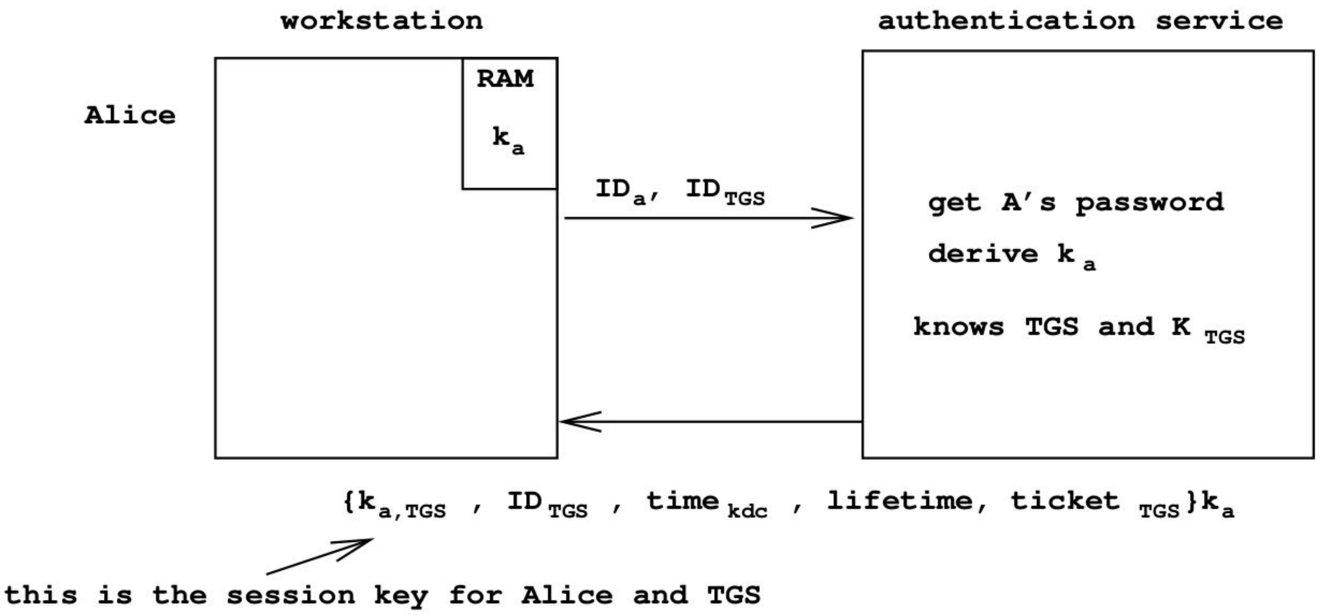

workstation
authentication service
Alice
RAM
k_a
ID_a, ID_TGS
get A's password

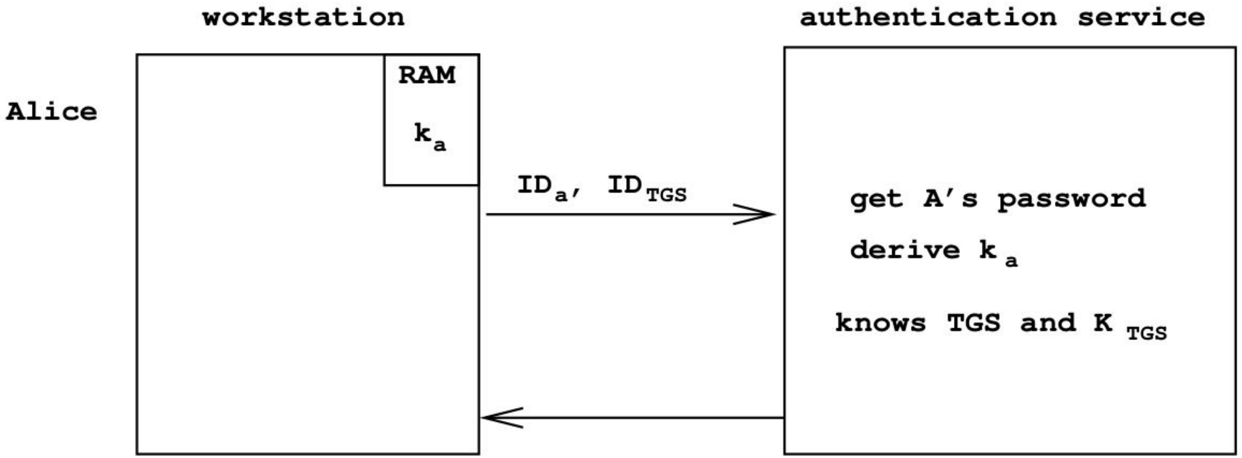

workstation
authentication service
Alice
RAM
k_a
ID_a, ID_{TGS}
get A's password
derive k_a


workstation
authentication service
Alice
RAM
k_a
ID_a, ID_{TGS}
get A's password
derive k_a
knows TGS and K_{TGS}


workstation
authentication service
Alice
RAM
k a
ID a, ID TGS
get A's password
derive k a
knows TGS and K TGS
{k a,TGS , ID TGS , time kdc , lifetime, ticket TGS}k a

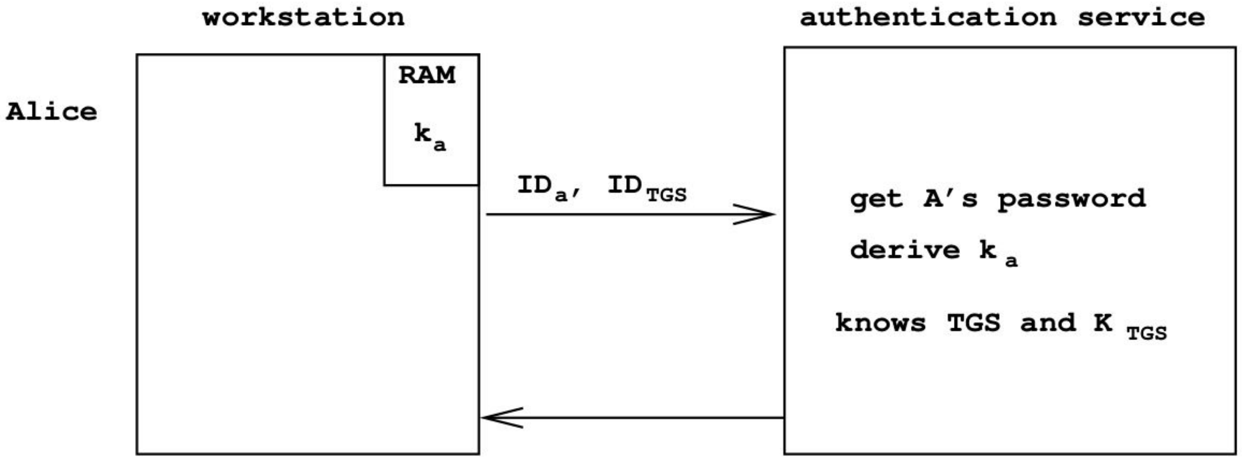

workstation
authentication service
Alice
RAM
k a
ID a, ID TGS
get A's password
derive k a
knows TGS and K TGS
{k a,TGS , ID TGS , time kdc , lifetime, ticket TGS}k a
all this is encrypted with k a


workstation
authentication service
Alice
RAM
k_a
ID_a, ID_{TGS}
get A's password
derive k_a
knows TGS and K_{TGS}
$\{k_{a,TGS}$, ID_{TGS} , $time_{kdc}$, lifetime, $ticket_{TGS}\}k_a$
this is the session key for Alice and TGS



$$\{k_{a,TGS}, ID_{TGS}, time_{kdc}, lifetime, ticket_{TGS}\}k_a$$

$$ticket_{TGS} = \{k_{A,TGS}, ID_A, time_{KCD}, lifetime, ID_{TGS}, addr_A\}k_{TGS}$$

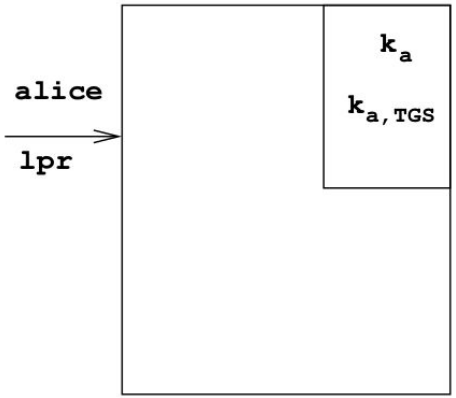


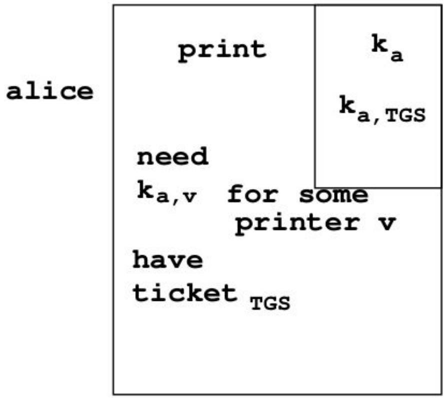
$\{k_{a,TGS}$, ID_{TGS} , $time_{kdc}$, lifetime, $ticket_{TGS}\}k_a$

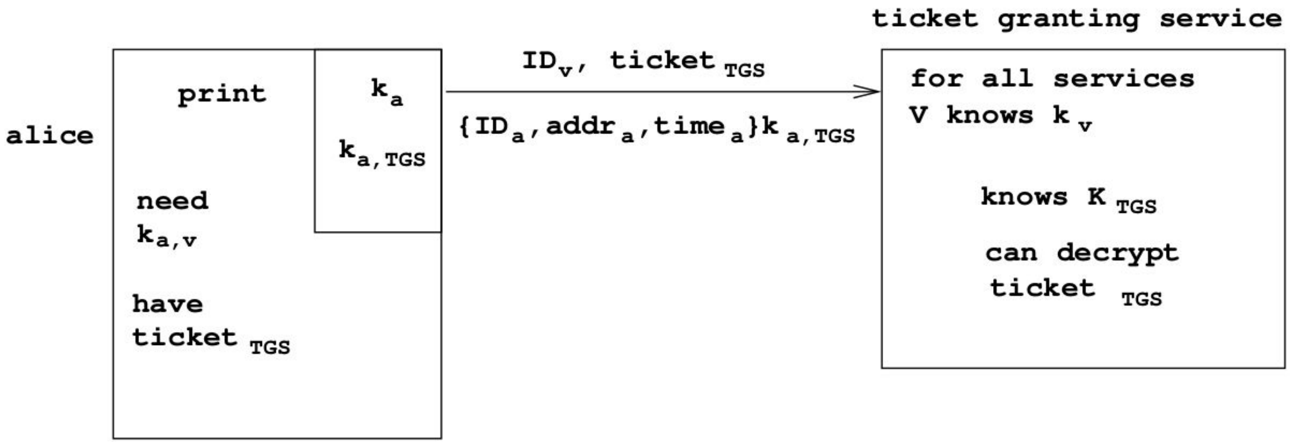
$ticket_{TGS}=\{k_{A,TGS}$, ID_A , $time_{KCD}$, lifetime, ID_{TGS}, $addr_A\}k_{TGS}$

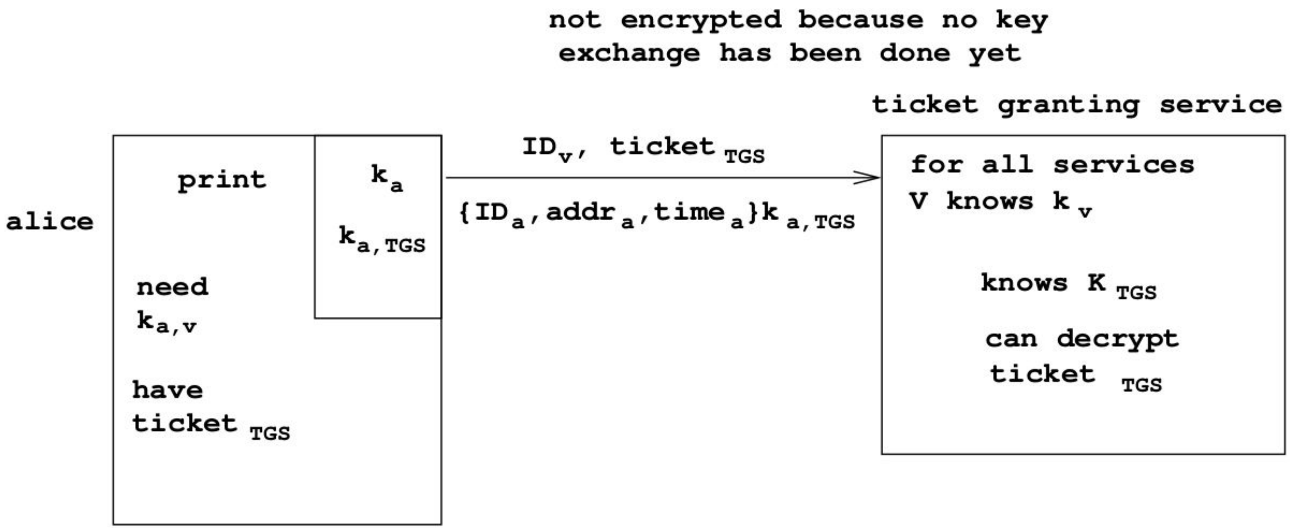
Alice can't understand this, but is expected to deliver it to TGS

alice
wants
to
print

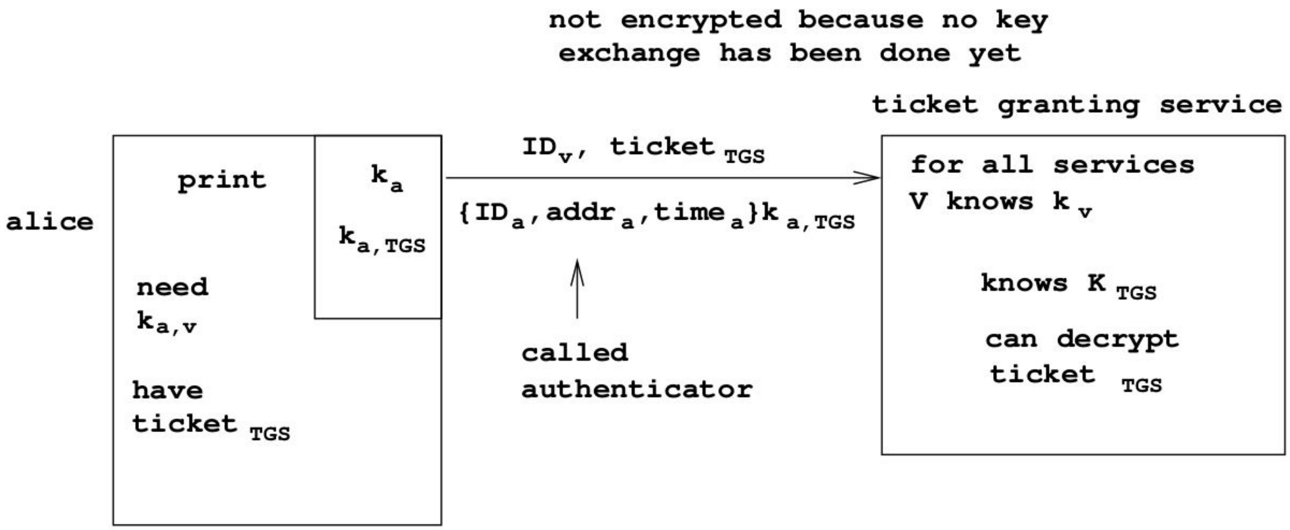

alice
lpr
k_a
$k_{a,TGS}$

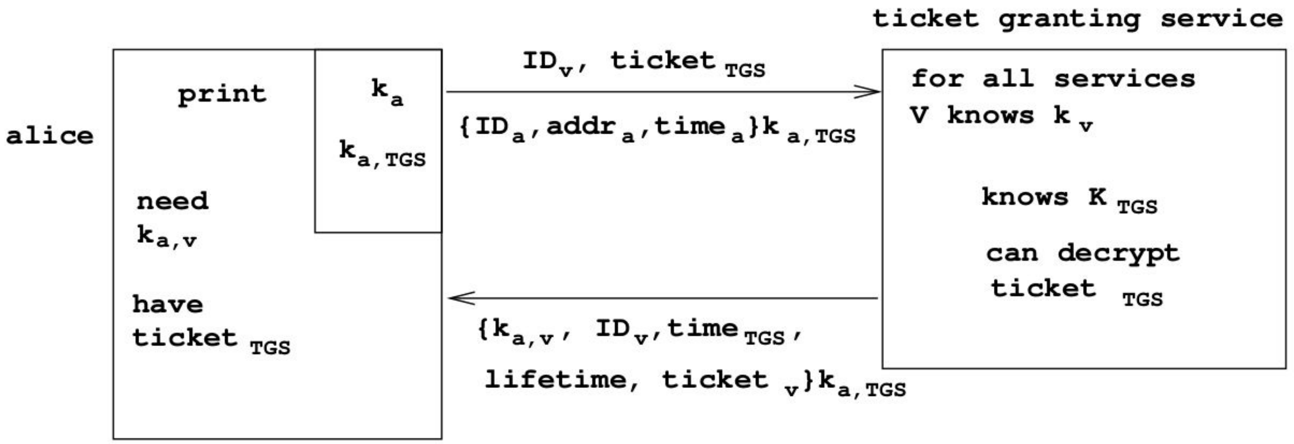

alice
print
k_a
$k_{a,TGS}$
need
$k_{a,v}$ for some printer v
have
$ticket_{TGS}$

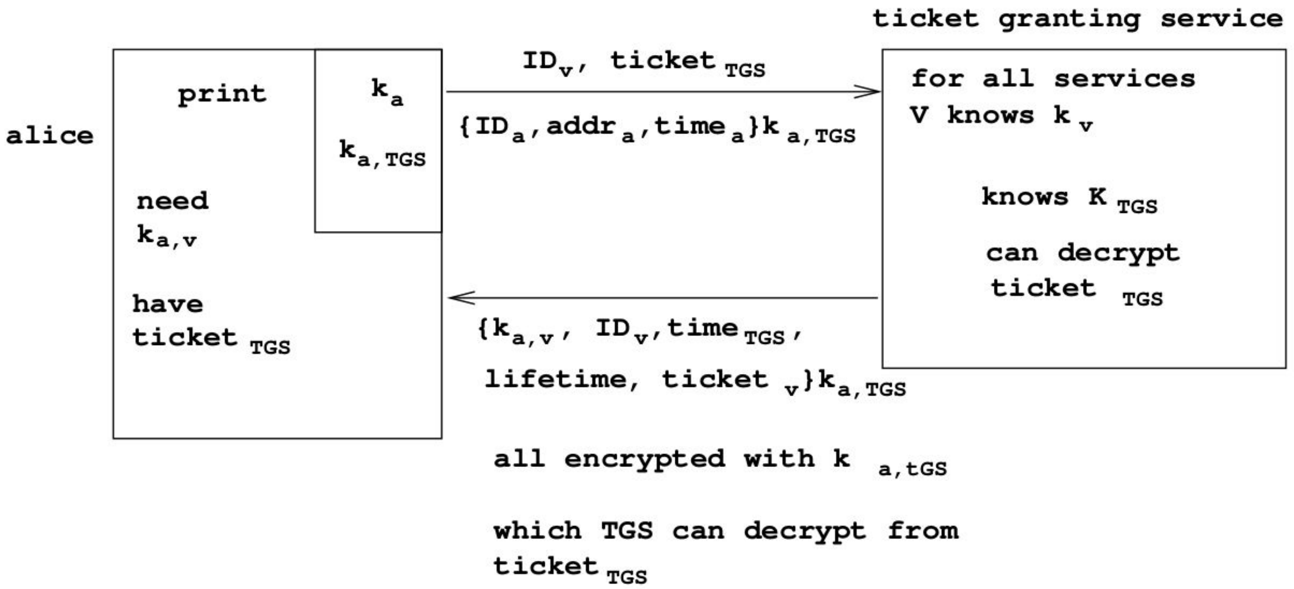

ticket granting service
alice
print
k_a
$k_{a,TGS}$
need
$k_{a,v}$
have
ticket $_{TGS}$
ID_v, ticket $_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services
V knows k_v
knows K_{TGS}
can decrypt
ticket $_{TGS}$

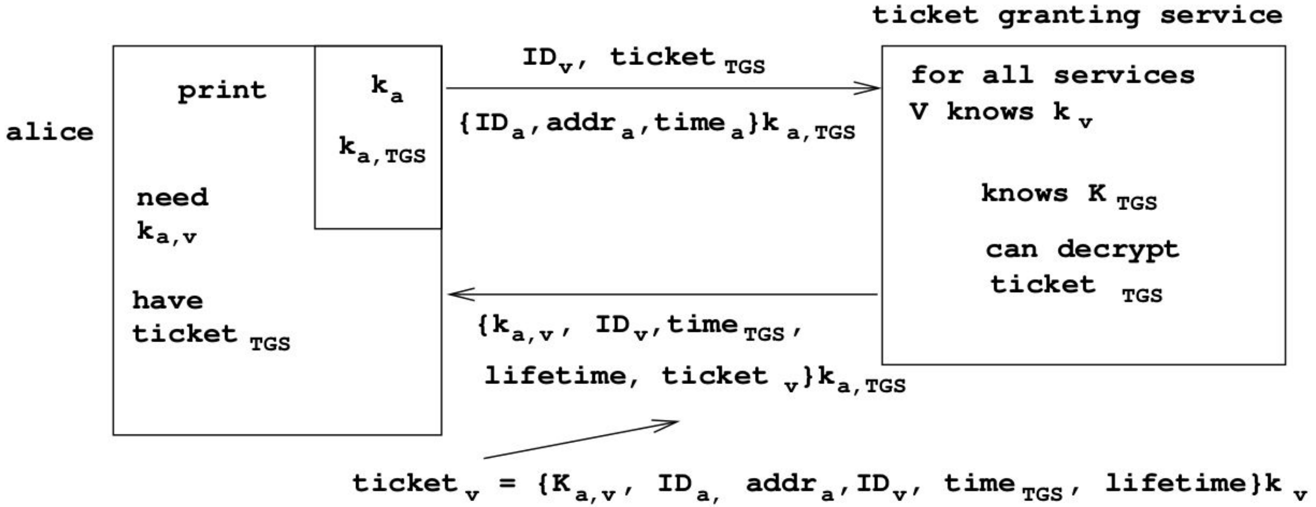


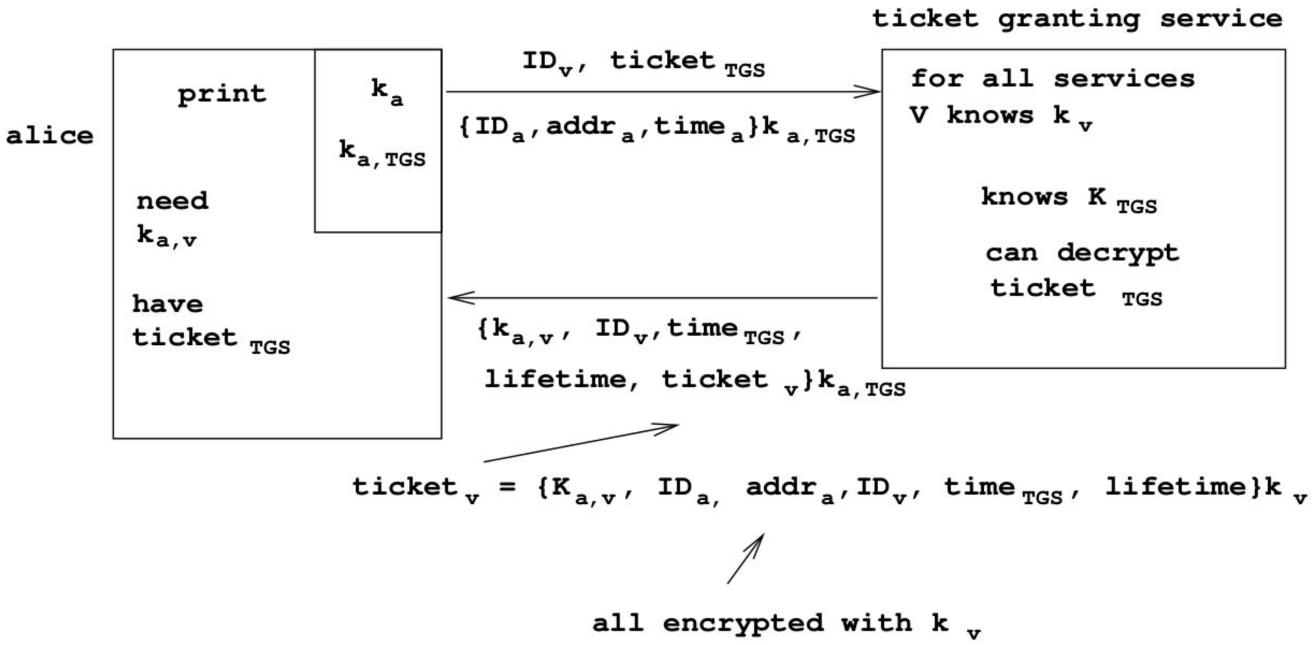
not encrypted because no key
exchange has been done yet
ticket granting service
alice
print
k_a
$k_{a,TGS}$
need
$k_{a,v}$
have
ticket $_{TGS}$
ID_v, ticket $_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services
V knows k_v
knows K_{TGS}
can decrypt
ticket $_{TGS}$


not encrypted because no key exchange has been done yet
ticket granting service
alice
print
k_a
$k_{a,TGS}$
need $k_{a,v}$
have $ticket_{TGS}$
ID_v, $ticket_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
called authenticator
for all services V knows k_v
knows K_{TGS}
can decrypt $ticket_{TGS}$

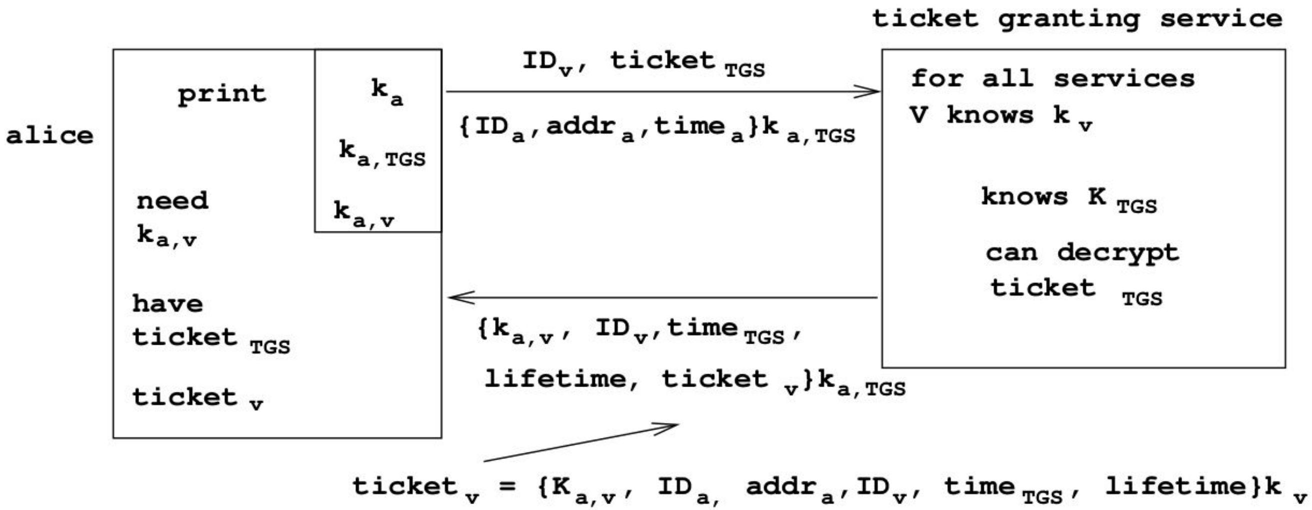

ticket granting service
alice
print
k_a
$k_{a,TGS}$
need
$k_{a,v}$
have
ticket $_{TGS}$
ID_v, ticket $_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services
V knows k_v
knows K_{TGS}
can decrypt
ticket $_{TGS}$
$\{k_{a,v}$, ID_v, $time_{TGS}$,
lifetime, ticket $_v\}k_{a,TGS}$


ticket granting service
alice
print
k_a
$k_{a,TGS}$
need $k_{a,v}$
have $ticket_{TGS}$
ID_v, $ticket_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services
V knows k_v
knows K_{TGS}
can decrypt $ticket_{TGS}$
$\{k_{a,v}$, ID_v, $time_{TGS}$,
lifetime, $ticket_v\}k_{a,TGS}$
all encrypted with $k_{a,tGS}$
which TGS can decrypt from $ticket_{TGS}$

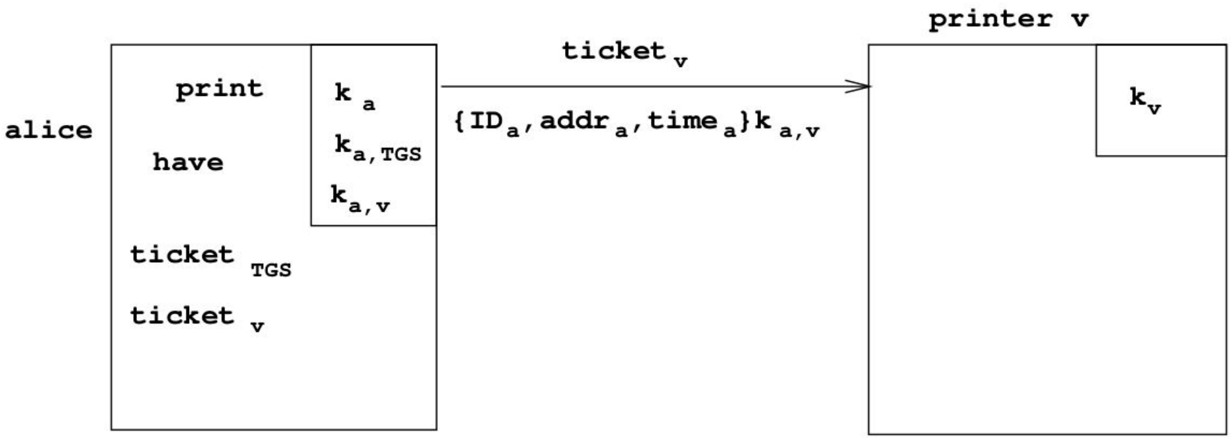

ticket granting service
alice
print
k_a
$k_{a,TGS}$
need $k_{a,v}$
have ticket $_{TGS}$
ID_v, ticket $_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services V knows k_v
knows K_{TGS}
can decrypt ticket $_{TGS}$
$\{k_{a,v}$, ID_v, $time_{TGS}$, lifetime, ticket $_v\}k_{a,TGS}$
ticket $_v$ = $\{K_{a,v}$, ID_a, $addr_a$, ID_v, $time_{TGS}$, lifetime$\}k_v$

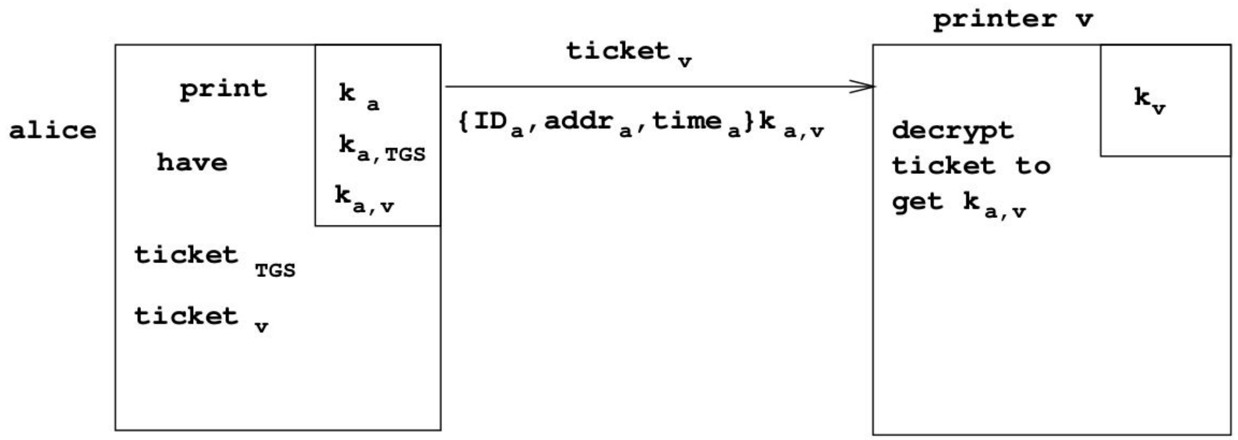


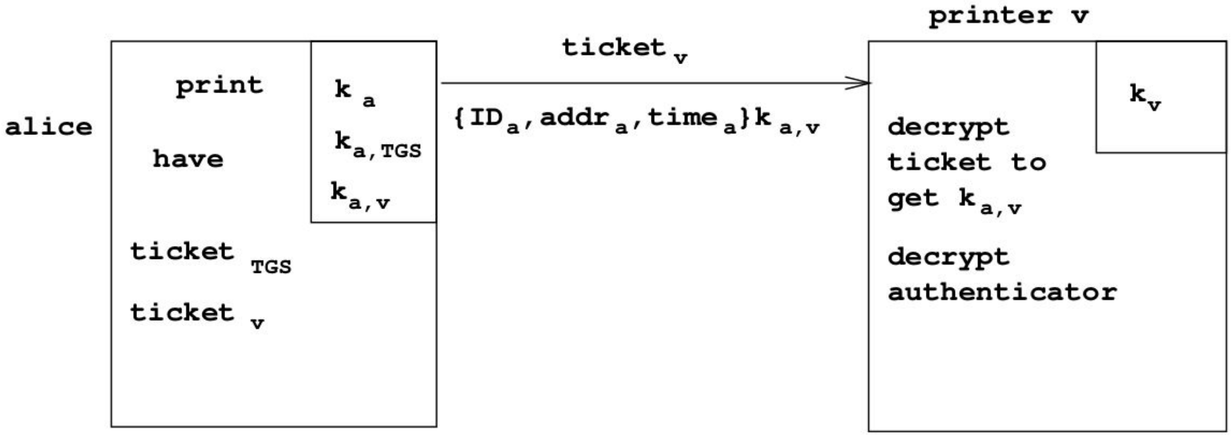
ticket granting service
alice
print
k_a
$k_{a,TGS}$
need $k_{a,v}$
have $ticket_{TGS}$
ID_v, $ticket_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services
V knows k_v
knows K_{TGS}
can decrypt $ticket_{TGS}$
$\{k_{a,v}, ID_v, time_{TGS},$
$lifetime, ticket_v\}k_{a,TGS}$
$ticket_v = \{K_{a,v}, ID_a, addr_a, ID_v, time_{TGS}, lifetime\}k_v$
all encrypted with k_v

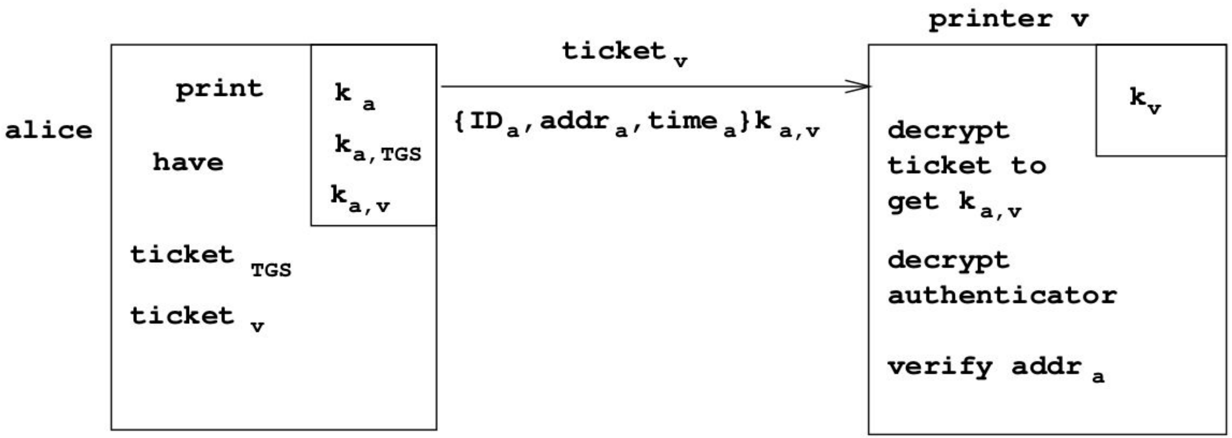


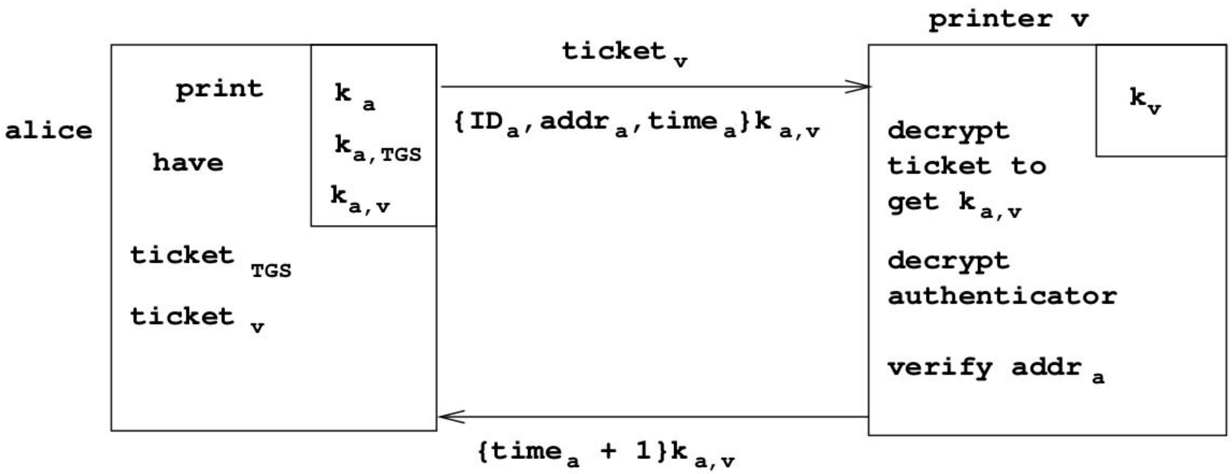
ticket granting service
alice
print
k_a
$k_{a,TGS}$
$k_{a,v}$
need $k_{a,v}$
have ticket $_{TGS}$
ticket $_v$
ID_v, ticket $_{TGS}$
$\{ID_a, addr_a, time_a\}k_{a,TGS}$
for all services
V knows k_v
knows K_{TGS}
can decrypt ticket $_{TGS}$
$\{k_{a,v}, ID_v, time_{TGS}$, lifetime, ticket $_v\}k_{a,TGS}$
ticket $_v$ = $\{K_{a,v}, ID_a, addr_a, ID_v, time_{TGS}$, lifetime$\}k_v$


alice
print
have
k_a
$k_{a,TGS}$
$k_{a,v}$
$ticket_{TGS}$
$ticket_v$
$ticket_v$
$\{ID_a, addr_a, time_a\}k_{a,v}$
printer v
k_v

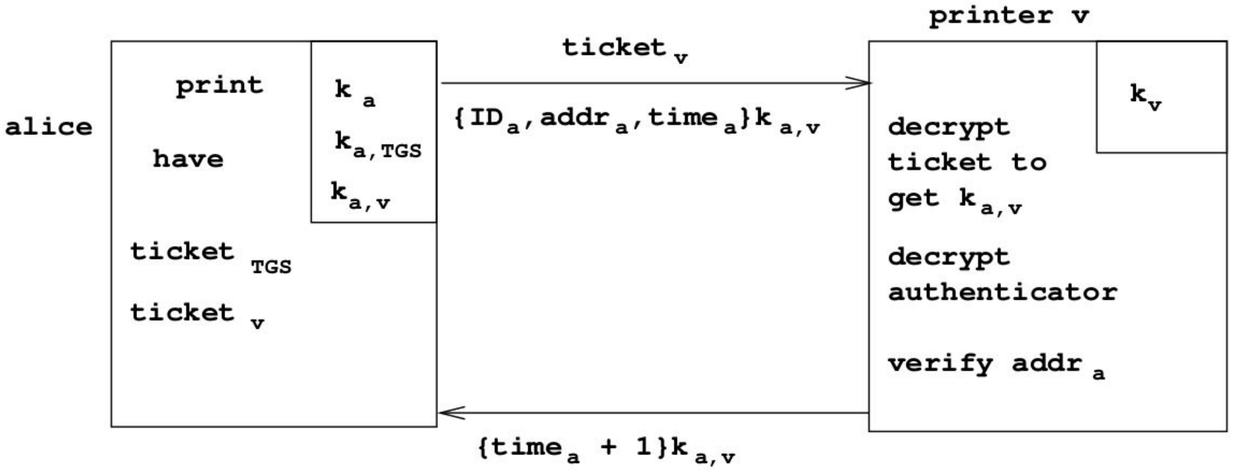

alice
print
have
k a
k a,TGS
k a,v
ticket TGS
ticket v
ticket v
{ID a, addr a, time a}k a,v
printer v
k v
decrypt ticket to get k a,v


alice
print
have
ticket TGS
ticket v
k a
k a,TGS
k a,v
ticket v
{ID a, addr a, time a}k a,v
printer v
k v
decrypt
ticket to
get k a,v
decrypt
authenticator


alice
print
have
k_a
$k_{a,TGS}$
$k_{a,v}$
$ticket_{TGS}$
$ticket_v$
$ticket_v$
$\{ID_a, addr_a, time_a\}k_{a,v}$
printer v
k_v
decrypt ticket to get $k_{a,v}$
decrypt authenticator
verify $addr_a$



printer v
alice
print
have
k_a
$k_{a,TGS}$
$k_{a,v}$
$ticket_{TGS}$
$ticket_v$
$ticket_v$
$\{ID_a, addr_a, time_a\}k_{a,v}$
k_v
decrypt ticket to get $k_{a,v}$
decrypt authenticator
verify $addr_a$
$\{time_a + 1\}k_{a,v}$



compute a non-trivial function on $time_a$ that proves knowledge of $k_{a,v}$ and thereby knowledge of k_v

Kerberos in Large Networks

- one KDC isn't enough
- network is divided into **realms**
  - KDCs in different realms have different key databases
- to access a service in another realm, users must:
  - get a ticket for home-realm TGS from home-realm KDC
  - get a ticket for remote-realm TGS from home-realm TGS
    - i.e., were the remote-realm TGS just a normal home-realm network service
  - get ticket for remote service from that realm's TGS
  - use remote-realm ticket to access service

Important Ideas in Kerberos

- short-term **session keys**
  - long-term secrets used only to secure delivery of short-term keys
  - separate session key for each user-server pair
    - re-used by multiple sessions between same user/server
- symmetric crypto only
  - fast, no expensive operations
- trusted third party
  - new users only need to register a password

Important Ideas in Kerberos

- proof of identity based on **authenticators**
  - client encrypts his identity, addr, time with session key
    - knowledge of key proves client has authenticated to KDC
    - also prevents replays if clocks are globally synchronized
  - server learns this key separately
    - via encrypted ticket that client can't decrypt
    - verifies client's authenticator