

# Robust and Secure Password and Key Change Method

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**Abstract.** This paper discusses issues and idiosyncrasies associated with changing passwords and keys in distributed computer systems. Current approaches are often complicated and fail to provide the desired level of security and fault tolerance. A novel and very simple approach to changing passwords/keys is presented and analyzed. It provides a means for human users and service programs to change passwords and keys in a robust and secure fashion.

## 1 Introduction: Changing One's Password

Much effort has recently gone into securing user access to computer systems over insecure communication lines from untrusted (or partially-trusted) workstations and other end-user devices. In a distributed and dynamic network environment, solutions are often based on the use of a highly-secure and trusted entity called an Authentication Server (AS). An AS processes authentication requests by acting as a trustworthy intermediary. As such, the AS has access to and control over the authenticating secrets of all its principals, be they human users or service programs. (Hereafter, we use the term *principal* to refer to both human users and service programs.)

Typically, a principal's password is a fairly long-term secret, i.e., most principals are not required to change their passwords more often than, say, once a month. When a principal wishes to change its password, an appropriately authenticated exchange with the AS must take place. Obviously, any such exchange must meet some basic security requirements such as resistance to guessing attacks and replays of change-password requests. Another desirable feature is the *correctness* of the change-password protocol. We say that a change-password protocol is correct if it provides a guarantee of state synchronization between the two parties involved (AS and principal) in the presence of possible crashes and network failures.

This last issue is not directly relevant to the protocol security and is thus frequently overlooked or not given enough consideration. However, it has to do

with the robustness and usability of the protocol which is, in the end, an issue of great importance to the end-users.

Supposing that a principal would like to change its password from  $K_{old}$  to  $K_{new}$ , six outcomes of the password change protocol are possible:

	Principal believes its secret is	AS believes principal's secret is
1	$K_{new}$	$K_{new}$
2	$K_{old}$	$K_{old}$
3	$K_{old}$	$K_{new}$
4	$K_{new}$	$K_{old}$
5	$K_{old}$	$K_{unk}$
6	$K_{new}$	$K_{unk}$

The first two outcomes are considered normal and desirable. In the first case, a successful password change takes place, i.e., the AS records the new password and the principal receives the change confirmation. In the second case, the new password is rejected for some reason and the principal is informed.

The rest of the cases represent anomalous situations and must be avoided at all costs. Case 3 may occur when a change acknowledgement is lost or when the AS crashes after making a change but before sending out the acknowledgement. The next situation (case 4) may take place if the acknowledgement is somehow spoofed, i.e., an adversary is able to compose a fake confirmation message.<sup>3</sup> Case 5 is the result of an adversary successfully manipulating the protocol in such a way that the AS changes the principal's key to some value ( $K_{unk}$ ) unknown to or, at least, not intended by, the principal. In fact, case 5 can occur without any activity on the part of the principal; the adversary may simply concoct the entire protocol. Finally, case 6 is very similar to case 5 except that here the principal is actually trying to run the protocol and the adversary not only succeeds in *convincing* the AS to change the principal's password to some  $K_{unk}$ , but also manages to convince the principal that the AS accepted  $K_{new}$ .

In the rest of this paper we review the current state-of-the-art (exemplified by Kerberos) and go on to develop a protocol that is at the same time simple, robust and secure. The protocol is explicitly constructed to handle anomalous behavior (i.e., events that can lead to cases 3-6 above) of the network and arbitrary failures of the components involved.

## 2 The *Kerberos* Approach

One of the most popular network security solutions in use today is the Kerberos Authentication and Key Distribution Server originated at MIT[2] and later integrated in the OSF DCE product[3]. Among its multitude of features, Kerberos

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<sup>3</sup> We do not consider the case when an AS fails to make the change but acknowledges it nonetheless.

includes a change password (CPW) protocol implemented by the `kpasswd` command which is part of the standard Kerberos distribution package. The actual protocol varies slightly between successive versions of Kerberos. The CPW protocol for Kerberos versions 4 and 5, is illustrated in Fig. 2.

The general course of events in Kerberos CPW protocols is as follows (unless noted otherwise, the following description applies to both versions):

1. Initially, the requesting principal engages in an authentication exchange with the AS to obtain credentials for the Admin server. An Admin server, in Kerberos parlance, is a logically distinct entity which is responsible for the maintenance of all information about principals. (In practice, Admin server is almost always co-located with an AS).

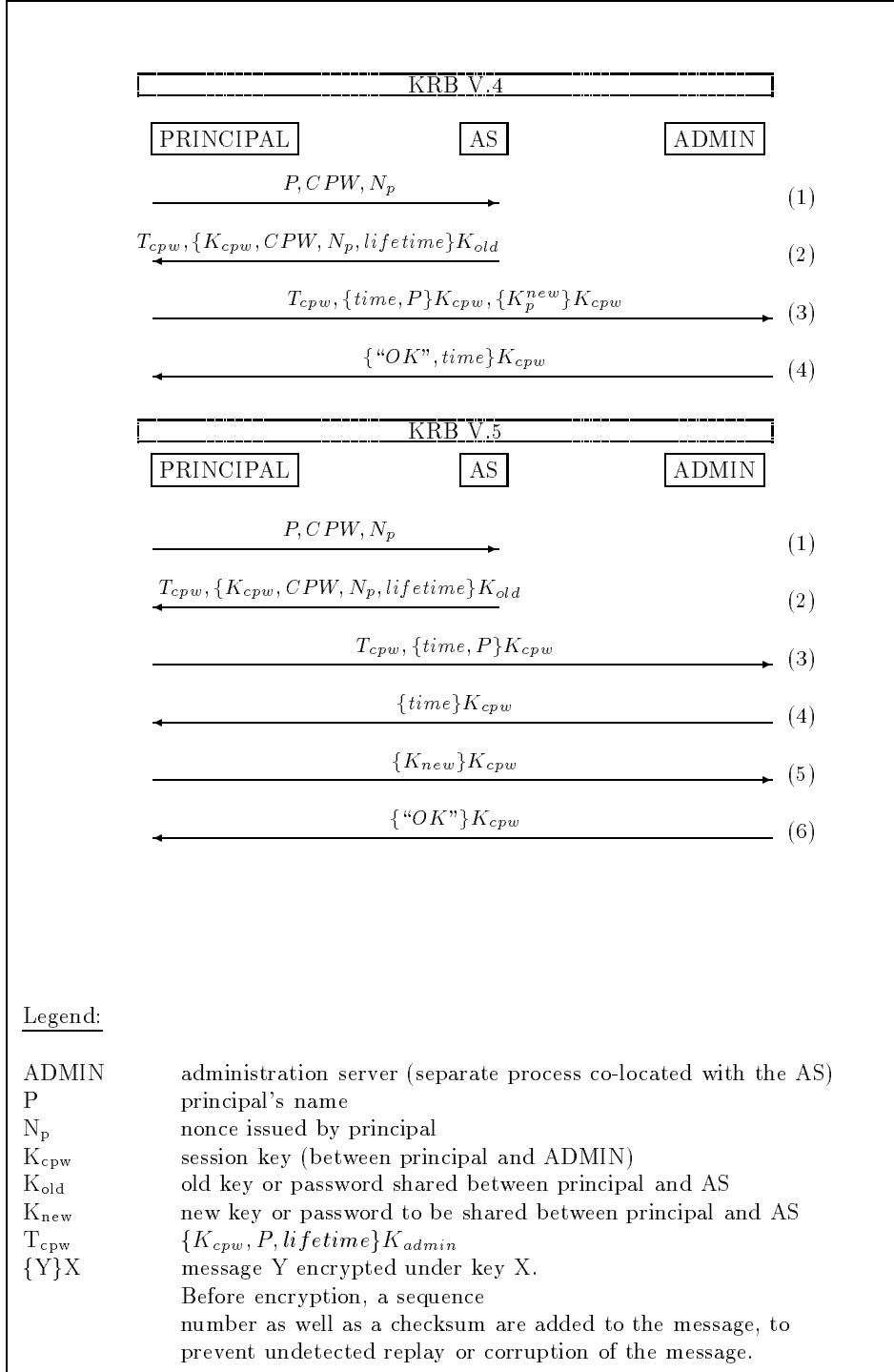
This initial exchange with the AS requires the principal to provide its current password. The credentials obtained consist of a temporary key  $K_{cpw}$  to be shared with the Admin server and a special CHangepw ticket ( $T_{cpw}$ ) with a reasonably short lifetime, typically set to one minute.

2. The second part of the protocol consists of an exchange between the principal and the Admin server. In the course of this exchange, the principal authenticates itself to Admin and sends along the new password, encrypted with the shared key  $K_{cpw}$ . In the version 5 protocol, a complete mutual authentication between principal and Admin takes place before the principal sends its encrypted password; while in the version 4 protocol, the same message carries the principal's authentication and the (encrypted) new password.

### 3 Discussion

The Kerberos CPW protocol is, essentially, capability-based. The capability is embodied in the CHangepw ticket which gives the principal the right to change its password. It *does not* restrict the number of times a principal may do so using the same capability. Thus, in general, a principal can use the same ticket multiple times (of course, as long as the ticket does not expire.) This feature is not a drawback in and of itself but it separates two important events that should ideally go hand-in-hand:

- The verification of the previous state of the principal (i.e., making sure that the principal knows the old key/password)  
and
- The verification of the new state of the principal (i.e., making sure that the new password is actually supplied by the true principal and is acceptable to the Admin server) plus the actual database change.



**Fig. 1.** The Kerberos CPW protocols

As is typical with capability-based approaches, revocation is very difficult if not impossible and is the source of many problems. Of course, a capability tightly bound by time (i.e., one minute in Kerberos) is not as dangerous, but on the other hand, the usual approach of using black-lists to provide for revocation is also not very effective because the assembly and distribution of such a list already might take a significant fraction of this short time.

The existence of the capability-like CHangepw ticket itself is dangerous because Kerberos stores its tickets in special cache files on disk. Within the lifetime of a CHangepw ticket (which is by default a minute) a trojan horse program could create an additional message changing the password to a value unknown to the principal but known to an adversary controlling the trojan horse. A similar problem could occur if the principal left the terminal unattended just after changing the password. Then, an adversary could walk by and, on the victim's behalf, run `kpasswd`. Since there can still be a valid CHangepw ticket cached locally, `kpasswd` could bypass prompting the principal (actually, the adversary) for the old password and use the CHangepw ticket to change the principal's password to anything the adversary chooses. It should be noted, that, in practice, the Kerberos `kpasswd` command promptly destroys the CHangepw ticket upon the completion of the protocol so that the described attack is mainly theoretical.

More often than not, a principal wanting to change its password already obtained a Ticket-Granting-Ticket (TGT) from the AS by going through the initial login procedure. Therefore, a principal already has a strong key that can be used to protect all subsequent communication from, among other things, password-guessing attacks. The Kerberos approach doesn't take advantage of this. Consequently, the Kerberos protocol is susceptible to password-guessing attacks: an adversary, having intercepted the second message of the protocol, can verify a password guess by decrypting the message with the candidate password ( $K_{old}$ ).

Another concern with the Kerberos approach is the number of protocol messages involved. As mentioned earlier, fault tolerance is of utmost importance when it comes to changing one's password. Therefore it is beneficial to minimize the number of protocol exchanges. In Kerberos, four (in version 4) or six (in version 5) messages are needed between the AS/Admin and the principal's end-system. This is a direct consequence of the Kerberos AS and the Admin server being logically distinct entities: the principal has to first authenticate itself to the AS before requesting the actual password change from Admin. As will be described below, it is possible and desirable to reduce the number of messages to just two, by authenticating the CPW request directly with the principal's password (or key) instead of a short-term key.

Perhaps one of the main issues is that in case of a loss of one of the (4 or 6) protocol messages, no algorithm is given to allow for automatic recovery without resorting to off-line means. In particular, if the last (number 4 or 6 depending on the version) protocol message is lost or if the Admin server crashes right

before sending out the last message, the protocol terminates in a state without automatic recovery. In other words, one has to resort to extra-protocol means such as trying to log in anew with, say, the old key and, if that fails, with the new key. Alternatively, one can try to change password once again and hope that the change has not gone through.

Despite the above criticism, Kerberos provides a reasonably workable and secure solution. However, there are several undesirable characteristics where improvement is possible:

- Too many protocol messages
- No provisions for *graceful* recovery in case of message loss and/or component failures
- Vulnerability to password-guessing attacks.

In the next section we try to address these issues. The protocol presented consists of only two messages (request and reply) and allows for automatic recovery from message loss or system failures during execution of the protocol. The basic protocol offers the same degree of security against password-guessing attacks as its Kerberos counterpart. Additionally, a strong key shared between the two parties (e.g. obtained during initial login) can be used to increase the protocol's resistance against this type of attack.

## 4 Solution

*NOTE:* For the sake of uniformity, the term *key* is used in reference to both passwords and keys.

Our approach addresses the following requirements:

- The change request should contain authentication of the sender. In case when the request originates with a human user at a remote workstation, the user must provide old (current) password in order to prevent fraudulent password changes when a workstation is left unattended.
- The request itself must be authenticated, i.e. the AS must be able to establish the integrity of the new key ( $K_{new}$ ) defined in the request.
- The AS has to confirm the outcome of the password change to the requesting principal. The acknowledgement itself must be authenticated.
- The AS must be able to identify retransmissions of previously processed requests and to issue acknowledgments for such retransmissions. This is necessary whenever the original acknowledgement is lost and the principal resubmits the change request. (There is no danger in that as long as the acknowledgements remain identical.)

- An adversary should not be able to gather any useful information from replaying a *stale* request message. This should hold even in the event that the principal makes a serious error of reusing passwords.

## 4.1 Assumptions

The following assumptions are made hereafter:

1. The principal does not start "believing" in  $K_{new}$  until successful completion of the CPW protocol. Of course,  $K_{new}$  is also not used if a negative acknowledgement rejecting  $K_{new}$  is received (e.g., because it is trivial, predictable, or otherwise unacceptable to the AS.)
2. If the CPW protocol does not terminate normally, the principal is capable of remembering the new and old password until the next attempt, i.e., the resumption of CPW protocol. In other words, if something abnormal takes place and the protocol does not complete, the principal does not **abandon** the change; instead the procedure is re-tried at some later time.
3. The AS needs to be no more than *single-state*. In other words, it only has to remember one (current) password per principal and does not have to keep any password history. Furthermore, it has a fairly accurate clock. Fairly accurate means that it is accurate with respect to the frequency of CPWs which happen infrequently, i.e., daily, weekly or monthly, but not every minute or hour.
4. The hosts or workstations (where CPW requests originate) also possess fairly accurate clocks. If not, the principal's wristwatch or wall-clock readings are good enough.
5. It is not taken for granted that the principal shares a strong key with the AS. (Such a key could be obtained during initial login by the principal, and cached locally). However, if such a strong key ( $K_{sso}$ ) is present, it may be used to increase the security of the change-password protocol.

## 4.2 Basics

The basic idea of the protocol is to construct an atomic "flip-flop" request in such a way that a change-key request from principal P to change its key (password) from  $K_{old}$  to  $K_{new}$  can be verified and honored by the AS **independent** of whether the AS knows only  $K_{old}$  or only  $K_{new}$ . In other words, the AS is able to recognize, authenticate and acknowledge a retransmission of the CPW request, even after having discarded  $K_{old}$  and replaced it with  $K_{new}$ . This feature enables the AS and P to resynchronize even in case a positive acknowledgment from the AS is lost or the AS has crashed at an inopportune moment.

If the initial request goes unacknowledged, the principal simply retransmits the request. In this case, the AS knows either  $K_{old}$  or  $K_{new}$  depending on whether it was the request or the acknowledgement that was lost. In any case, the flip-flop construction of the request enables the AS to process the request message correctly regardless of the current state.

As soon as the AS receives a well-formed authentic request, it replies with an acknowledgement. If the AS receives the same request again, the acknowledgement must have been lost, thus the database is left untouched and another acknowledgement (the exact copy of the original one) is re-generated.

The result of this simple protocol is that there may be a temporary uncertainty on the side of the principal as to the current state of the AS, but this requires no action by the principal beyond retransmitting the original request. The principal may do so *ad nauseum* but, eventually, when communication is re-established, the first acknowledgement re-synchronizes the two sides.

### 4.3 Protocol Description

The actual protocol is depicted in Fig. 2. It consists of only two messages. In the first message (REQ\\_CPW), P transmits two tickets to the AS: a ticket  $T(K_{new})K_{old}$  containing the new key  $K_{new}$ , and sealed with  $K_{old}$ ; and a “sanity check” ticket  $T(K_{old})K_{new}$  sealed with  $K_{new}$ , and containing  $K_{old}$ . The ticket expressions are similar to those used in the KryptoKnight Authentication and Key Distribution Service [9]. (See also [7, 8, 6].)

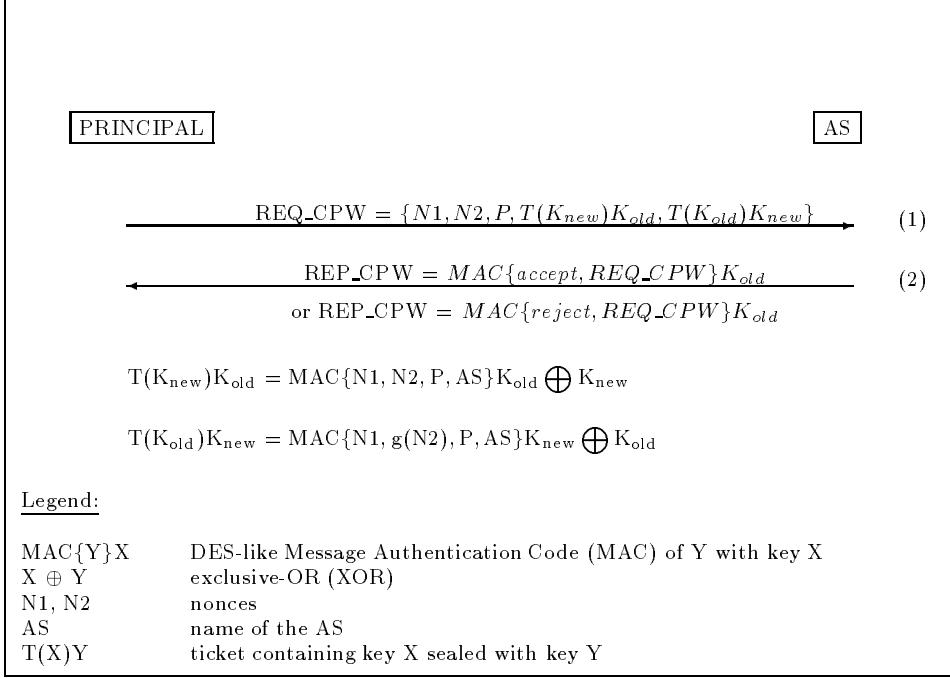
If the request is well-formed and authentic, AS replies with an authenticated acknowledgment REP\\_CPW which can take on two flavors: ACK (*accept*) or NACK (*reject*). The AS generates a NACK if only if  $K_{new}$  is not acceptable for some reason (e.g., predictable password). However,  $K_{new}$  must still satisfy the “flip-flop” property of the REQ\\_CPW. In other words, AS replies (be it with an ACK or a NACK) only if REQ\\_CPW is genuine.

#### 4.3.1 Details of the REQ\\_CPW Message.

As shown in the ticket expression of  $T(K_{old})K_{new}$  in Fig. 2, the function “g” provides for asymmetry between the two tickets in such a way that an adversary cannot swap the two tickets and convince a server to switch back to the old key. We note that “g” must be asymmetric, otherwise manipulation of the plaintext N2 (e.g. reciprocal value or XOR with N1) would re-enable the above swapping attack.

With the above requirement in mind, one possibility is  $g=(x+1)$ . Another one is  $g=\{N2\}K_{new}$ .

If the principal already obtained a strong key  $K_{sso}$  (perhaps during the initial login) then “g” could depend on  $K_{sso}$ . For example we can set  $g=\{N2\}K_{sso}$ . This increases the resistance of the protocol against password-guessing attacks (since



**Fig. 2.** Secure and fault-tolerant CPW protocol

an adversary would have to break  $K_{ss,o}$  before attacking  $K_{old}$  and/or  $K_{new}$ ). Resistance against this type of attack is discussed in more detail in section 5.

The first nonce N1 is chosen at random. In contrast, N2 is set to the current time. This does not require synchronized clocks because the maximum workstation clock-skew is assumed to be smaller than the frequency of key changes. An adversary could still set a workstation's clock to some random time in the future. The AS would reject the REQ\_CPW because of the wrong timestamp, but the adversary could replay it later when the timestamp becomes *ripe*. However, according to the second assumption (in Section 4.1), the principal does not abandon the change but retries at a later time. Eventually, a re-try will be acknowledged by the AS.

All in all, two items provide for AS-principal synchronization:  $K_{old}$  and N2 which represents a timestamp.

#### 4.3.2 Processing REQ\_CPW.

- Having received a REQ\_CPW, the AS first extracts  $K'_{new}$  from  $T(K_{new})K_{old}$ , using  $K_{as}$  – the principal's key currently in the database. (Assuming, so

far, that  $K_{as} = K_{old}$ .)

2. Then, using  $K'_{new}$ , the AS extracts  $K'_{old}$  from  $T(K_{old})K_{new}$ .
3. If  $K'_{old} = K_{as}$ , the AS is assured that it still has the principal's old key and  $K'_{new}$  is the new key intended. AS then stores  $K_{new}$  in the database and sends back a positive acknowledgement, i.e., REP-CPW(accept) the format of which is described below.
4. If  $K'_{old} \neq K_{as}$ , the message could still be a re-try from a principal who didn't receive the original REP-CPW(accept) message for a successful key-change. In this case,  $K_{as}$  would already be the same as  $K_{new}$ .
  - (a) Using  $K_{as}$ , the AS extracts  $K'_{old}$  from  $T(K_{old})K_{new}$ .
  - (b) Using  $K'_{old}$ , the AS extracts  $K'_{new}$  from  $T(K_{new})K_{old}$ .
  - (c) If  $K'_{new} = K_{as}$ , the AS is assured that it already has the new key stored in the database; it then generates REP-CPW(accept) for requesting principal.

#### 4.3.3 Acknowledgements.

Acknowledgments for the following cases must be provided:

- key successfully changed to  $K_{new}$  as a result of either this or some previous REQ-CPW. (In the latter case, the present REQ-CPW is a re-transmission.)
- $K_{new}$  is unacceptable but REQ-CPW is well-formed, i.e., its token structure is correct.

The acknowledgement message has the following form:

REP-CPW = token( $K_{old}$ ) containing [ accept/reject, REQ-CPW ]

This token is an integrity check of the above two components of REP-CPW.

An incorrect or malformed REQ-CPW is one where:

- $K_{old}/K_{new}$  do not satisfy the "flip-flop" structure described above,  
or
- the timestamp represented by N2 is unacceptable, i.e., outside the limits of maximum acceptable clock skew.

Malformed (not authentic) REQ-CPWs are not acknowledged at all. A clear-text error message is a possible alternative. However, any kind of authenticated acknowledgment in response to an incorrect REQ-CPW is out of the question. This is because doing so would require using the principal's current stored key

which would present an opportunity for a known plaintext attack (the AS would become an *oracle*, see [4]). Therefore, the mechanism on the principal's side must at least provide for an error message which after a certain number of unanswered REQ-CPW (timeout) checks for the general availability of the AS and suggests resorting to off-line means for re-synchronization.

Obviously, the acknowledgment (REP-CPW) must be protected. If it is not protected by a strong integrity check, an adversary could trap the original REQ-CPW, prevent it from reaching the AS and convince the principal that the change has taken place. The key used to protect REP-CPW can be any of:  $K_{new}$ ,  $K_{old}$  or  $K_{sso}$ . However, if  $K_{sso}$  is used, the previous flow, REQ-CPW, must additionally contain the ticket with  $K_{sso}$ . One problem with using  $K_{new}$  is when the AS rejects  $K_{new}$  for some reason (e.g., weak key) it cannot very well use the same key it just rejected to compute the integrity check. Therefore,  $K_{old}$  must be used in this case. Alternatively, for the sake of uniformity and simplicity,  $K_{old}$  can be used in all cases (i.e., ACK or NACK).

## 5 Some Remarks on the Security of the Proposed Protocol

In addition to the threats already addressed in the protocol description above, the following possible attack on the basic protocol must be considered: if the adversary eavesdrops on a REQ-CPW, the "flip-flop" feature allows for an off-line key-search attack. This attack is possible because the very same structure of REQ-CPW that allows the AS to verify  $K_{new}$  and  $K_{old}$  allows the adversary to verify its guesses by iterating through the key space. While less of a concern when changing a strong key (e.g. a server master key), the exposure is especially a problem when  $K_{old}$  and  $K_{new}$  are (weak) user passwords.

The protocol can be made more secure by involving  $K_{sso}$  in the function "g": an attacker would have to break  $K_{sso}$  before attacking  $K_{new}$  and/or  $K_{old}$ .

Clearly, if the initial login itself is vulnerable to password-guessing attacks, this enhancement only closes the smaller of two holes (login, which is executed far more often, being the bigger one), and thus hardly increases the overall security of a user's password.

However, whether or not the password was exposed at login, it is not exposed in addition by a  $K_{sso}$ -protected password change. This feature can provide significant additional security when combined with a login method which itself is secure against password-guessing attacks (e.g. [5]).

## 6 Protocol Correctness

In this section we analyze the correctness of the proposed protocol.

## 6.1 Assumptions

To aid in our analysis, the following assumptions are made:

- **Assumption 1:** The principal generates a different key at every execution of the change password protocol. Therefore the password history has no cycles. An execution of CPW means a protocol run until successful completion or synchronization by out-of-band means.
- **Assumption 2:**  
Each message will be received after a finite number of retransmission attempts.
- **Assumption 3:**  
To simplify the proof of correctness, we will assume that the AS only sends positive acknowledgments (*rejected* requests are not acknowledged).

## 6.2 Idealized Protocol

Before we proceed to the formal analysis we need an idealized and formal representation of the protocol.

### Idealized representation of the protocol:

The protocol consists of two communicating state machines U and AS depicted in Fig. 3, that respectively represent the behavior of the change password program on the principal’s side and the behaviour of the AS in response to the presented change password protocol.

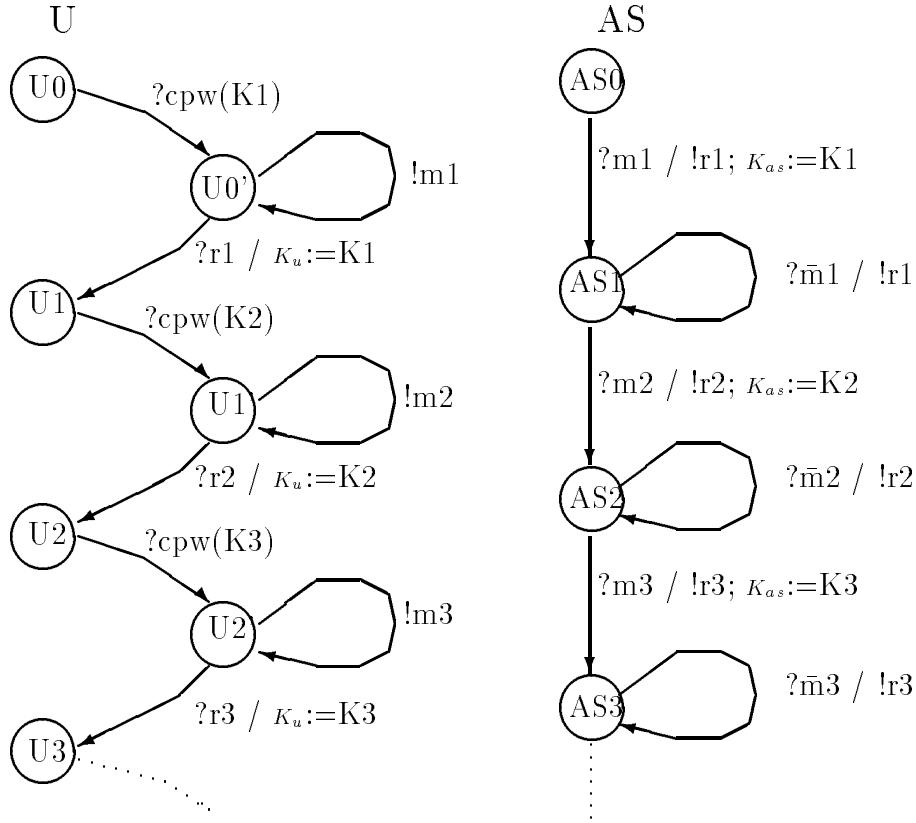
#### Notation:

- Since each key generated by the principal is different from all the ones that were previously generated (Assumption 1), the keys form a *totally ordered set*

$$K = \{K_0, K_1, K_2, \dots\}$$

whereby  $K_i$  is generated before  $K_j$  if  $i < j$  or, equivalently,  $K_i$  is the last key generated before  $K_{i+1}$ .

- $U_i$  is the *stable state* of U characterized by the knowledge of  $K_i$  as the current key.
- $U'_i$  is the *transient state* of U corresponding to the transition from state  $U_i$  to state  $U_{i+1}$ .
- $AS_i$  is the state of AS characterized by the knowledge of  $K_i$  as the current key representing the principal.
- $!m$  represents the sending of message m.



**Fig. 3.** Idealized CPW protocol

- $?m$  represents the receipt of message  $m$ .
- $:=$  denotes the assignment operation.
- $K_u$  is the state variable of U that represents the current key.
- $K_{as}$  is the state variable of AS that represents the current key.
- $cpw(K_i)$  is the command entered by the principal that triggers a password change operation on U. The old password is  $K_i$  and the new one is  $K_{i+1}$ .
- $m_i$  is the REQ\_CPW message where  $K_{old} = K_i$  and  $K_{new} = K_{i+1}$
- $mbar_i$  is the REQ\_CPW message, a retransmission from the AS's point of view, where  $K_{new} = K_{i+1}$  and  $K_{old}$  can take any value.

- $r_i$  is the positive (*accept*) response to  $m_i$ .

### 6.3 Properties of the Idealized Protocol

Owing to its message structure, the protocol has the following properties:

**Property 1:**

$AS_i$  can correctly determine the transition (the loop or the transition to the next state) to be executed because  $AS_i$  can always tell apart  $m_i$  from  $m_{i+1}$ . When  $AS_i$  receives a message  $m$ , it can identify the message as  $m_i$  if  $K_{old} = K_{as}$  and as  $m_{i+1}$  if  $K_{new} = K_{as}$ . This property is based on Assumption 1 and on the structure of REQ-CPW's which distinguishes the "new" key from the "old" one. In other words,  $K_{new}$  can never be mistaken for  $K_{old}$  and vice versa.

**Property 2:**

With the knowledge of  $K_i$ ,  $AS_i$  can always extract the new key  $K_{i+1}$  ( $K_{new}$ ) contained in message  $m_{i+1}$ .

### 6.4 Analysis

**Goal:**

Now we can show that, using this protocol, the principal and the AS will always (eventually) agree on the same key and that there will never be a deadlock situation even in the presence of message losses and replay attacks.

**Basic Idea :**

We will first show the single step correctness of the protocol, that is, if the principal and the AS both are in a state where both "know" the same key, and the principal triggers the password change protocol, then the following events take place:

- the protocol terminates after a finite period of time.
- after the termination of the protocol, both the principal and the AS will have replaced the old key with the new key provided by the principal.

**Initial Equilibrium:**

A complete proof of the protocol correctness requires that the system start in a *good* initial state, i.e., the combination of the states of the principal and the AS when both are *initialized* with the same key.

**Single step correctness:**

Let's assume that U is in state  $U_i$ , that AS in state  $AS_i$ , that they both consider  $K_i$  as the current key and that the principal enters cpw( $K_{i+1}$ ),

- **the protocol terminates:** because of Assumption 2 there will eventually be a pair of messages  $m_{i+1}$  and  $r_{i+1}$  that will be received (by AS and principal, respectively) after a finite number of retransmissions. After protocol termination U will reach state  $U_{i+1}$  and AS the state  $AS_{i+1}$ . Any

transition of U to a state other than  $U_{i+1}$  and any transition of AS to a state other than  $AS_{i+1}$  are excluded because of Property 1.

- **after protocol termination U and AS will have replaced the old key with the key provided by the principal:** The value of  $K_u$  in state  $U_{i+1}$  can only be  $K_{i+1}$  since this is assured by the good behaviour of the program independently of the communication between U and AS. By definition  $m_{i+1}$  contains  $K_{i+1}$  in the position of the new key and by virtue of property 2 AS<sub>i</sub> can extract  $K_{i+1}$  from  $m_{i+1}$  and assign its value to  $K_{as}$ . Thus AS also knows  $K_{i+1}$  in state  $AS_{i+1}$ .

The correctness proof is still valid when we take into account the effect of a *crash* on the side of either the principal or the AS. If the principal's end-system crashes in a transient state  $U'_i$  between state  $U_i$  and  $U_{i+1}$  the principal needs only to restart the protocol by entering cpw( $K_{i+1}$ ) ( $K_{old} = K_i$  and  $K_{new} = K_{i+1}$ ) in order to properly terminate the single step execution of the protocol. If the AS crashes, assuming that its non-volatile memory is crash-proof (otherwise there would be no recovery at all), and if the duration of the crash and recovery is comparable to a period of retransmissions from the principal's point of view, the crash has the same effect as the loss of a message and the protocol has been shown correct in the presence of failures and message losses. If the crash and recovery takes a very long time, the change password command will abort and the principal must restart from state  $U_i$  as in the case of the crash at the principal's side, but this is still considered to be only *one* protocol run and the principal must stick to  $K_{new} = K_{i+1}$  since the server might have updated the password database before the crash.

## 7 Summary

The proposed protocol is based on a single and atomic challenge/response exchange. The possibility of atomic re-tries provides for a level of robustness and security that is not possible with current protocols. The advantages of the proposed key change mechanism can be summarized as follows:

1. The protocol is resistant to replay attacks due to the asymmetric flip-flop property of the token construction in REQ-CPW.
2. Unlike traditional authentication protocols, the messages in CPW do not need to contain an explicit challenge (timestamp or nonce) to demonstrate their freshness and to counter replay attacks. This property is a result of the logical temporal order provided by the sequence of keys and the robustness of the protocol messages. Because of the inherent strong synchronization on keys that the protocol provides, replay detection can be based on the sequencing of keys.

3. The protocol offers protection against walk-by-attacks whereby a previously authenticated principal leaves the workstation unattended.
4. Optionally, the protocol can permit recycling of keys without being susceptible to replay. By using a timestamp as one of the "nonces", the key sequence can be roughly anchored in time without requiring secure time-services. This is because the timestamp has to be *fresh* only with respect to the relatively low frequency of password changes.
5. The protocol can be resumed after a system crash on the side of either the AS or the requesting principal.
6. Last, but not least, the protocol is compact both in number of messages and individual message sizes, and it requires very few cryptographic computations.

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