On The Limitation of Some Fully Observable Multiple Session Resilient Shoulder Surfing Defense Mechanisms

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Abstract
Using password based authentication technique, a system maintains the login credentials (username, password) of the users in a password file. Once the password file is compromised, an adversary obtains both the login credentials. With the advancement of technology, even if a password is maintained in hashed format, then also the adversary can invert the hashed password to get the original one. To mitigate this threat, most of the systems now a days store some system generated fake passwords (also known as honeywords) along with the original password of a user. This type of setup confuses an adversary while selecting the original password. If the adversary chooses any of these honeywords and submits that as a login credential, then system detects the attack.

A large number of significant work have been done on designing methodologies (identified as MDSOA) that can protect password against observation or, shoulder surfing attack. Under this attack scenario, an adversary observes (or records) the login information entered by a user and later uses those credentials to impersonate the genuine user. In this paper, we have shown that because of their design principle, a large subset of MDSOA (identified as MFODSOSA) cannot afford to store honeywords in password file. Thus these methods, belonging to MFODSOSA are unable to provide any kind of security once password file gets compromised. Through our contribution in this paper, by still using the concept of honeywords, we have proposed few generic principles to mask the original password of MFODSOSA category methods. We also consider few well established methods like S3PAS, CHC, PAS and COP belonging to MFODSOSA, to show that proposed idea is implementable in practice.

Keywords: Fully observable methods, Shoulder surfing attack, Honeyword, Password, Security.

1. Introduction
Password based authentication remains as one of the most dominant forms of identity verification since last few decades [Hayashi and Hong, 2011]. However, this scheme is found to be vulnerable under different types of attack [Alsaleh et al., 2012] [Kirda and Kruegel, 2006] [Ortolani et al., 2013] [Pinkas and Sander, 2002]. Inversion attack is one such lately developed attack model on the password based schemes which threats its security standard to a great extent [Weir et al., 2009] [Gaylord, 2012].

Inversion attack: Once the password file (identified as FP: on Unix systems the file FP might be /etc/passwd or /etc/shadow) gets compromised, an adversary may found that the passwords are either

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maintained in plaintext or, in the hashed format. If the passwords are stored in plaintext, then the adversary can directly impersonate all the users. Even if the passwords are maintained in hashed format, then also the adversary may conduct guessing attack to invert (i.e., deriving \( P \) from \( H(P) \): where \( H(P) \) denotes a hashed password) those. Initially, to break a password, brute force attack was conducted by guessing many possible combinations. But the time complexity of brute force search technique used to be very high as an attacker tried for every possible option to crack a password. In 2008, proposed algorithm by John the Ripper significantly reduced the complexity of password guessing process compared to the brute force search technique (John the Ripper 2008). In 2009, using the concept of probabilistic context free grammar, Weir et al. were able to crack 28% – 129% more passwords than John the Ripper password cracking algorithm (Weir et al. 2009). Recently, based on Markov chain model, modern password crackers further improve the inversion rate (Ma et al. 2014).

Evidence: There are some strong evidence of inversion attack in the recent past. In 2013, almost 50 million passwords of Evernote were compromised under this attack model (Gross 2013). Giant web based organizations like LinkedIn, Yahoo, RockYou have gone through the same misery (Gaylord 2012). Thus, there was urgency in developing an authentication technique which can address this attack. Till date, Honeyword Based Authentication Technique (HBAT) is the best known approach which mitigates this threat to a great extent (Juels and Rivest 2013).

HBAT framework: In HBAT framework, along with the original password, a system maintains another \( k-1 \)(\( k \geq 2 \)) dummy passwords for each user’s account. These system generated dummy passwords are also known as honeywords. The original password and the honeywords are collectively known as sweetwords. All these sweetwords are very close to each other, but they are not exactly the same. Let the username and password of a user be \( alex \) and \( alex1992 \), respectively. Then the system may maintain the following list of \( k \) (considered as 6 here) sweetwords against the username \( alex \).

\[
\begin{align*}
\text{alex1990} & \quad \text{alex1994} & \quad \text{alex1991} \\
\text{alex1992} & \quad \text{alex1995} & \quad \text{alex1993}
\end{align*}
\]

The index of the original password (here 4, starting from 1), along with username (\( alex \)), is maintained in another file in a different server, known as honeyChecker.

Therefore, under the HBAT framework, an adversary gets confused among \( k \) (> 1) sweetwords by looking at a compromised \( F_P \). In order to login successfully, an adversary needs to guess the original password correctly from the list of \( k \) probable options. This yields probability of selecting the correct password as \( 1/k \).

HBAT threat detection strategy: Let us assume that the guessed and the submitted password by the adversary belongs to the \( t^{th} \) (\( 1 \leq t \leq k \)) index position in the list of \( k \) sweetwords. From the password submitted by the adversary, system then retrieves the index position (here \( t \)) of the password. Along with the username, the index value is then communicated to the honeyChecker. For the targeted username, if the received index value gets matched with the stored one, the honeyChecker then sends a positive feedback signal to the system administrator otherwise, sets off a security alarm by detecting the security breach.

In a nutshell, by maintaining a list of \( k \) sweetwords against each user’s account, the success probability of an attacker to crack the original password is reduced to \( 1/k \). As HBAT maintains the password information in two different servers, thus it provides a distributed security framework which is harder to compromise as a whole (Kontaxis et al. 2013) (Juels and Rivest 2013).

Motivation and Contribution: Most of the recent researches indicate that along with the original passwords, there is a clear need of maintaining the honeywords in \( F_P \) (Juels and Rivest 2013) (Erguler 2016). But we have found that a large set of defense schemes (identified as MFODS) that provide security against strong observation attack (or strong adversary) in fully observable environment (see detailed in Section 2.1) require a direct referral to the original plaintext password for authenticating a legitimate user.
Hence to avoid confusion in selecting the original password from the set of *sweetwords* during authentication, these methods cannot afford to store *honeywords* in $F_P$.

Mainly motivated by this, we have made the following major contributions in this paper.

- **Contribution 1**: We analyze the working principle of $M^{FODS}_{SOA}$ category methods in detail and show why migration to *honeyword* based scheme is not immediate for a method belonging to this class.

- **Contribution 2**: To fill the security gap, we propose few generic principles and show that by following those, *honeywords* can be incorporated to any method belonging to $M^{FODS}_{SOA}$ class.

- **Contribution 3**: We consider few well known approaches (e.g., S3PAS [Zhao and Li, 2007], CHC [Wiedenbeck et al., 2006], PAS [Bai et al., 2008] and COP [Asghar et al., 2010]) of $M^{FODS}_{SOA}$ class and show – by following the proposed principles, how HBAT can be incorporated to those to materialize the proposed idea.

**Roadmap**: The rest of the paper is organized as follows. Section 2 gives a quick overview of observation attack and classifications of defense strategy. This section also includes a detail analysis to show that with existing setups, why methods belonging to $M^{FODS}_{SOA}$ class cannot afford to store *honeywords* in $F_P$. Followed by this, Section 3 introduces the proposed password masking strategy to guard the original password of $M^{FODS}_{SOA}$ category methods. Section 4 then elaborates the security and usability parameters of *honeyword* based approaches which help in determining the overall security and usability standard of a method belonging to $M^{FODS}_{SOA}$ class after incorporating the HBAT framework. Section 5 shows how the proposed password masking strategy to $M^{FODS}_{SOA}$ class can be implemented in practice. Finally, the paper is concluded in Section 6 by identifying an open problem in this direction.

2. Identifying The Gap In $M^{FODS}_{SOA}$

Likewise inversion attack, the threat of shoulder surfing can also significantly affect the security standard of password based schemes. Due to increase in activities of shoulder surfers, in 2002, the International Standard for PIN Management (ISO 9564) mandates that a PIN entry device should be installed in such a manner so that it can prevent *shoulder surfing attack* (SSA) [Report, 2002]. While performing SSA, to obtain the login credentials, an adversary can either record the submitted login information with the help of some recording device (e.g., conceal camera) or, may simply look at the screen/keyboard by standing next to the user. Later, she may use that obtained login credentials to impersonate the genuine user. Depending on the equipments used by an adversary to conduct SSA, the eavesdropper can be classified into following two categories.

- **Strong adversary** uses some recording devices (e.g., conceal camera) to monitor, intercept and analyze each part of a login session [Matsumoto and Imai, 1991] (Asghar et al., 2010).

- **Weak adversary** relies upon her limited cognitive skills and performs the attack without using any equipment [Roth et al., 2004] [Kwon et al., 2014].

It is important to note here that if the observation attack is conducted by a strong adversary then it is refereed as strong SSA [Bai et al., 2008]. On the other hand, weak adversary is responsible for performing the weak SSA only [Kwon et al., 2014]. Methods belonging to $M^{FODS}_{SOA}$ class build security against strong eavesdropper.

2.1. Defense strategy and its classifications

**Defense Strategy**: Many methodologies have been developed that can provide security against SSA. In this literature, we identify all these methods as $M^{DS}_{SOA}$. The $M^{DS}_{SOA}$ follow a challenge (C) response (R) protocol to avoid the attack. Password (P) can be considered as a shared secret between the user and system. From a set of finite elements, the system first generates a challenge and communicates it to the user. Based on
the challenge and password, the user then derives a response and sends it back to the system. Thus, $R$ can roughly be thought of as: $R = f(C, P)$. The challenge in each session gets vary and as a consequence, response in each session also gets changed. Therefore without knowing the original password and, just by seeing the passive key entry, it becomes hard for the adversary to derive the actual password.

**Classifications of method:** Based on how the challenge is being communicated to a user, $M^\text{PODS}_{OA}$ can be classified into two categories. The first variation is known as *Partially Observable Defense Scheme (PODS)*, where the generated challenge by the system is covertly communicated (may be with the help of an earphone) to the user [Perković et al., 2009] [Lee et al., 2016]. All methods belonging to this category are identified as $M^\text{PODS}_{OA}$. The covert channel in PODS is always assumed to be secure. Thus all the methods belonging to $M^\text{PODS}_{OA}$ category assume that except the user, no one can access to the challenge.

In the latter variation, known as *Fully Observable Defense Scheme (FODS)*, the challenge is communicated to the user by using an overt medium [Asghar et al., 2010] [Bai et al., 2008]. We identify all the methods belonging to this class as $M^\text{FODS}_{OA}$. Therefore, the challenge in $M^\text{FODS}_{OA}$ can be accessed by all.

As challenge in PODS is always assumed to be conveyed through a secure channel (between the prover and verifier), thus, in spite of using all the recording gadgets, an adversary fails in retrieving the communicated challenge. This in turn resists the adversary to derive the original password from the recorded response only. Therefore, all the methods belonging to $M^\text{PODS}_{OA}$ category are capable of defeating the strong adversary.

In contrast, as challenge is overtly communicated by the methods of $M^\text{FODS}_{OA}$ class, thus an adversary may look at it with/without using a recording device. Hence existing literatures further classify the methods of $M^\text{FODS}_{OA}$ class into two categories – (a) $M^\text{FODS}_{OA}$ against strong adversary [Bai et al., 2008]. We identify this as $M^\text{FODS}_{OA}$ and, (b) $M^\text{FODS}_{OA}$ against weak adversary [Kwon et al., 2014]. These methods are identified as $M^\text{FODS}_{WOA}$.

From the above discussion it is quite intuitive that methods which can defeat strong adversary are also capable of defeating the weak adversary too, but vice versa is not true. In Figure 1 and Table 1, we have shown a pictorial overview of the classifications and meaning of the notations related to categorization of methodologies, respectively.

![Figure 1: Classification of defense mechanisms against SSA.](image)

Remaining of this section unfolds in the following manner:

- First, we describe the working principle of both $M^\text{PODS}_{OA}$ and $M^\text{FODS}_{WOA}$ and show why methods belonging to these classes are capable of storing *honeywords* with the original password in $F_P$.

- Followed by this, we elaborate on how the authentication procedure is carried out by the methods belonging to $M^\text{FODS}_{OA}$ and show why migration to HBAT is not immediate for these methods.
### Table 1: Related notations for categorization of methods

| Notation   | Meaning                                                                 |
|------------|-------------------------------------------------------------------------|
| M\textsuperscript{PODS}\textsubscript{OA} | All the defense schemes against observation attack                       |
| M\textsuperscript{PODS}\textsubscript{OA} | Partially observable defense scheme against observation attack           |
| M\textsuperscript{FODS}\textsubscript{OA} | Fully observable defense scheme against observation attack               |
| M\textsuperscript{FODS}\textsubscript{SOA} | Fully observable defense scheme against strong observation attack        |
| M\textsuperscript{FODS}\textsubscript{WOA} | Fully observable defense scheme against weak observation attack           |

#### 2.2. Authentication process of M\textsuperscript{PODS}\textsubscript{OA} and M\textsuperscript{FODS}\textsubscript{WOA}

In Figure 2, we have shown the **authentication procedure of M\textsuperscript{PODS}\textsubscript{OA}**. Let P be the shared secret between a user and the system and, this is maintained in $F_P$ by the system. In a session, let the user assumes $P^*$ as her original secret and performs login based on this assumed token. From the challenge C in that session, the user then generates her response R by using a method $f(P^*, C)$ (ref. to Figure 2). From the submitted R and with the help of C, the verifier then becomes able to generate the same token $P^*$ (utilized for generating the R) by using a method $g_P(C, R)$. Here $g_P()$ indicates a generator function, used by the verifier to generate the token (here $P^*$) which has been used by the prover in forming the response. The verifier then checks for a match between the $P^*$ and the original P. If both P and $P^*$ get matched, the verifier then allows the login otherwise, denies the prover.

![Figure 2: Authentication procedure of M\textsuperscript{PODS}\textsubscript{OA}](image)

Except the fact that the system securely communicates a challenge, **authentication procedure of M\textsuperscript{FODS}\textsubscript{WOA}** follow the same working principle as of M\textsuperscript{PODS}\textsubscript{OA}. Methods belonging to this class work on the assumption that an adversary is not allowed to use any computational/recording device to derive the $P^*$ from $g_P(C, R)$. Thus for M\textsuperscript{FODS}\textsubscript{WOA} category methods, the function $g_P()$ is designed in such a manner so that reverse computation of $P^*$ from $g_P(C, R)$ falls beyond the capacities of limited human cognitive skills [Kwon et al., 2014].

**Feasibility of incorporating the honeywords:** From the above discussion, it is understandable that if a user provides her response with reference to a secret then with the help of the communicated challenge, system can uniquely derive that secret from the submitted response. Let both M\textsuperscript{PODS} and M\textsuperscript{FODS} support the HBAT framework where the login information of a user is maintained in the following manner.

\[
F_P: \quad P_1, P_2, ..., P_k
\]

\[
honeyChecker: \quad t
\]
where \( P_i \) denotes a password maintained at \( i^{th} \) index and, \( P_t \) and \( t (1 \leq t \leq k) \) correspond to the original password and index position of the original password, respectively.

From the compromised \( F_P \), if the eavesdropper gets this list (\( P_1, P_2, \ldots, P_k \)) and guesses \( P_i \) \((1 \leq i \leq k)\) as the original password, then from the submitted response by the attacker, the system will uniquely be able to derive that \( P_i \) by using the generator function \( g_P() \). This in turn makes system understand that the login has been performed by using the secret stored at \( i^{th} \) index. System then communicates this index value to the honeyChecker and follows the normal HBAT authentication routine to detect the threat. This infers that both \( M_{\text{PODS}}^{\text{OA}} \) and \( M_{\text{WOA}}^{\text{FODS}} \) can readily support HBAT to reinforce their security standard.

2.3. Authentication process of \( M_{\text{SOA}}^{\text{FODS}} \)

Methods fall under this category are designed to defeat the strong adversary where the challenge is overtly communicated over an insecure channel. The adversary here may use recording gadgets to monitor, intercept and analyze each part of an authentication session. Therefore, if authentication procedure in \( M_{\text{SOA}}^{\text{FODS}} \) follow the same path as of \( M_{\text{SOA}}^{\text{PODS}} \) (or \( M_{\text{WOA}}^{\text{FODS}} \)) then from the recorded challenge \( C \) (communicated by the system) and the response \( R \) (submitted by user), the adversary can easily derive the original password uniquely by using the same function \( g_P(C,R) \). Hence, \( M_{\text{SOA}}^{\text{FODS}} \) follow a different strategy to defeat the powerful adversary. In Figure 3 we have shown the authentication procedure followed by \( M_{\text{SOA}}^{\text{FODS}} \) category methods.

![Figure 3: Authentication procedure in \( M_{\text{SOA}}^{\text{FODS}} \)](image)

Like PODS, after receiving the challenge, the user generates a response in the similar fashion. To validate the response provided by the user, a different method namely, \( g_F(P,C) \) is used by \( M_{\text{SOA}}^{\text{FODS}} \). Below we gist characteristic of the generator function \( g_F() \)

- As inputs, it takes the original secret of user (\( P \)) maintained in \( F_P \) and the challenge (\( C \)) communicated by the system.

- From those inputs, it generates a set of probable response elements. The set may contain a single (e.g., COP described in Section 5.4) or multiple elements (e.g., S3PAS described in Section 5.1). We identify this as response set \( R_S \).

If the submitted response by user belongs to \( R_S \) then only \( M_{\text{SOA}}^{\text{PODS}} \) allows the login. From the response submitted by the user and the communicated challenge by the system, an adversary always derives multiple probable secrets and hence cannot derive the original secret uniquely before recording a certain number (> 1) of authentication sessions (or challenge-response pairs).
To defeat a strong adversary for more number of authentication sessions, most of the existing methods of MSOA class follow complex login strategies. Therefore to explain the working principle of MFSOA with an example, we have designed a hypothetical approach which holds all properties of MFSOA category methods though follows a simple authentication procedure.

**Hypothetical FODS (an example):** Let a set of 36 elements (digits and alphabets) be used to design the hypothetical method. The user selects an alphanumeric password of length 4 for authentication. In a session, all the 36 elements from the alphanumeric set are randomly arranged in a 6 × 6 matrix and are displayed on the login screen. This matrix acts as a challenge in this hypothetical system and in Figure 4, we have shown one instance of this.

![Visual interface of the hypothetical method belonging to MFSOA class.](image)

We assume that an authentication session in this hypothetical system be of 4 login rounds. In order to give response to a challenge, in each login round, the user first selects two consecutive characters of her password (in a cyclic manner) and locates those characters on the matrix. Then user connects those two characters by means of a virtual line and selects a character belonging to that line as response.

Let the password chosen by the user be 6YJC. Therefore in order to generate the responses, the user selects 6Y in the first round, YJ in the second round, JC in the third round and C6 in the last round. System also selects the password by parts to generate the RS with reference to the challenge matrix shown in Figure 4. For example, in the first round, as both M and W belong to the straight line connecting 6 and Y, thus, system forms the RS as \{M, W\} in the first round. In other words, gF() returns the response set as \{M, W\} in the first round. To pass the first authentication round, the user may enter either of these elements as response. The login procedure for remaining rounds follow the same path with changes in the elements of RS and the user response.

2.4. **Identifying the gap**

The discussion from the previous section infers that methods belonging to MFSOA class require a reference to the original password to build the response set RS which in turn validates the submitted response by a user. Let a method of MFSOA class supports HBAT framework and, maintains \(k - 1\) (\(k > 1\)) honeywords along with the original password in FP.

Now, to conduct an authentication session, system first generates a challenge. Thereafter, in order to generate the RS, the function gF() requires both communicated challenge and the original password. Though gF() can readily avail the challenge, but gets confused among \(k\) sweetwords while selecting the original password for formation of RS. As output of gF() changes with change in any of its parameters, thus selecting any honeyword instead of the original password will produce a different response set which may deny the correct response of a legitimate user. To avoid such confusion – in distinguishing the original password from the set of honeywords, any method belonging to MFSOA class cannot afford to support HBAT.

It is very important to note here that though each sweetword will generate a different RS with respect to a fixed challenge, but there may exist some overlapping among the elements of RS. For example, for
two different *sweetwords* 6Y and LF, the generated $R_{S}$ with respect to the challenge shown in Figure 4 will be [M, W] and {5, M}, respectively. This shows that though generated $R_{S}$ are different for two different *sweetwords*, but they share a common element $M$.

2.5. Out of scope threat

We do not attempt to address password compromise due to SSA by an adversary who already obtains the password file. Even if the original password is guarded by the *honeywords*, by seeing the response, the adversary will always identify the original password. Building a defense mechanism which can address such attack is an open problem till date.

3. Proposed Password Masking Strategy

As we discuss the authentication procedure of $M_{\text{FODS SOA}}$ category methods under the light of a hypothetical scheme in Section 2.3, most of the existing schemes of $M_{\text{FODS SOA}}$ class display the challenge on the login terminal (Yan et al., 2015). In order to generate the response, user then finds appropriate clue from the challenge with reference to her original password. To verify the submitted response, system first generates a set of valid responses ($R_{S}$) with reference to the challenge and the original password of the user. If the provided response by the user belongs to $R_{S}$ then system validates the user otherwise, denies the login.

While identifying the existing security gap of the methods belonging to $M_{\text{FODS SOA}}$ class in Section 2.4, we have made a very important point there. Though there may exist some overlapping, but with reference to a challenge, each *sweetword* creates a different $R_{S}$. The core of this contribution is mainly influenced by this. As function $g_{F}()$ in $M_{\text{SOA}}$ takes two parameters (password and challenge) to generate the $R_{S}$, therefore in order to fit $k−1$ *honeywords* in $M_{\text{FODS SOA}}$, we will adopt the following strategy.

- System first selects $k$ different *sweetwords* in such a manner so that given any of some particular challenges, they are capable of generating $k$ mutually exclusive (non-overlapping) $R_{S}$ by using the generator function $g_{F}()$.
- With respect to those *sweetwords*, system then generates a challenge in such a way so that produced $R_{S}$ by each of $k$ *sweetwords* are mutually exclusive.
- As response sets are mutually exclusive, thus, if provided response element by a user belongs to a particular $R_{S}$ then that will not be a member of any other $R_{S}$.
- Therefore, from the response submitted by the user, system can uniquely identify the corresponding $R_{S}$, which in turn makes system understand the corresponding *sweetword* responsible for creating that $R_{S}$.
- Finally, with reference to the index of that *sweetword*, by communicating with the *honeyChecker*, system can detect the breach.

As above method looks promising for incorporating the *honeywords* to the methods belonging to $M_{\text{FODS SOA}}$ class, thus we have identified few factors (e.g., selection of *honeywords*, principle behind generating the challenge) that will play a crucial role to materialize this concept.

3.1. Principles for generating the challenge and honeywords

Let the algorithm used by the $M_{\text{SOA}}$ (without incorporating *honeywords*), for carrying out the authentication procedure be denoted by $A$. With the existing setup, therefore $A$ only generates a single $R_{S}$ with reference to a visual challenge and the password maintained in $F_{P}$. But to adopt the HBAT framework, a visual challenge should be generated in such a manner so that $k$ *sweetwords*, with reference to the visual challenge, can form $k$ mutually exclusive (or non-overlapping) $R_{S}$. Hence to support HBAT, some modifications are required to $A$. We identify the modified algorithm as $A^{+}$. Formation of $k$ non-overlapping $R_{S}$
is mainly driven by two components – the visual challenge and sweetwords. In this section, we mainly focus on how these two collaborate to incorporate HBAT framework in $M^{FODS}_{SOA}$. 

During the discussion of the working principle of $M^{FODS}_{SOA}$ category methods under the light of a hypothetical system in Section 2.3 we show that system (and user) may consider a substring of the password to conduct each round of an authentication session. Let for a password of length $\ell$ ($>0$), a method of $M^{FODS}_{SOA}$ class takes $lr$ ($>0$) login rounds to complete an authentication session. Next, we define two important factors that play very crucial roles in incorporating HBAT to $M^{FODS}_{SOA}$ category methods.

**Definition 1: Partial Password Information:** Partial password information or PPI is the smallest sub part of the password accepted by $g_F()$ to conduct each round of an authentication session.

For a password of length $\ell$, the length of PPI may vary between 1 and $\ell$. For example, $g_F()$ in S3PAS (Zhao and Li, 2007) always accepts a PPI of length lesser than $\ell$ whereas, $g_F()$ in COP (Asghar et al. 2010) accepts the whole password as PPI.

**Definition 2: Partial Response Set:** The response set returned by the $g_F()$, which accepts a PPI and the challenge as parameters, is identified as partial response set or PRS.

For example, for the PPI as $6Y$, the $g_F()$ of the hypothetical system in Section 2.3 will return the PRS as $\{M, W\}$ with reference to the visual challenge shown in Figure 4.

**Note 1:** The basic motivation behind modifying the $A$ to $A^+$ is to incorporate HBAT framework to $M^{FODS}_{SOA}$. With $A^+$ running at back end, let us assume that a method belonging to $M^{FODS}_{SOA}$ class is maintaining $k$ sweetwords. In the $i^{th}$ round, let PPI and PRS corresponding to the $j^{th}$ ($1 \leq j \leq k$) sweetword be denoted as $PPI^j_i$ and $PRS^j_i$, respectively. With reference to the challenge $C$, $g_F(PPI^j_i, C)$ then returns $PRS^j_i$ in the $i^{th}$ round. Now, for $k$ mutually exclusive PRS in each round, if submitted response by a user always belongs to a PRS, formed by the PPI of $t^{th}$ sweetword, then a method of $M^{FODS}_{SOA}$ class understands that the user has performed login against the $t^{th}$ sweetword.

**Note 2:** Generating a visual challenge which will form $k$ mutually exclusive PRS in each round may not be a feasible solution as this may consume a huge amount of time. Therefore, a more feasible solution will be to generate a visual challenge in such a way that can generate $k$ mutually exclusive PRS at least in a single round. Based on this, we first propose the following principle.

**Principle 1:** During authentication, a method belonging to $M^{FODS}_{SOA}$ class should maintain $k$ ($\geq 2$) sweetwords in such a manner so that at least in a round (say $i^{th}$ round: where $1 \leq i \leq lr$), $A^+$ will generate a visual interface (challenge) on which $PRS^1_i, PRS^2_i \ldots PRS^k_i$ will be mutually exclusive.

**Discussion 1:** This principle infers how challenge should be generated by $M^{FODS}_{SOA}$ category methods. According to the above principle, except in a particular round, say $i$, generated $k$ PRS by the PPI of sweetwords may get overlapped. Therefore, except in $i^{th}$ round, system may find that provided response by a user is belonging to multiple PRS. But in the $i^{th}$ round, if the submitted response belongs to $t^{th}$ ($1 \leq t \leq k$) PRS (formed by the $t^{th}$ PPI) then that must not belong to any other PRS. Not only in $i^{th}$ round, but response in each round if maps to a PRS formed by the $t^{th}$ PPI, then only the system considers that the login has been performed against $t^{th}$ sweetword. The system then directs the index value $t$ (along with username) to the honeyChecker server and performs normal HBAT routine to detect the breach.

Other than the visual challenge, the selection strategy of sweetwords are equally important for incorporating the HBAT framework to $M^{FODS}_{SOA}$ as $g_F()$ takes both the challenge and sweetword as inputs to carry out an authentication session. Therefore, next principle focuses on how the sweetwords are needed to be
chosen by a method of $M_{SOA}^{FODS}$ class.

**Principle 2:** Not only the sweetwords, but in each round, PPI of the sweetwords must also be different.

**Discussion 2:** Let $6YJC$ and $6YM5$ be the two sweetwords maintained by the hypothetical system belonging to $M_{SOA}^{FODS}$ (ref. to Section 2.3). Though these two sweetwords are different, but PPI of those in the first round are same (i.e., $6Y$). Now if the $A^+$ randomly chooses first round to generated 2 non-overlapping PRS then it would not be possible as both the PPI are same. Thus for an algorithm, dynamically selects a round to generate $k$ mutually exclusive PRS, must follow the above principle while selecting the sweetwords.

During incorporation of HBAT framework to $M_{SOA}^{FODS}$, the value of $k$ plays a major role to protect the original password. As $k$ increases, it creates more confusion in a attacker’s mind. Thus we state the following principle which guides any method of $M_{SOA}^{FODS}$ class for choosing a suitable value of $k$.

**Principle 3:** Number of sweetwords (i.e., value of $k$) varies depending on a method belonging to $M_{SOA}^{FODS}$ class and it varies between 2 and number of all possible responses.

**Discussion 3:** Let the number of all possible responses that can be generated by a user be $Z(\geq 2)$. Let the number of average response elements belonging to each PRS be $E(\geq 1)$. If $k$ PRS in a round are capable of covering all the response elements, then the following equation stands

$$k = \frac{Z}{E} \quad (1)$$

Now as value of $Z$ varies depending on a method of $M_{SOA}^{FODS}$ category (e.g., $Z = 94$ for S3PAS (Zhao and Li, 2007) and that of $Z = 4$ for PAS (Bai et al., 2008)) so does $E$. Thus the ratio of these two components, $k$, also varies.

It is important to note here that to create illusion in attacker’s mind a system must store atleast one honeyword along with the original password. Thus $k$ always gets a minimum value 2. On the other hand, as there will be atleast one element in each PRS, hence maximum value of $k$ can be reached up to $Z$.

### 3.2. Proof of the concept

In this section, we will show that aforementioned 3 principles are sufficient for incorporating HBAT to any method belonging to $M_{SOA}^{FODS}$ class.

Obeying their existing authentication routine, following things stand for any method of $M_{SOA}^{FODS}$ class.

$$g_F(P, C) \rightarrow R_S \quad \text{and} \quad f(P, C) \rightarrow R$$

and,

In verification phase $\Rightarrow \begin{cases} \text{Allows prover} & \text{if } R \in R_S \\ \text{Denies the login} & \text{otherwise} \end{cases}$

By following the modified framework, let a method of $M_{SOA}^{FODS}$ category chooses $i^{th}$ $(1 \leq i \leq lr)$ round for distinguishing original password from the set of $k$ sweetwords. As already shown previously, the value of $k$ can be reached maximum up to $Z$ and cannot be no lesser than 2 (see the proof of Principle 3 in the previous section). We denote $j^{th}$ $(1 \leq j \leq k)$ sweetword as $S_j$ and PPI of it in $i^{th}$ round is identified as $PPI_i(S_j)$. Let the response element corresponding to $j^{th}$ sweetword in the $i^{th}$ round be denoted by $r_{i}^{j}$. Therefore in the $i^{th}$ round, following equation must stand to eliminate the ambiguity

$$r_{i}^{1} \neq \ldots \neq r_{i}^{k-1} \neq r_{i}^{k} \quad (2)$$
For those methods, generating $R_S$ of single element, the following equation then stands immediately

$$i^j R_S^1 \neq ... \neq i^j R_S^{k-1} \neq i^j R_S^k$$

(3)

where $i^j R_S^j$ denotes a response set generated by $j^{th}$ sweetword in the $i^{th}$ round.

As proposed principles here are intended to cover all the methods belonging to $M_{SOA}^{FODS}$ class, therefore, authentication protocols that generate $R_S$ having more than one element must also need to satisfy the above equation.

**Proposition 1:** Above discussion implies that in a round, there is a clear need of generating $k$ mutually exclusive response sets for incorporating HBAT to any method of $M_{SOA}^{FODS}$ class.

Equation 3 also complements the fact which can be described in the form of the following equation

$$g_F(PPI_i(S_1), C) \neq g_F(PPI_i(S_{k-1}), C) \neq g_F(PPI_i(S_k), C)$$

(4)

**Proposition 2:** As Equation 4 shows that response set returned by each $g_F(PPI_i(S_j), C)$ are unique, therefore for the fixed challenge value $C$, PPI of each sweetword must be different.

**Proposition 3:** Also, as $g_F()$ takes $C$ as one of the parameters, therefore, both Equation 3 and Equation 4 suggest that generated $C$ by the system plays a huge role in generating $k$ non-overlapping $R_S$.

**Note 3:** As system selects the value of $i$ randomly, therefore proposition 2 proofs the Principle 2. Also, proposition 1 along with proposition 3 validates Principle 1. In Section 3.1, we already proof the third principle and hence, we may claim that proposed principles here are sufficient for incorporating HBAT to any method belonging to $M_{SOA}^{FODS}$ class.

In Section 5 too, we show that by following Principle 1 to Principle 3, any method belonging to $M_{SOA}^{FODS}$ class can afford to store honeywords in practice. As the existing underlying algorithm ($A$) needs to be modified (to $A^+$) for incorporating the HBAT, thus it may impact the whole authentication procedure. Next we discuss the impact of this modification on $M_{SOA}^{FODS}$.

### 3.3. Impact of modification from $A$ to $A^+$

The impact of the modification may cause some changes either in system’s behaviour or, in user’s behaviour or, both. By adopting the $A^+$, a system may change its visual (login) interface and/or, a user may require to remember some additional information for login. From now onwards, we denote change in system’s login interface as **CSLI** and remembering an extra information by the user as **REI**. As HBAT can be considered as an extended version of the password based authentication, thus a balance is required between the security and usability factors. We have analyzed the effect of the modification from both security and usability perspectives.

#### 3.3.1. Impact of the modification from security perspective

During modification from $A$ to $A^+$, basic security standard (includes security against observation attack through brute force search, password guessing attack (Kelley et al., 2012) etc.) of $A$ can be influenced in one of the following three ways –

1. $A^+$ may provide enhanced security compared to $A$.
2. $A^+$ may provide same security as of $A$.
3. $A^+$ may provide lesser security than $A$.

During modification to $A^+$, the target should always be to ensure higher security standard (if possible) or atleast the same security standard as of $A$. 


3.3.2. Impact of the modification from usability perspective

CSLI may influence the login procedure. We identify the change in login procedure as CLP. Modification to $A^+$ may also cause REI by a user. Based on CSLI, a prover may have to face any one of the following two situations during login – (a) CSLI with CLP and (b) No CSLI with no CLP. It is also noticeable that CLP will cause REI by a prover and vice versa is also true. On the other hand, no CLP will cause no REI by a user. Now by combining these three components – CSLI, REI and CLP, the overall usability standard of $A^+$ can fall under one of the following categories –

1. CSLI with CLP and REI.
2. No CSLI with no CLP no and REI.

While modifying to $A^+$, desired objective will be achieving no CLP and no REI from the user end.

4. Integrated Usability and Security Features

HBAT framework has its own security and usability parameters. While incorporating HBAT to MFDOS, then it inherits the usability and security parameters of HBAT.

4.1. HBAT usability features

There are three well defined usability features (Juels and Rivest, 2013) related to a HBAT – (a) System interference, (b) Stress on memorability and (c) Typo safety.

(a) System interference: During registration, some HBAT (like take-a-tail (Juels and Rivest, 2013)) require an extra information to be remembered by a user. This extra information is used as part of user’s login credential. In this situation, as a HBAT interferes on the password choice of user, thus this property is known as system interference. If a user needs to remember $n$ system generated information for $n$ different login accounts then system interference becomes high (e.g., take-a-tail (Juels and Rivest, 2013)). If a HBAT allows a user to choose the extra information then user can use that information for login into $n$ different accounts. This is identified as low system interference (e.g., modified-tail (Chakraborty and Mondal, 2015)). There are some HBAT too which do not force users to remember any extra information (Bojinov et al., 2010). A HBAT, having high system interference, does not provide good usability standard.

(b) Stress on memorability: There exists a relationship between the system interference and stress on memorability. If a honeyword based scheme imposes high system interference, then a user has to remember different system generated information for different login accounts. This increases the stress on user’s mind and threats the usability standard. On the other hand, user may use the same login credential for different login accounts using a HBAT having low or, no system interference. This causes low stress on memorability which is a desirable criteria for a HBAT to be user friendly.

(c) Typo safety: A honeyword generation algorithm is called typo safe if typing mistake of a user rarely matches with any honeyword, maintained against that user account. A less typo safe method, due to typing mistake of the legitimate user, may mislead the honeyChecker in generating a negative feedback signal even though $F_P$ has not been compromised.

4.2. HBAT security features

There are three well defined security parameters related to a HBAT – (a) Denial of Service (DoS) resistivity, (b) Defending Multiple system vulnerability (MSV) and (c) Flatness.

(a) DoS resistivity: Without compromising $F_P$, if an adversary becomes able to guess any honeyword then the honeyword based approach is identified as weak DoS resilient one (Chakraborty and Mondal, 2015). There are few honeyword generation techniques which help adversary to guess a honeyword easily if
the original password is known to her. In such situation, an attacker may intentionally submit a *honeyword* to make system understand that $FP$ has been compromised. Once system senses submission of a *honeyword*, it blocks each user account and denies any further login attempt. To mount DoS attack, an attacker needs to know the original password of a user. To get the original password, adversary may either perform observation attack or, may create her own account.

Though above discussion is fruitful to give a generic idea about how DoS attack is performed, but the nature of the attack slightly gets changed while incorporating HBAT to M$^{FODS}_{SOA}$. In a particular round (say $i : 1 \leq i \leq lr$), to identify a *sweetword* uniquely, $A^+$ maps each *sweetword* to a unique $RS$. Therefore, if an adversary can successfully guess both the $i$ and an element of a $RS$, formed by the PPI of a *honeyword*, then she can intentionally submit that element to facilitate her chances in mounting the DoS attack. Particularly, for a small value of $lr$ and $k \approx Z$, chances of mounting this attack become higher.

Therefore, if possible, with providing moderate threat detection rate, the value of $k$ should be chosen in such a manner so that the response sets generated by the *sweetwords* do not cover all possible response elements. For the systems provide weak security against DoS, light security policy against DoS (Erguler 2015) may be adopted to defend the attack. Under light security policy, a system only blocks that account against which it senses submission of a *honeyword*.

(b) **Defending MSV:** Recent reports strongly suggest that normal users mostly select same passwords for multiple accounts (Das et al. 2014) (Shen et al. 2016). During registration, after receiving password from a user, system generates a list of *honeywords*. One of the characteristics of any *honeyword* generation approach is to generate different list of *honeywords* at different run of the algorithm even though the password remains same. Eventually, the lists of *sweetwords* in two different systems differ even if the same password is used.

Now if an adversary becomes successful in obtaining $FP$ from both these systems then there is a high probability that intersection between two lists of *sweetwords* will reveal the original password of the user. This is known as Multiple System Vulnerability or, MSV crisis of HBAT.

(c) **Flatness:** From the compromised $FP$, maintaining *honeywords* along with the original password, an attacker gets confused among $k$ *sweetwords* for each user account. Now sometimes it may happen that the adversary can easily identify the original password of a user from the list of *sweetwords* (e.g., if there exists a correlation between the username and password). A HBAT is said to be *perfectly flat* if an adversary has no advantage in identifying the original password of the user from the list of *sweetwords*. Thus, for a *perfectly flat* *honeyword* generation algorithm, the probability of selecting the original password becomes $1/k$. For an *approximately-flat* HBAT, the probability of selecting the original password from the list of *sweetwords* becomes slightly higher than $1/k$. A good *honeyword* generation algorithm is required to be *perfectly-flat* to obfuscate the attacker properly.

While incorporating *honeywords* to the $FP$ of a method belonging to M$^{FODS}_{SOA}$ class, it is important to analyze the security and usability aspects associated with the HBAT framework. Next we show how the concept of password masking strategy can be incorporated to some of the methods belonging to M$^{FODS}_{SOA}$ category in practice.

5. **Incorporating Honeywords to M$^{FODS}_{SOA}$**

To the best of our belief, long back in 1991, proposed concept of Matsumoto and Imai (Matsumoto and Imai 1991) can be considered as the very first contribution in the domain of M$^{FODS}_{SOA}$ category methods. Researchers have introduced many methodologies (belonging to M$^{FODS}_{SOA}$ class) thereafter (Li and Shum 2005) (Wiedenbeck et al. 2006) (Weinshall 2006) (Asghar et al. 2010). Among them, while some provide really good security against powerful eavesdropper with lower usability standard (Hopper and Blum 2001) (Weinshall 2006), the others, come with good usability standard though lagging in providing good security against strong adversary. In this section, we focus on some of the methods that maintain a nice balance
between the security and usability aspects. Therefore, to show that proposed idea is implementable in practice, the methods we have considered here are — S3PAS (Zhao and Li, 2007), CHC (Wiedenbeck et al., 2006), PAS (Bai et al., 2008) and COP (Asghar et al., 2010). Next, we consider these methods one by one and incorporate HBAT to those by following the proposed principles in Section 3.1.

5.1. Incorporating Honeywords to S3PAS

In this section, we first give a quick overview of the existing working principle of S3PAS (Zhao and Li, 2007) belonging to $M_{FODS}^{SOA}$. Then we show how HBAT framework can be integrated with this existing approach.

5.1.1. Working principle of S3PAS

In basic S3PAS, from a character set of $T$ elements, a user first selects a password of length 4. In each session, $T$ characters are randomly arranged in a $m \times n$ matrix and displayed on a visual interface. The orientation of characters in the $m \times n$ matrix remains static for an entire session.

![Visual interface of S3PAS](image)

Figure 5: Visual interface of S3PAS with $T = 80$. Responses in first two rounds for the password $2KZW$. The formed virtual triangles (marked by black border) in the first two rounds are $\triangle 2KZ$ and $\triangle KZW$. The valid responses may be “−” for $\triangle 2KZ$ and “M” for $\triangle KZW$.

S3PAS is comprising of 4 login rounds in each session. Starting from $i^{th}$ index of the password, in each round $i$ (from 1 to 4), the prover selects 3 consecutive characters of her password in a cyclic manner. On the visual interface, the prover then creates a virtual triangle by using three consecutive password characters correspond to that round. To submit her response, the user selects any character that falls under the area of the formed virtual triangle in that round. Let the password of a user be $2KZW$. Therefore formed virtual triangles are $\triangle 2KZ$ in $1^{st}$ round, $\triangle KZW$ in $2^{nd}$ round, $\triangle ZW2$ in $3^{rd}$ round and $\triangle W2K$ in $4^{th}$ round. In Figure 5, we have shown the visual interface of S3PAS and formed virtual triangles in first two rounds.

5.1.2. Proposed modification for incorporating HBAT framework

By following principle 1 (in Section 3.1), at least in a round, there must be no common elements among the $PRS$ of $sweetwords$. In S3PAS, as elements inside a triangle form a $PRS$, thus, $honeywords$ need to be selected (and challenge should be created) in such a manner so that there exist no overlapping areas among the formed triangles in a particular round. To ensure this, verifier selects $k$ $sweetwords$ in such a manner so that formed triangles (or $PPI$ of $sweetwords$) in any round are different (ref. to principle 2).
Therefore, for the password $2KZW$, generated *honeywords* (for $k$ as 6) may be $8IMN$, $6ABS$, $0XRJ$, $3OVB$ and $rD1$; as for any login round, $PPI$ of these *sweetwords* are different. For example, without loss of generality, the $PPI$ of *sweetwords* in the $3^{rd}$ round are $ZW2$, $MN8$, $BS6$, $RJ0$, $VB3$, and $rD1$; as for any login round, $PPI$ of these *sweetwords* are different. For example, without loss of generality, the $PPI$ of *sweetwords* in the $3^{rd}$ round are $ZW2$, $MN8$, $BS6$, $RJ0$, $VB3$, and $rD1$.

Let the background algorithm of existing S3PAS scheme be denoted by $A_{S3PAS}$. We denote the modified algorithm that supports HBAT feature as $A^+_{S3PAS}$. The working principle of $A^+_{S3PAS}$ is following.

- **Step 1:** $A^+_{S3PAS}$ first randomly selects a round for generating $k$ non-overlapping triangles by the $PPI$ of *sweetwords* on the visual interface. Let the selected round be $i$: where $(1 \leq i \leq 4)$.

- **Step 2:** Verifier randomly allocates $T$ characters to $m \times n$ matrix.

- **Step 3:** Verifier then checks whether the formed triangles, by the $PPI$ of *sweetwords* in $i^{th}$ round, are getting overlapped or not.

- **Step 4:** If there is no overlapping, $A^+_{S3PAS}$ moves to Step 5 otherwise, goes back to Step 2.

- **Step 5:** Fixes the $m \times n$ matrix as obtained from Step 2 and displays the matrix on the visual interface.

- **Step 6:** From the submitted response in each round, $A^+_{S3PAS}$ checks that which triangles, formed by $PPI$ of *sweetwords*, hold that response element. The verifier then records index position of the corresponding *sweetwords*.

- **Step 7:** At the end of all login rounds, verifier selects that *sweetword*, whose index position is recorded in all the rounds.

- **Step 8:** If no common index value is found then verifier denies the login otherwise, $A^+_{S3PAS}$ moves to Step 9.

- **Step 9:** Along with the username, index value is directed to the *honeyChecker* server.

- **Step 10:** On the receiving the positive feedback from *honeyChecker*, $A^+_{S3PAS}$ allows login otherwise, blocks the user.

We explain the above procedure with an example. Let for $k$ as 6, a verifier maintains the following list of *sweetwords* – $2KZW$, $8IMN$, $6ABS$, $0XRJ$, $3OVB$ and $rD1$, in $F_P$. Now suppose $A^+_{S3PAS}$ randomly selects $4^{th}$ round to distinguish the original password from the *honeywords*. In Figure 6 we show the visual interface (or challenge) generated by the verifier. The visual interface ensures that formed triangles in $4^{th}$ round share no common elements.

As shown in Figure 6, submitted response in any other round (except $4^{th}$) may belong to more than one triangles as they may share some common areas. But, atleast from the submitted response in the $4^{th}$ round, system will able to understand for which *sweetword*, the response is being submitted. Thus, by following *Principle 1* and *Principle 2*, modified S3PAS can differentiate the original password from the set of *honeywords*.

5.1.3. Determining the value of $k$

According to *Principle 3*, the number of *sweetwords* in $A^+_{S3PAS}$ may vary between 2 to 80 (number of response elements). But as a PRS generated by $A^+_{S3PAS}$ is expected to hold more than one element, thus maximum limit of 80 cannot be reached in practice.

$A^+_{S3PAS}$ gets stuck in a loop (between Step 2 and Step 4) until $k$ non-overlapping triangles are formed in a particular round, decided at Step 1. The triangles need to be fitted on the visual interface which is nothing but a $10 \times 8$ matrix of $T$ (= 80) elements. As $k$ non-overlapping triangles are needed to be constructed on a fixed area, thus we make the following claim to determine a suitable value of $k$. 

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Figure 6: Above figure presents visual interface returned by $A^{+}_{S3PAS}$. This interface ensures that generated triangles in the fourth round, uniquely identify user response for the sweetwords 2KZW, 8IMN, 6ABS, 0XRJ, 3OVB and rD1ℓ. (a) Formed overlapping virtual triangles in first round on the interface of modified S3PAS. Corresponding PPI of the sweetwords are 2KZ, 8IM, 6AB, 0XR, 3OV and rD1.

(b) Formed overlapping virtual triangles in second round on the interface of modified S3PAS. Corresponding PPI of the sweetwords are KZW, IMN, ABS, XRJ, OVB and D1ℓ. (c) Formed overlapping virtual triangles in third round on the interface of modified S3PAS. Corresponding PPI of the sweetwords are ZW2, MN8, BS6, RJ0, VB3 and 1rℓ. (d) Formed non overlapping virtual triangles in fourth round on the interface of modified S3PAS. Corresponding PPI of the sweetwords are W2K, N8I, S6A, J0X, B3O and ℓrd.

Theorem 1. On a fixed area, if we randomly draw $k (> 1)$ triangles, then probability of overlapping among them is directly proportional to $k$.

Proof: Let us assume that the size of the visual interface is $AR$ units. The average area of each triangle is considered as $TR (< AR)$ units. The triangles can only be overlapped if there exists atleast one triangle prior to choosing the vertices for the second triangle. Thus, according to Roulette Wheel selection principle (Sher, 1998), the probability of overlapping between $k = 2$ triangles can be determined as $TR/AR$. Similarly, the probability that $k^{th}$ triangle will overlap with any of the existing $k-1$ triangles can be derived by using the following Equation 5.

$$(k - 1) \times \frac{TR}{AR} \quad \text{where:} \quad k > 1 \quad \text{and} \quad k \times TR \leq AR$$

From the above equation, it is easily understandable that for drawing $k$ non-overlapping triangles on a fixed area, the value of $k$ can not be arbitrarily large.

Experimental analysis for determining the value of $k$: We also perform an experimental analysis for choosing a suitable value of $k$. In $A^{+}_{S3PAS}$, there is a loop from Step 2 to Step 4. The loop only breaks if $k$ non-overlapping triangles are generated in a round, predetermined by the $A^{+}_{S3PAS}$. From Equation 5, it is quite evident that with the increasing value of $k$, formation of non-overlapping triangles on a fixed plane will be difficult. Thus, we determine a suitable value of $k$ based on the average number of iterations and average time consumed by the loop.

Table 2 reflects the details of experimental analysis performed on a system having software specification – OS: Windows 7, PHP version: 5.4.3 and Server API: Apache 2.0 Handler and, hardware specification – processor: 32 bit core i3 and primary memory: 4GB. To conduct the experiment, we have varied $k$ from 4 to 8. From Table 2, it can be seen that for $k$ as 7, the system took 7.08 seconds at max (on average 3.7 seconds) to produce a challenge which can differentiate among 7 sweetwords from the response of a user. When $k$ reached to 8, the average time for generating visual interface was 16.2 seconds. Thus, while $k$ was set to 7 and 8, we found that it affected the session (login) time and usability standard. So, we prefer the
Table 2: Above table shows for different values of $k$, number of iterations and running time required by the loop to generate $k$ non-overlapping triangles in a round. The data is collected after 20 runs of $A_{S3PAS}^+$ for each value of $k$.

| value of $k$ | no. of max iteration | no. of min iteration | avg iteration | max exec time (ms) | min exec time (ms) | avg exec time (ms) |
|-------------|----------------------|----------------------|--------------|--------------------|--------------------|--------------------|
| 4           | 34                   | 1                    | 16           | 1132               | 1018               | 1035               |
| 6           | 48                   | 1                    | 16           | 1246               | 1012               | 1083               |
| 7           | 251                  | 3                    | 63           | 2530               | 1012               | 1391               |
| 8           | 595                  | 9                    | 492          | 2530               | 1032               | 1391               |

value of $k$ as 6 over the others as it took approx 1.39 seconds on average (and that of 2.53 seconds at max) to generate the visual interface.

Also, as large value of $k$ covers more response elements, thus selecting a higher value of $k$ may degrade the security standard of the modified scheme against DoS attack (see Section 4.2). Therefore, $k$ as 6 does not put any significant overhead on the session time and, with moderate security against DoS (also see details in Section 5.1.4), it provides a healthy detection rate of 83.34%.

5.1.4. Security analysis of modified S3PAS

As mentioned in Section 3.3.1, modification from $A_{S3PAS}$ to $A_{S3PAS}^+$ may have some impacts on the existing security standard of S3PAS. Also security notion of HBAT framework gets added to the basic security standard to reinforce the overall security level. To start with, we show how proposed modification influences the basic security features of S3PAS.

**Basic security features:** The basic security feature of S3PAS includes security against observation attack through brute force search, password guessing attack and random click attack as shown in (Zhao and Li, 2007). Thus, we determine the basic security standard of modified S3PAS against these three attack models.

(a) **Security against observation attack through brute force search:** Brute force attack is a general pruning-based learning process, where the eavesdropper keeps eliminating irrelevant candidates when more and more cues are available. To perform this attack, the adversary first lists all possible candidates for the password and for each independent observation of challenge response pair, she checks the validity of each password candidate by running the verification algorithm used by the server. Thereafter she discards invalid candidates from the candidate set. The aforementioned procedure is continued until the attacker derives a candidate set of small threshold.

The complexity of this attack for basic S3PAS scheme can be derived by following the same path as proposed in (Wiedenbeck et al., 2006) and can be represented in the form of $O\left(\left|T\right|\left|PPI\right|\right)$; where $\left|PPI\right|$ denotes the length of $PPI$ whose default value is 3. As values of both $\left|T\right|$ and $\left|PPI\right|$ remain unchanged in modified S3PAS, thus security standard against this attack remains same for both the variations of S3PAS.

(b) **Security against password guessing attack:** To perform this attack, an adversary tries to guess actual password to pass through a session (Kelley et al., 2012). Therefore, success probability of adversary depends upon two components – length of the password and the password space. As values of both these components remain same for both the existing and modified schemes, thus modified S3PAS maintains same security standard against this threat.

(c) **Security against random click attack:** Security against this attack is heavily dependent on the expected triangle area (denoted as $E(S)$) (Zhao and Li, 2007). Except in $i^{th}$ round (dedicated to form $k$ non-overlapping triangles on the user interface), modified scheme does not impose any restriction on the area of the triangles in any other round. In (Zhao and Li, 2007), authors determine the $E(S)$ in the form of
the following equation

\[ E[S] = \sum_{f=1}^{n} \sum_{g=1}^{n} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} \sum_{h=1}^{n} \sum_{l=1}^{n} \sum_{m=1}^{n} 1/2 (f/n - g/n) (i/n - k/n) - (f/n - h/n) (i/n - j/n) 1/6 \] (6)

For the basic S3PAS scheme, we may consider value of \( n \) as 9 here as a grid of dimension 9 \( \times \) 9 is capable of holding all \( T = 80 \) elements. Therefore for \( n = 9 \) the above equation yields to 0.753. This infers that probability of success under random click attack in each round is 0.753.

In the modified scheme, as value of \( T \) remains same as of the basic S3PAS, thus proposed modification provides same security standard against this attack too.

**Inherited HBAT security features:** As discussed earlier, HBAT security feature is comprising of security against DoS and MSV. Achieving flatness is another security property which comes under HBAT framework. Next we show how well modified S3PAS satisfies these HBAT security features.

**(a) Security against DoS attack:** As discussed in Section 4.2 to provide robust security against DoS, a method belonging to \( M_{FODS}^{SOA} \) must satisfy following two criteria —

- Generated *honeywords* must be hard to guess.
- Value of \( k \) should be chosen in such a manner so that it does not cover all the response elements.

For generating hard to guess *honeyword*, modified S3PAS may use modelling-syntax-approach (Bojinov et al., 2010). As value of \( k \) cannot be chosen arbitrarily large (ref. to Section 5.1.3), therefore by virtue of its design, proposed modification satisfies second criterion too. Thus we may claim that modified S3PAS successfully mitigates the threat of DoS attack.

**(b) Security against MSV:** Though modelling-syntax-approach provides good security to resist DoS attack, but it provides weak security against MSV. In fact, till date there exists no solution which provides strong security against both these attacks without having any system interference. System interference degrades the usability standard of a HBAT to a great extent.

**(c) Flatness:** Modelling-syntax-approach can generate absolutely flat list of *sweetwords*. Thus, modified S3PAS achieves absolute flatness, only if there exists no correlation between the username and password.

Therefore, having some scope of improvements in terms of providing security against MSV, modified S3PAS satisfies almost all security parameters.

5.1.5. Usability analysis of modified S3PAS

As mentioned in Section 3.3.2 to get compatible with HBAT framework, modification of \( A_{S3PAS} \) may influence the login behaviour of a user. Moreover, usability features of HBAT are also added to determine the overall usability standard.

**Basic usability features:** The usability standard of the existing scheme can be determined with respect to two parameters – *login time* and, *percentage of error* during login. Modified scheme imposes no CSLI and the login procedure remains exactly same as of the existing one. A user even does not require to remember any extra information to get compatible with the proposed architecture. Thus, proposed scheme can be categorized as – no CSLI with no CLP and no REI (ref. to Section 3.3.2) and hence, modified S3PAS provides same usability standard as of the existing one.

**Inherited HBAT usability features:** Modified S3PAS makes no impact on the password choice of the user and hence, it neither imposes any stress on user’s mind nor has any system interference. Typing mistake of a genuine user will set off an alarm by the *honeyChecker* server, only if, response submitted
by the user in each round corresponds to PPI of a particular honeyword. Let each character takes 1 unit area to fit into the visual interface of S3PAS. Let the average area of each triangle be \( TR \) units, then for \( T (= 80) \) response elements, probability of hitting the same honeyword becomes \( (\frac{TR}{T})^T \). While determining a suitable value of \( k \) (see Section 5.1.3), we found that for the value \( k = 6 \), a virtual triangle mostly holds 3 elements in it. Therefore by considering \( TR = 3 \), for the default values of parameters, the probability can be derived as \( 1.9 \times 10^{-6} \). So we may claim that proposed approach is typo safe.

**Note 4:** Proposed modification of basic S3PAS allows no degradation of basic security and usability standards. We also show that except MSV, modified S3PAS satisfies all security parameters of HBAT with moderate value of \( k = 6 \) (particularly helpful to resist the DoS attack). Finally, modified scheme well supports all HBAT usability features to provide adequate user friendliness.

### 5.2. Incorporating honeywords to CHC

In this section, first we briefly introduce Convex-Hull-Click (CHC) protocol ([Wiedenbeck et al., 2006](#)) and then show how HBAT can be incorporated to this.

#### 5.2.1. Working principle of CHC

From their functional aspect, CHC and S3PAS are very similar in nature ([Yan et al., 2015](#)). In CHC, instead of choosing a password of length 4, user selects \( K (\geq 3) \) pass icons as her secret out of \( N \) icons. At each round, system randomly chooses \( M \) icons including \( K_c (3 \leq K_c \leq K) \) pass icons and display those on the login terminal. To give her response, a user first locates those \( K_c \) pass icons on the login screen and makes a convex hull by using those. Then the user selects a point (icon) inside that convex hull and submits that as a response.

It is very easy to relate that for basic S3PAS, \( N = M \) and we select value of that as 80. Also, at each round in S3PAS, the user needs to locate \( K_c = 3 \) consecutive characters from her password of length \( K = 4 \).

#### 5.2.2. Proposed modification for incorporating HBAT framework

Due to similarity between the approaches, proposed modification here follows the same path as of S3PAS. System should choose \( k \) sweetwords in such a manner so that at any given round, PPI of those are different (ref. to Principle 2). To authenticate the user in a session, system first randomly selects a round and ensures that with reference to the visual challenge in that particular round, generated \( k \) convex hulls by the PPI of the sweetwords share no common area (ref. to Principle 1). Thus at the end of the authentication session, from the submitted response by the user, system can uniquely identify the sweetword against which the login has been performed. System then follows the normal HBAT routine to detect the breach.

#### 5.2.3. Security analysis of modified CHC

Along with basic security characteristics, Security analysis here includes inherited security features due to incorporation of HBAT. As shown in ([Wiedenbeck et al., 2006](#)), the basic security feature comprises of security against observation attack through brute force search and password guessing attack. Also, due to difference in distribution of secret icons and non secret icons, security of basic CHC may be threatened under probabilistic attack too ([Asghar et al., 2013](#) Section 4, pp. 6). For modified CHC, next we elaborate these attack scenarios one by one.

**(a) Security against observation attack through brute force search:** Security analysis against this attack is done in the same way as proposed in ([Wiedenbeck et al., 2006](#)). Attacker initially forms a list containing all possible \( K \) combinations of icons out of \( N \) icons. After recording each challenge response pair, attacker then discards all those combinations from the list whose convex hull do not include that response point. The sole remaining \( K \) combination is then become the \( K \) secret labels of the user. Therefore, order the attack can be derived as \( O(\binom{N}{K}) \). As modified scheme does not influence the parameters of existing
CHC protocol, therefore, the complexity of the attack remains same for the proposed modification.

(b) Security against password guessing attack: Using the modified approach, user is allowed to select the same password as of the existing one. Hence, security standard against password guessing attack does not get changed.

(c) Security against probabilistic attack: In CHC, in each round, out of $\mathcal{N}$ icons $\mathcal{M}$ icons are displayed on the visual interface and, visual interface always contains $\mathcal{K}^c$ ($3 \leq \mathcal{K}^c \leq \mathcal{K}$) pass icons. But there is no such restriction on non pass icons. For the basic CHC scheme, authors in [Asghar et al., 2013] present the expected number of times an icon ($I$) appears in $r$ challenges in the form of following equation

$$E[I^r, I \notin \mathcal{K}] = r \times \frac{1}{\mathcal{K} - 2} \times \frac{1}{\mathcal{N} - \mathcal{K}}(\mathcal{M}(\mathcal{K} - 2) - \frac{\mathcal{K}(\mathcal{K} + 1)}{2} + 3)$$  

(7)

where $I$ does not belong to the set of pass icons.

and,

$$E[I^r, I \in \mathcal{K}] = r \times \frac{1}{\mathcal{K}(\mathcal{K} - 2)}(\frac{\mathcal{K}(\mathcal{K} + 1)}{2} - 3)$$

(8)

where $I$ belongs to the set of pass icons.

By following Equation 7 and Equation 8 in [Asghar et al., 2013], authors derive that for $\mathcal{N} = 112$, $\mathcal{M} = 70$, $\mathcal{K} = 5$ and $r = 100$, secret icons and non secret icons are expected to appear 80 times and 62 times, respectively. Thus, in basic CHC, observation of $\mathcal{K}$ most frequently occurring icons in $r$ challenge help adversary to get the secret.

In the modified CHC, though values of $\mathcal{N}$ and $\mathcal{M}$ remain same, but due to incorporating honeywords, number of sweet icons increases. This in turn increase number of icons that must appear on visual interface in a round. We denote number of sweet icons as $I^S$; where $I^S > \mathcal{K}$. While replacing $\mathcal{K}$ in the above equations by $I^S$, we always expect to get a lesser value from Equation 8 and thus, we may claim that to obtain all sweet icons, an attacker needs to go through more number of rounds.

Inherited HBAT security features: As modified CHC inherits the HBAT in almost the same way as of modified S3PAS, therefore it can provide good security in terms of achieving flatness and defending DoS. But this method falls short while building security against MSV.

5.2.4. Usability analysis of modified CHC

Usability analysis of modified CHC protocol comprises of basic usability features and usability parameters of HBAT. As user remembers same password information and does not face any change during login, therefore without any REI from user end, modified CHC imposes no CSLI and no CLP. This infers that basic usability standard remains same for both the existing CHC and modified one.

Also from HBAT usability aspect too, this method can be considered as typo safe (because of the similar reason discussed in Section 5.1.5) without any system interference and no stress-on-memorability.

Note 5: Likewise modified S3PAS, proposed modification of CHC maintains the same basic security standard in terms of resisting brute force attack and password guessing. In fact, modified CHC performs better by increasing the complexity of probabilistic attack. The basic usability standard is maintained same as of the existing CHC protocol. Also, except MSV, modified CHC satisfies all security and usability aspects of HBAT.

5.3. Incorporating honeywords to PAS

Under the scope of this section, first, we briefly describe the basic PAS scheme [Bai et al., 2008] and, thereafter we show a direction towards integrating HBAT into this.
5.3.1. Working principle of PAS

To login into the system, a user remembers two predicates as secret. Each predicate contains one index value along with an alphabet. For example, 23E and 41P are two valid predicates chosen by the user. The login interface of PAS contains two tables. Each table is made of 25 blocks and each block is denoted by an index value starting from (1, 1) to (5, 5). Along with a block number (i.e., an index value), each block holds 13 alphabets chosen randomly from the set of 26 alphabets. The first cell of a block always contains the index value.

In Figure 7, we have shown two challenge tables of PAS. To enter response with respect to her first predicate (i.e., 23E) and the challenge shown in Figure 7, the user first moves to the block denoted by (2, 3) in the first challenge table and searches for character E there. As E is not present in that block, therefore user derives NO as answer. For searching E again, the user then moves to the block number (2, 3) in the second challenge table. As block (2, 3) contains character E in this table, thus user derives YES as her answer. Therefore, from the first predicate 23E and with respect to the challenge tables shown in Figure 7, the user derives the answer sequence NO, YES.

In the same way, with respect to her second predicate (i.e., 41P) and the challenge shown in Figure 7, derived answer sequence by the user will be YES, YES. User remembers this cumulative answer sequence as \{NO, YES, YES, YES\}. To give a response with respect to the derived answer sequence, the user takes help of the response table shown in Figure 8.

The derived answer from the first predicate and the second one correspond to the row index and the column index of the response table, respectively. Thus, user derives her response as R with reference to this
example. After typing the response user is led to the next round. It is important to note here that in the remaining login rounds, with changes in the content of challenge tables, the user follows the same procedure to generate the responses with respect to the same predicate pair 23E and 41P.

5.3.2. Proposed modification for incorporating HBAT framework

In the basic PAS scheme, user chooses her response from a set of 4 elements \{P, Q, R, S\}. Therefore, first of all, according to the Principle 3, the value of \( k \) cannot go beyond 4. Next, as \( PPI \) of sweetwords are required to be different (ref. to Principle 2) and predicates act as \( PPI \) here, thus modified PAS needs to generate predicates of honeyword in such a manner so that they are unique. To generate different predicates, system may either vary the index in a predicate, or the character in it, or both. With out loss of generality, our proposal here alters both to generate the honeywords with respect to the original predicates of the user.

In PAS, user uses two predicates to pass an entire authentication session. Hence, to satisfy Principle 1, modified PAS should generate the challenge in such a manner so that at least in a round, predicates of each sweetword map to a unique response set. It is important to note here that in PAS, each response set holds a single element only. Now as shown in Figure 8 each response in the response table gets mapped to 4 answer sequences and, the relation between response elements and answer sequences is shown in Table 3.

| Response element | Corresponding answer sequences |
|------------------|--------------------------------|
| P                | \{NO, NO, NO, NO\}, \{NO, YES, YES, NO\}, \{YES, NO, YES, YES\}, \{YES, YES, NO, YES\} |
| Q                | \{NO, NO, NO, NO\}, \{NO, YES, NO, NO\}, \{YES, NO, NO, NO\}, \{YES, YES, YES, NO\} |
| R                | \{NO, NO, YES, NO\}, \{NO, YES, YES, YES\}, \{YES, NO, NO, NO\}, \{YES, YES, NO, NO\} |
| S                | \{NO, NO, YES, YES\}, \{NO, YES, NO, NO\}, \{YES, NO, NO, NO\}, \{YES, YES, NO, NO\} |

Table 3: Relationship between the response elements and the answer sequences with reference to the Figure 8

To satisfy Principle 1 in \( i^{th} \) round (1 \( \leq i \leq lr \)), modified PAS may adopt the following strategy. In round \( i \), it first randomly selects one answer sequence corresponding to each response. Then one of these (here 4) selected answer sequences is assigned to each sweetword. During formation of challenge tables, each sweetword then try to satisfy the answer sequence assigned to it. Satisfying a answer sequence automatically satisfies corresponding response element. Thus, each sweetword maps to a different response through the communicated challenge in the \( i^{th} \) round. Except in \( i^{th} \) round, multiple sweetwords may map to a single response element in other rounds.

For example, with respect to the original predicates as \((23E, 41P)\) system selects other 3 predicate pairs as \((32S, 51T)\), \((34Y, 11M)\) and \((15Z, 55B)\) and hence satisfies both the principles – Principle 2 and Principle 3.

Let the assigned answer sequence to the original predicates be \{YES, NO, NO, NO\} which satisfies the response element \( S \). Hence, while first predicate (i.e., 23E) ensures that alphabet \( E \) appears in block (2, 3) in the first table and does not appear in the same block of the second table, the other predicate (i.e., 41P) restricts alphabet \( P \) from appearing in block (4, 1) in both the tables. In such manner, predicate \((23E, 41P)\) satisfies the answer sequence \{YES, NO, NO, NO\} and maps to the response element \( S \). In Figure 8 we show the challenge interface in which (with reference to the response table shown in Figure 5)

- Predicate \((15Z, 55B)\) is satisfying answer sequence \{NO, NO, NO, NO\} and maps to the response element \( P \).
- Predicate \((34Y, 11M)\) is satisfying answer sequence \{YES, NO, YES, NO\} and maps to the response element \( Q \).
- Predicate \((32S, 51T)\) is satisfying answer sequence \{NO, YES, YES, YES\} and maps to the response element \( R \).
- Predicate \((23E, 41P)\) is satisfying answer sequence \{YES, NO, NO, NO\} and maps to the response element \( S \).

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Therefore, using proposed modification of PAS, even though there may exist some overlapping in other rounds, but from the submitted response in the $i^{th}$ round, system can uniquely derive the sweetword against which user performs the login operation. For generating the honeywords, likewise modified S3PAS and modified CHC protocols, modelling-syntax-approach (Bojinov et al., 2010) may also be adopted here.

5.3.3. Security analysis of modified PAS

Security analysis of modified PAS scheme includes basic security features and inherited HBAT security features. To start with we will focus on basic security features.

**Basic security features:** As shown in (Li et al., 2009), the basic security features of PAS include security against observation attack through brute force search and password guessing attack. Next we elaborate these one by one.

(a) Security against observation attack through brute force search: Under this attack model, an attacker initially considers all possible predicate pair and narrows the list after observing each challenge response pair. In (Li et al., 2009), authors show that computational complexity of this attack can be determined as $O\left(\left(MH+c-1\right)^p\right)$ where $M$, $H$, $c$ and $p$ denote number of cells in the challenge table, number of all possible characters, number of indices in each predicate and number of predicates in the secret, respectively. As modified PAS does not make any impact on these parameters, therefore, it maintains the same security standard against this attack as of the basic PAS scheme.

(b) Security against password guessing attack: Success probability of an attacker under this attack scenario depends on the password space and the length of the password. As both these factors remain unchanged in the modified scheme, thus basic PAS and modified one provide same security standard against this attack model too.

**Inherited HBAT security features:** As discussed previously, along with achieving flatness, integrated HBAT security feature includes security against DoS attack and MSV.

(a) Security against DoS attack: As user response is confined within 4 response elements only, thus, mounting DoS attack becomes easy for the proposed modified PAS. Therefore, as suggested in (Erguler, 2015), modified PAS may adopt light security policy against DoS attack.
(b) Achieving flatness and security against MSV: As modelling-syntax-approach can be used for generating the honeywords, therefore, though proposed scheme achieves complete flatness, but cannot provide robust security against MSV.

5.3.4. Usability analysis of modified PAS

Usability analysis of proposed modification is done against basic usability features and integrated HBAT usability features.

Basic usability standard: As modified PAS falls under the category of no CSLI with no CLP and no REI, thus it provides the same usability standard as of the basic PAS scheme.

Inherited HBAT usability standard: Proposed modification here neither imposes stress on user mind nor have any system interference. Probability of typing mistake, that raises the false alarm, is influenced by two factors — number of login rounds \( (r = 5) \) and probability of submitting the wrong response (here \( 3/4 \)), and can be derived as \( \frac{20}{25} \) for the default values of parameters. Thus with moderate typo-safety, modified PAS well satisfies all other HBAT usability parameters.

Note 6: Modified PAS does not affect the basic security and usability standards of the basic PAS scheme. From HBAT security point of view, it provides weak security against DoS which can be handled by adopting light security policy against this attack as suggested in \( \text{Erguler, 2015} \). Proposed modification here though cannot robustly handle the MSV crisis, but achieves absolute flatness to obfuscate the attacker properly. Form the HBAT usability aspect too, modified scheme well satisfies almost all the usability parameters.

5.4. Integrating honeywords to Count-On-Plane

In this section, first we briefly introduce the proposed protocol in \( \text{[Asghar et al., 2010]} \) which we name as Count-On-Plane (COP) in this literature. Thereafter, we show how HBAT features can be added to this protocol by following the proposed principles in Section 3.1.

5.4.1. Working principle of COP

To login through COP, a user remembers a secret of length \( \ell \) (here 4) from a set of 66 characters comprising of \{A,..., Z, a,...,z, 0,..., 9, *, #, @, & \}. By maintaining a specific order, these characters are arranged on a 2D plane of dimension \( n = a \times b \). On the 2D plane (visual interface), a value from 0 to 9 is randomly assigned to each character of the set. In Figure 10, we have shown an instance of challenge interface of COP protocol for \( a = 11 \) and \( b = 6 \). Yellow cells in the grid hold the characters from the set

| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 2 | 5 | 4 | 0 | 9 | 3 | 6 | 7 | 9 | 9 |
| L | M | N | O | P | Q | R | S | T | U | V |
| 2 | 1 | 6 | 7 | 7 | 2 | 8 | 0 | 8 | 3 | 1 |
| W | X | Y | Z | a | b | c | d | e | f | g |
| 7 | 4 | 6 | 1 | 2 | 3 | 1 | 8 | 1 | 8 | 8 |
| h | i | j | k | l | m | n | o | p | q | r |
| 1 | 6 | 2 | 4 | 3 | 0 | 8 | 1 | 6 | 9 | 6 |
| s | t | u | v | w | x | y | z | 0 | 1 | 2 |
| 8 | 4 | 9 | 5 | 4 | 5 | 9 | 2 | 9 | 2 | 3 |
| 1 | 4 | 5 | 6 | 7 | 8 | 9 | * | # | @ | & |
| 8 | 4 | 5 | 2 | 9 | 7 | 5 | 9 | 5 | 8 | 3 |

Figure 10: Challenge grid in COP
of 66 elements and their position remain static in each session. White cells in the grid contain a random number from 0 to 9 and content of these cells change in every session.

Let the password remembered by a user be $A1B3$. To login (with reference to the challenge grid shown in Figure 10), the user first goes to the character cell $A$ and looks at the digit corresponding to it. As user finds the digit as 6 here, therefore in a circular way, she moves 6 steps vertically downwards, and thus reaching the same character location, $A$. Except first, for the remaining characters of her password (i.e., $1B3$), user then adds all the digits assigned to these characters. For this example, for the remaining characters $1B3$, this yields to $2 + 2 + 8 = 12$. From character position $A$ (reached after vertical shifts), the user then moves 12 steps horizontally to reach to character $M$ and outputs the digit (here 6) corresponding to $M$.

5.4.2. Proposed modification for incorporating HBAT framework

In COP protocol, as a user chooses her response from the set of 10 elements \( \{0, \ldots, 9\} \), therefore the value of \( k \) can be reached upto 10 at maximum (ref. to Principle 3). For providing better security against DoS, we consider value of \( k \) as 5 here. Next, to satisfy Principle 2, modified COP must generate \( k \) (\( 1 \leq k \leq 10 \)) sweetwords in such a manner so that they are different and also satisfy Principle 1.

To meet with Principle 2, modified COP produces \( k = 5 \) sweetwords in such a manner so that they share no common element among them. For example, for original password as $A1B3$, system may generate 4 other honeywords as $-QJw9$, $2XTD$, $YSRK$ and $icat$. To give her response, as a user must reach to a particular cell (identified as response cell) and enter the digit corresponding to it, therefore, to validate a user under the light of integrated HBAT, we adopt the following strategy.

- **Step 1**: For length of each sweetword as \( \ell = 4 \), except the elements of sweetwords, system first selects \( k = 5 \) response cells randomly from \( 66 - (4 \times 5) = 46 \) probable response cells.
- **Step 2**: System then assigns a unique value (between 0 to 9) to each of the selected response cells.
- **Step 3**: System then assigns each response cell to a sweetword.
- **Step 4**: For each sweetword, system then does the following.
  - **Step 4.1**: In a circular way, system first calculates the path length between the first element of a sweetword and the corresponding response cell assigned to it. Let the derived path length be \( P_L \).
  - **Step 4.2**: \( P_L \) is then get divided by \( a \).
  - **Step 4.3**: System assigns the value of quotient to first element of the sweetword.
  - **Step 4.4**: The remainder (\( r \)) gets partitioned into \( \ell - 1 \) parts (say \( a \), \( b \) and \( c \)) such that \( r = a + b + c \).
  - **Step 4.5**: The partition values are then assigned to the remaining characters of the sweetword.
- **Step 5**: This type of setup maps each sweetword to a unique response cell, assigned by the system in Step 3.
- **Step 6**: As each response cell contains a unique value, thus it enables the system to understand that against which sweetword the login has been performed.

From the above discussion, it is understandable that each sweetword maps to a unique response set of cardinality 1 to satisfy the Principle 1 and PPI in COP are nothing but the whole password string. Next, we discuss the above procedure with an example.

For the sweetwords as $A1B3$, $QJw9$, $2XTD$, $YSRK$ and $icat$, system randomly assigns

- response cell $Z$ to $A1B3$ having \( P_L = 25 \) from A to Z. A value 3 is assigned to Z.

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• response cell $C$ to $QJw9$ having $P_L = 52$ from $Q$ to $C$. A value 1 is assigned to $C$.
• response cell $M$ to $2XTD$ having $P_L = 24$ from $2$ to $M$. A value 5 is assigned to $M$.
• response cell $H$ to $YSRK$ having $P_L = 49$ from $Y$ to $H$. A value 6 is assigned to $H$.
• response cell $h$ to $icat$ having $P_L = 65$ from $i$ to $h$. A value 8 is assigned to $h$.

For $a = 11$, system then divides 25 by 11 and assigns the quotient 2 to $A$. The remainder $25 - 22 = 3$ gets partitioned into 0, 0 and 3 and are allocated to 1, $B$ and 3, respectively (ref. to Figure 11). System follows the aforementioned strategy for assigning values to the elements of all other sweetwords.

Figure 11: Challenge grid in modified COP

Now, as challenge (see Figure 11) is generated in such a way that each sweetword maps to a unique response element, therefore, from the response submitted by the user, system will uniquely be able to identify the corresponding sweetword.

5.4.3. Security analysis of modified COP

Security analysis of modified COP has been performed against basic security features and integrated HBAT security features. To start with, we will focus on basic security features.

Basic security features: As discussed in original contribution [Asghar et al., 2010], basic security features mainly includes security against observation attack through brute force search and password guessing attack. Next we show how modified COP defends these attacks.

(a) Security against observation attack through brute force search: In [Asghar et al., 2010], authors have determined the complexity of this attack as $O(n^{(n+\ell-2)})$, where $n$ and $\ell$ denote the number of cells in the grid and length of the secret, respectively. As values of both these factors remain same in the proposed modification, thus modified COP provides same security standard as of the basic COP to resist this attack.

(b) Security against password guessing attack: In their analysis, in [Asghar et al., 2010], authors derive the probability of guessing the correct secret as $(n^{(n+\ell-2)})^{-1}$. Therefore, it is easily understandable that due to no change in values of $n$ and $\ell$, proposed modification maintains the same security standard to resist this attack.

Inherited HBAT security features: Along with achieving flatness, integrated HBAT security feature includes security against DoS attack and MSV.
(a) **Security against DoS**: As modified COP utilizes 50% of the total response set to create illusion in attacker’s mind therefore, it can provide security against DoS with a probability of $1/2$.

(b) **Achieving flatness and security against MSV**: As modelling-syntax-approach may be used for creating the *honeywords*, therefore though achieves complete flatness, but modified COP cannot provide adequate security against MSV.

5.4.4. **Usability analysis of modified COP**

Usability analysis of modified COP is done against basic usability features and inherited HBAT usability features.

**Basic usability standard**: Modification of COP falls under the category of no CSLI with no CLP and no REI. Thus, it provides the same usability standard as of the basic COP method.

**Inherited HBAT usability standard**: Proposed modification here neither imposes stress on user mind nor has any system interference. But probability of setting off a false alarm due to typing mistake of user becomes $4/9$ here which infers that this method is not much typo-safe. To increase typo-safety, system may ask a user to enter her response multiple (may be 2) times so that probability of typing mistake becomes less.

**Note 7**: Proposed modification of COP does not make any impact on the basic security and usability standard of the basic COP scheme. From HBAT security point of view, it provides weak security against DoS which can be handled by adopting light security policy against this attack as shown in [Erguler, 2015]. Modified COP here though cannot robustly handle the MSV crisis, but can achieve absolute flatness to lure the attacker properly. Form the HBAT usability aspect too, except typo-safety (may be increased though), modified COP meets with almost all the usability features.

**Takeaway**: Though a large number of methods fall under $M_{SOA}^{FODS}$ class, but with existing setup, they cannot provide any kind of security once $F_P$ gets compromised. Due to their design principle, migration to *honeyword* based scheme is not immediate for these methods. By still using the concept of *honeywords*, this paper deals with masking of plaintext password of the methods belonging to $M_{SOA}^{FODS}$ class. Influenced by the facts described in Note 1 and Note 2, we propose few principles in Section 5.1 by following which, any method belonging to $M_{SOA}^{FODS}$ class can store *honeywords* in $F_P$. While Note 3 infers that proposed principles are sufficient for incorporating *honeywords* to any method of the targeted class in theory, Note 4 to Note 7 suggest that HBAT framework can successfully be integrated with existing methods of $M_{SOA}^{FODS}$ class in practice too.

Also, our proposal reveals that some methods (e.g., modified S3PAS) cannot choose a large value of $k$ as this may threat the usability standard. Though the large value of $k$ creates more confusion in attacker’s mind, but we have shown that large value of $k$ makes it more likely to mount DoS attack. Hence, the value of $k$ needs to be chosen carefully to balance the security and usability aspects. As discussed previously, methods that provide weak security against DoS can adopt light security policy to resist this attack as advised in [Erguler, 2015]. To mitigate typing error (especially for modified COP), a user may submit the derived response multiple time (may be twice) without allowing much degradation in usability standard.

6. **Conclusion**

Many fully observable defense mechanisms, identified as $M_{SOA}^{FODS}$, maintain password in plaintext format and migration to a *honeyword* based scheme is not immediate for these methods. This makes any method of $M_{SOA}^{FODS}$ class vulnerable as the password can be easily obtained from the compromised password file. In this paper, our contribution overcomes this limitation of password maintenance mechanism by the $M_{SOA}^{FODS}$ category methods. We show how *honeywords* can be used effectively to fill the existing security gap. To
validate the practicality of our proposed solution, we have considered few well known shoulder surfing attack resilient defense mechanism which cannot afford to store *honeywords* in their existing format. Modification of these schemes results in storing the *honeywords* successfully. The modified schemes provide a satisfactory balance between usability and security features. Our study in this context also reveals an open problem regarding securing user’s plaintext passwords from an adversary who can perform shoulder surfing attack even after obtaining the password file. Nevertheless, this paper shows use of *honeywords* in a new direction and will motivate researchers for further usage of *honeywords*.

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