A Security Analysis, and a Fix, of a Code-Corrupted Honeywords System

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Abstract: In 2013 Juels and Rivest introduced the Honeywords System, a password-based authentication system designed to detect when a password file has been stolen. A Honeywords System stores passwords together with indistinguishable decoy words so when an intruder steals the file, retrieves the words, and tries to log-in, he does not know which one is the password. By guessing one from the decoy words, he may not be lucky and reveal the leak. Juels and Rivest left a problem open: how to make the system secure even when the intruder corrupted the login server's code. In this paper we study and solve the problem. However, since "code corruption" is a powerful attack, we first define rigorously the threat and set a few assumptions under which the problem is still solvable, before showing meaningful attacks against the original Honeywords System. Then we elicit a fundamental security requirement, implementing which, we are able to restore the Honeywords System's security despite a corrupted login service. We verify the new protocol's security formally, using ProVerif for this task. We also implement the protocol and test its performance. Finally, at the light of our findings, we discuss whether it is still worth using a fixed honeywords-based system against such a powerful threat, or whether it is better, in order to be resilient against code corruption attacks, to design afresh a completely different password-based authentication solution.

1 INTRODUCTION

Password-based authentication is the most used method to validate users (Furnell et al., 2000). For users is very simple: they type username and password and submit the pair by pressing the return key or a mouse's button. For servers, it is easy as well: they check the credentials against a database of legitimate user-password pairs and grant access if the search succeeds.

The authentication process is trustworthy only if passwords remain secret. Users are expected to keep them safe, they are supposedly transmitted over encrypted channels, and servers are expected not to store them in cleartext but rather to keep them hashed (usually with some "salt") in a file called the *password file*.

Keeping passwords safe never works perfectly. Users can (or can be lured to) reveal their credentials, and servers can be hacked and have the password file stolen, exposing the hashed passwords to offline dictionary attacks. In both cases, intruders will gain, illegitimately, an *authorized* access. Recent news reports on the extent of the problem. In 2016, the NY Times wrote: "Yahoo!, already reeling from its September disclosure that 500 million user accounts had been hacked in 2014, disclosed Wednesday that a different attack in 2013 compromised more than 1 billion accounts" (Goel and Perlroth, 2016). In the month in which we wrote this paper, Oct. 2017, Yahoo admitted that indeed the number of accounts affected by the data breach in 2013 is above 3 billion (Newman, 2017). As well in 2016, Mashable reported: "MySpace and Tumblr have recently joined LinkedIn on the list of websites that had millions of login credentials stolen and put up for sale later. More than 64 million Tumblr accounts and more than 360 million MySpace accounts were affected by the data breaches." (Beck, 2016). The theft was discovered in 2016 when someone tried to sell the credentials in the black market. In these examples, what hits as dramatic as the number of passwords lost is the large delay that has passed between an attack and its detection. Failing to detect a password breakage on time worsens the problem. It delays the application of countermeasures to limit the damage.

To improve the awareness of password(s) theft, computer security research has proposed solutions.

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For instance, Google monitors suspicious activities and invites users to review from what device and from which location they have accessed their account. But of course, more critical is to ensure that a service become aware of the theft of a password file because, from it, a great deal of passwords is exposed at once. This is what we discuss next.

2 RESEARCH CONTEXT

In 2013, Juels and Rivest proposed to modify the classical password-based authentication scheme (Juels and Rivest, 2013). They called the new system, the *Honeywords System*.

A Honeywords System hides and stores a user (hashed) password in a list of decoy words, called *honeywords*. Honeywords are to mimic the password, so that the password cannot be distinguished from them. So, "redsun3" is a good honeyword for "whitemoon5". A sweetword should have the same probability to be guessed e.g., by dictionary search as the original password, enjoying a property called *flatness* (Juels and Rivest, 2013; Erguler, 2016). Several algorithms to generate (flat) honeyword's are extensively discussed in (Juels and Rivest, 2013). The relevant point is that, since it is very unlikely that a user types a honeyword purely by chance, any attempt to log in with a honeyword instead of the password indicates that the password file has been leaked. In that case, the system flags the event and contingency actions are taken (e.g., system administrators are alerted, monitors are activated, user's execution rights are reduced, user's actions are run in a sandbox, and so on).

The Honeywords System's architecture is logically organized in two modules: (1) a "computer system" which, according to Juels and Rivest, is "any system that allows a user to 'log in' after she has provided a username and a password" (*ibid*) and which we call the *Login Server (LS)*; (2) an auxiliary *hardened secure* server that assists with the use of honeywords, which Juels and Rivest call the *Honeychecker (HC)*.

For each registered user u, LS keeps (in the password file) the ordered list of u's sweetwords (so are called collectively honeywords and passwords), denoted here by $[h(w_x)]_u$, for $x \in [1,k]$ where k is the fixed number of sweetwords. In turn, HC stores c_u, the index of u's password in the list.

At authentication, the system runs a simple protocol: LS receives (u,w); then, it searches the hashed version of w, in the list of (hashed) sweetwords of u. If no match is found, login is denied. Otherwise the LS sends to the HC the message (u,j), where j is

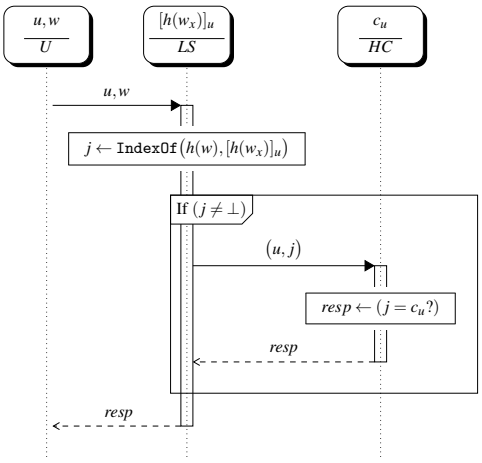


Figure 1: Honeywords System Protocol.

the found position. This communication occurs over dedicated and/or encrypted and authenticated channels. The HC checks whether $j = c_u$. In case the test succeeds, access is granted. In case the test fails, it is up to the HC to decide what to do. Juels and Rivest say: "Depending on the policy chosen, the honeychecker may or may not reply to the computer system when a login is attempted. When it detects that something is amiss with the login attempt, it could signal to the computer system that login should be denied. On the other hand it may merely signal a 'silent alarm' to an administrator, and let the login on the computer system proceed. In the latter case, we could perhaps call the honeychecker a 'login monitor' rather than a 'honeychecker'."(*ibid*). Figure 1 illustrates the protocol considering a responsive honeychecker.

The Honeywords System does not impede that a password file is stolen nor it avoids impersonation: an intruder who has retrieved by an offline dictionary attack the sweetwords can still succeed in guessing the correct password of a user by random choice.

Contribution. Juels and Rivest have left open several problems. One of them reads as follows (the italics is ours):

> "How can a Honeywords System best be designed to withstand active attacks e.g., malicious messages issued by a compromised computer system or *code modification of the computer system*?" (*ibid*).

Here we take on the task to discuss the part of the problem regarding "to withstand code modification of the *computer system*", which we remind is the module that we call the LS. The corruption of this component poses indeed the interesting case: it is discussed in (Juels and Rivest, 2013) where the authors state:

"compromising only the honeychecker at worst reduces security to the level it was before the introduction of honeywords and the honeychecker". Instead, the situation worsens if HC and LS were both corrupted. In this case we are inclined to believe that there is no way to detect the leakage of password file whereas the intruder has a way to gain access unnoticed, but only a rigorous analysis, out of scope but suitable for future work, can provide evidence to this claim.

Thus, we study security of the Honeywords System against an adversary that has succeeded in "code modifying the LS" and we propose a solution for it. However, since the notion of "code modification" was left informal in Juels and Rivest's work and it is not clear enough to understand the real nature of the threat, we first need to critically discuss it.

In §3 we give a rigorous definition for the threat "code modification", which we rename "*code corruption*" to stress its maliciousness. We also state a few foundational assumptions before thoroughly giving the analysis of security of the original Honeywords System under the threat.

In §4 we prove the Honeywords System insecure, illustrating an attack that works when the LS's code has been corrupted according to our model and under our assumptions. The attack reveals that when confronted against the threat, the original Honeywords System has a core weakness. From studying the root cause of the attack we elicit a security requirement and by fulfilling it we are able to provide a solution to the problem.

In §5 we describe a new cryptographic protocol which we argue that removes the weakness and so restores security. We sustain this statement formally in §7. We model in ProVerif the protocol together with the code-corrupting adversary and we run an automatic analysis. The results of the verification confirm that the previous attack is no more possible. Actually, we prove that there are no more attacks against the new protocol, in the given model.

Our solution is meant to be primarily of theoretical interest, but because its cryptographic primitives rely on a generous use of exponentiation, we thought useful to implement the protocol and benchmark its performance with respect to the original Honeywords System. The results of the tests are reported in §8: they show that although slower than the original Honeywords System, the loss in performance is linear in k, the number of sweetwords. Roughly speaking, our scheme can handle a few hundred authentication requests per second on a laptop with the service running on a virtual machine. It is reasonable to expect better results on more performing servers.

At the end, in §9, we discuss our solution in a wider perspective. We look at it from distance to conclude that, although it solves the open problem and works against the code-corruption threat that we have defined, it actually suggests a completely innovative design for password-based authentication stronger than that of the fixed Honeywords System.

3 ADVERSARY MODELS

What is a reasonable goal for an adversary that intends to code corrupt the system? What is *code corruption*? What levels of corruption are interesting to study?

We have to answer these questions to fully understand the threat. And understanding code corruption requires also introducing *assumptions* that limit the extension of the threat. Code corruption can be very disruptive and not all its instances are interesting, in the sense that they do not bring to insights that help up understanding fundamental weaknesses of the system design. What understanding do we gain from a code corruption that, for instance, causes a shut-down of the entire systems? In short, we have to define rigorously our adversary model.

We start with an obvious assumption that follows from the original Juels and Rivest's paper:

Assumption 1. *The adversary, before code-corrupting the LS, knows the sweetwords but not the passwords.*

Assumption 1 says that the adversary has stolen the password file and has reverse-engineered all the k sweetwords of, say, user u: yet, he does not know which one among u's sweetwords is the password. The adversary can try to guess it and log in with that guess, which means that his probability to log in without the HC's raising an alarm is $1/k$ in the worst case, when the intruder naïvely picks at random a sweetword. Additional factors, such as knowing social information about a specific user, might be used to increase the probability of guessing the password. Let us call this event a "successful log-in".

Let us now start answering the first question: "what is a reasonable goal for an adversary that intends to code corrupt the system?". We will consider as the answer that a reasonable goal is to increase the intruder's probability of a successful log-in to a value higher than that the intruder would have by guessing the password and with an honest LS.

Definition 1. *The goal of a code corruption attack is to increase the adversary's probability to successfully log in with respect to the probability of guessing the password among the sweetwords retrieved from the passwords file.*

We answer the second question "what is code corruption?" gradually. We start with a very general and powerful definition, but we will later constrain it while answering the last question "what levels of corruption are reasonable to consider"?

Definition 2. *Let* ls.exe *be the code that defines the protocol executed by the LS. Code corruption of LS means changing* ls.exe*.*

With its code corrupted, the LS's working can change completely. An intruder can reprogram it to do whatever, e.g., to play chess.[1] However, we are not interested in attacks that change the functionality of the LS, for the reason that they do not help the adversary to increase its probability of successful logging in. For a similar reason, we are not interested in attacks that shut-down the systems or cause Denial-of-Service. These are important attacks from which to seek defense, but out-of-scope in this study.

We also exclude attacks such as those consisting in changing ls.exe to always grant access. Actually, there is a technical reason for this choice. The original paper does not give full detail of the architecture of the "computer system", our LS, but it seems reasonable to assume that Honeywords System implements a *separation of duties* (Botha and Eloff, 2001). And the duty of LS is only to search the proffered password in the password file, to consult the HC, and possibly to report the decision to the user, but not to grant or deny accesses.

So, what is a reasonable code corruption? We consider here a particular type of corruption, as much as possible "undetectable", that is working without raising suspect of LS's misbehaving into the other modules. This can be achieved by changing `ls.exe` in such a way that LS's behaviour remains the same from the point of view of the modules it interacts with, mainly from the viewpoint of who can raise alarms, primarily the HC and, secondarily, the system administrators.

Assumption 2. *A code corruption against LS does not change the LS's observable behaviour.*

The rationale of this assumption is that, if the adversary changes the observable behaviour of LS, this would result in an anomaly that can be detected, triggering an alert in response to which a safe version of the `ls.exe` can be restored. Since the adversary may have a once-in-lifetime opportunity to corrupt LS's code, he may not want to see his efforts vanishing in this way. Of course not all attackers will be so concerned about being undetected. They can be satisfied by managing to log in and say ex-filtrate sensitive data might be fine, even if this leaves a trail. But we decided to scope our analysis only within the context of Assumption 2.

However, even under Assumption 2 there are subtleties that need to be addressed. Interpreted strictly it does not allow the creation of any back door between the adversary and the LS that this last can use at anytime to leak information. This is because, interpreting strictly the term "undetectability", an exchange of messages from the LS towards the adversary and outside the protocol's message flow can be eventually detected (e.g., by monitoring the net traffic), leading to have a safe version of the `ls.exe` re-installed. Thus according to this interpretation, Assumption 2 says that if the intruder wants to communicate with the corrupted LS, it must use the same channels from which legitimate users log in, and must respect the message flow of the honest protocol. This does not exclude that, when re-coding `ls.exe`, the adversary can use the knowledge he has gained from having hacked the password file in the first place. It can use the user's IDs and sweetwords, and it can hard-code this information in the corrupted `ls.exe`.

Still, if we take Assumption 2 less strictly, it admits that some information can flow back to the adversary, for example, in message *resp*. And, as we will discuss in detail in §4, letting LS to communicate back to the adversary leads to a powerful attack that breaks the original Honeywords System. In short, the attack works because LS can learn u's password (or the hash of it). This is a feature more than a vulnerability but a feature that a collusive adversary able to invert the hash can exploit to know the password. So, an incentive for code corrupting the LS is exactly to create this retroactive communication and we cannot exclude this possibility in our analysis. We propose thus the following methodology. By default we interpret Assumption 2 strictly but, separately, we always discuss what happens if we relax this constraint and let LS leak information to the intruder.

Notably, the new protocol that we describe in §5, although designed to secure the Honeywords System under an Assumption 2 interpreted strictly turns out to be efficient also when we relax it. The new protocol will not impede the leak nor stop the adversary from learning u's password, but will make that information useless for the adversary because it will not be able log in with it into the system. Somehow our solution reduces considerably the role of the password as the only authentication token.

[1] This is what R. Gonggrijp did when, in 2006, proved insecure a Dutch electronic voting machine.

4 ATTACKS

As future reference, we write down how ls.exe looks like. Algorithm 1 shows it in pseudo-code, using a notation whose commands are self-explanatory. Here, passwd is the password file, passwd_u is the row of user u, and H is a hash function (e.g., SHA-3 (NIST, 2015)). We also assume that u is a legitimate user's name.

Algorithm 1: Login Server Authentication.

```
1: procedure ls.exe(passwd)
2:     while true do;
3:         ReceiveFrom(U;(u,w));
4:         j ← IndexOf(H(w), passwd_u);
5:         SendTo(HC;(u,j));
6:         ReceiveFrom(HC;resp);
7:         SendTo(U;resp);
```

Algorithm 2: Code Corrupted LS.

```
1: procedure ls'.exe(passwd)
2:     (u',w') ← (⊥,⊥)                          ▷ init good (u,w)
3:     while true do;
4:         ReceiveFrom(U;(u,w));
5:         if (u' ≠ ⊥) ∧ (u = Mallory) then
6:             (u,w) ← (u',w')
7:         j ← IndexOf(H(w), passwd_u);
8:         SendTo(HC;(u,j));
9:         ReceiveFrom(HC;resp);
10:        if (resp = granted) then
11:            (u',w') ← (u,w)                   ▷ good (u,w)
12:        SendTo(U;resp);
```

If the adversary can corrupt ls.exe, even under our Assumption 2 taken strictly, there is an obvious attack. The corrupted ls′.exe is reported in Algorithm 2. It stores a good user's password when LS sees it, and then it reuses that knowledge to let the adversary gain access, when the adversary reveals itself at the log-in with a specific user name (e.g., "Mallory").

Actually, LS could remember only the valid j (in step 11) and, in a next round, skip searching the passwd_u (step 7), and send that j to the HC (step 8). But the corrupted ls.exe outlined above mimics the behaviour of LS more faithfully and shows also that *LS gets knowledge of a user's valid password*. This, we will see, is the root of serious vulnerability.

Algorithm 2 represents an ideal attack. Not always, in instruction 10, the LS learns u's password with certainty. This may happen, for instance, when the HC follows a contingency policy that dictate to respond by granting access even when he sees a sweetword, as suggested in the original work (see also our quote of it in §2). However, the following strategy gives the LS at least a good chance to guess the password, especially when the strategy is coordinated with the adversary: since the adversary is the only one that can submit honeywords, it refrains itself from trying to access for a certain time. During this interval, the only requests that arrive to the LS pretending to be from user u are actually from the legitimate u; all the w that come with the requests then must be the u's legitimate password. Surely, the user can sometimes misspell the password, but that will never collide with a honeyword (because honeywords are flat, see §2). It is therefore possible for the LS, purely by statistical analysis and by cross comparison between what u submits, to infer the u's real password and at that moment the LS can so help the adversary as we illustrated in our ideal version of the attack. The adversary has raised its probability to gain a successful access to values higher than $1/k$.

This attack is already serious but under a relaxed Assumption 2, LS can further send the password back to the adversary, who now can use the u's credentials at any time.

Discussion. The root cause of the attack seems therefore to lie in the fact that LS knows u's password. Only hashing the password will not help, since the LS can search the position in the password file or, under a relaxed Assumption 2, send the hash back to the adversary who can reserve the hash. The main problems seem then rooted into three concomitant facts: (a) LS receives username and password in clear; (b) LS can query HC as an oracle to know whether that submitted password is the user u's valid password (in this way it also get to know the hash of the password); (c) LS can retrieve the index of the password in passwd_u. So, if a solution exists that makes the system secure despite a corrupted ls.exe then it would be such that it avoids that LS could perform all these three actions (a)-(c) together. We state this finding as a requirement:

Requirement 1. *A solution for a LS resilient to code corruption should not (1) let the LS receive usernames and (tentative) passwords in clear, (2) let it know when the typed input refers to a valid password, and (3) allow it to reuse that pair to retrieve a valid index at any moment that is not when a legitimate user logs in.*

5 TOWARDS A SOLUTION

In searching for a solution we are not interested in pragmatic fixes like checking regularly the integrity

of `ls.exe` and reinstalling a safe copy. Our lack of interest is not because solutions like that are not fully effective (e.g., the intruder can still execute its attack before any integrity check is performed) but because such pragmatic fixes do not give any insights about the real weakness of the system. The same argument holds for best practices like forcing users changing the password frequently. Thus, if a solution exists then it must be searched in a strategy that satisfies our requirement's items (1)-(3).

One way to comply with them is by implementing the following countermeasures: (i) passwd_u is *shuffled each time* LS queries HC: this avoids that LS can reuse an index j that it has learned to be the index of u's password; (ii) passwd_u is *re-hashed each time* LS queries HC: this avoids that LS can search again for the index of a typed password that it got to know being a valid u's password; (iii) let the *LS know what to search in* passwd_u *only when user u is logging in*: this precaution is to avoid that LS can perform off-line searches on passwd_u.

The countermeasures (i)-(ii), and so requirements (1)-(2), can be implemented *leaving HC in charge of shuffling and re-hashing the password file each time that a user logs in and that the LS questions the HC about index j*.

The shuffling does not require particular explanation. It must be randomized but is a standard step: given a row $[w_1,\ldots,w_k]$, and a permutation π, it returns $[w_{\pi(1)},\ldots,w_{\pi(k)}]$.

The re-hashing, instead, needs to be explained. It is implemented by *cryptographic exponentiation*. For each user, HC possesses g, a generator of a multiplicative subgroup $\mathbb{G}$ of order q (so, actually, g should be written g_u, but to lighten the notation we omit the index u). When first the list of sweetwords is generated, the file is initially hashed using g^{r_0}, where $r_0 \in \{1,\cdots,q-1\}$ is a random number. The u's row of the file is therefore $[g^{r_0\cdot w_1},\ldots,g^{r_0\cdot w_k}]$, which we write $[h^{r_0(w_1)},\ldots,h^{r_0(w_k)}]$ to stress that this is a hashing. More synthetically we also write it as $h^{r_0}(\overline{w})$.

To rehash the row and obtain $h^{r_1}(\overline{w})$, HC choses a new random number $r_1 \in \{1,\cdots,q-1\}$ and, for each element w_i of the row, it calculates

$$h^{r_0}(w_i)^{\frac{r_1}{r_0}} = (g^{r_0\cdot w_i})^{\frac{r_1}{r_0}} = g^{r_0\cdot\frac{r_1}{r_0}\cdot w_i} = g^{r_1\cdot w_i}.$$

The process can be iterated: to re-hash token $h^{r_n}(\overline{w})$, HC selects another number $r_{n+1} \in \{1,\cdots,q-1\}$ and computes $(h^{r_n}(\overline{w}))^{r_{n+1}/r_n}$ which is the re-hashed token $h^{r_{n+1}}(\overline{w})$.

In fact, HC reshuffles and re-hashes passwd_u in one single step as shown in Figure 2.

So far, we are envisioning a message flow as follows: when HC receives from LS a check query, it

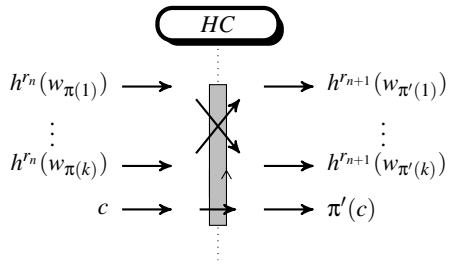


Figure 2: Shuffling/re-hashing w's and updating c.

also receives $\mathsf{passwd}_u^{r_n}$, which it shuffles using a new ordering π', and re-hashes using a freshly generated r_{n+1}. The re-hashed, re-shuffled row of u, passwd_u, is therefore $[h^{r_n}(w_{u,\pi'(i)})]_{i\in\{1,\ldots,k\}}$, which we write compactly as $\mathsf{passwd}_u^{r_{n+1}}$. HC *performs these three steps indivisibly*: the $\mathsf{passwd}_u^{r_n}$ should not be accessed by concurrent versions of the HC before it has been shuffled and re-hashed.

What explained so far implements countermeasures (i) and (ii). However, each n^{th} time that a user u logs in and submits the password w, LS needs first to calculate $h^{r_n}(w) = g^{r_n\cdot w}$ before being able to search for w's index in $\mathsf{passwd}_u^{r_n}$.

Letting LS to do this while avoiding that it gets to know u's password (i.e., by taking advantage of knowing the re-hashed password file $\mathsf{passwd}_u^{r_n}$ and the re-hashed $h^{r_n}(w)$, so anticipating the search and using HC as an oracle) is not obvious. We need to implement countermeasure (iii) and *prevent LS from searching the file at any time that is not when a legitimate user u logs in*.

Our final solution is explained in §6 and its workflow is illustrated in Figure 3. Its core idea is to inform the HC when a user is logging in, but without passing through the LS which may otherwise interfere with the communication. Because of the risk of man-in-the-middle attacks, this communication should not be over the Internet either. Instead, it *must happen on a secure second channel between the user and the HC*, which we suggest to be the *ether* and implement by letting them use a One-Time-Password (OTP) device. We are aware that, introduced without an adequate explanation, the need of a second channel and our suggestion to use an OTP may appear arbitrary and unjustified. They are not. Thus, in the next section we briefly explain our reasons, but the reader interested only in the new protocol can skip it, and restart the reading from §6.

Why a Second Channel? Before concluding that we need a *second channel* between the user and the HC we tried to comply with countermeasure (iii) by other ways. One attempt was to add a module, called

Keys Register (KR), to keep r_n. Abstractly, this suggests to outsource the calculation of the hash of the submitted password out from the LS. In particular, we let KR receive (u,w) and calculate the $h^{r_n}(w)$. The token is thus forwarded to the LS, who also receives the username u. Notably, KR's role cannot be played by LS itself. This would lead it to know the hash of the password and so its valid index, consequently enabling an attack as we have described previously. KR's role apart, the authentication process is not different from what we described before, with the HC that also shuffles, re-hashes, and returns the password file to the LS, but at the end the HC sends the new r_{n+1} only to the KR, which is ready for a new session.

This solution works i.e., it is secure, but only if KR cannot be code-corrupted. This is not an assumption that we intend to take easily. According to Juels and Rivest, the only component that is hardened secure is the HC. Thus, KR should be considered corruptible. And if it is so, the intermediate solution has a flaw. An adversary can compromise both kr.exe and ls.exe and, even under a strict Assumption2 with no back doors, manage to successfully log in. The attack is implemented by the following corrupted code, where we assume h' and passwd'_u be updates of h and passwd_u. The corrupted instructions are in red:

Algorithm 3: Code Corrupted KR.

```
1: procedure kr'.exe(r_n)
2:     while true do;
3:         ReceiveFrom(U;(u,w));
4:         SendTo(LS;h^{r_n}(w));
5:         ReceiveFrom(HC;r_{n+1});
6:         SendTo(LS;h^{r_{n+1}}(w));
```

KR resends the last w, re-hashed using the new r_{n+1} received from HC. KR does not know whether w is a valid password, but a corrupted LS does. The attack works because LS gets pieces of information beforehand, using which, he can anticipate querying the new password file and get a valid j that can be used to let the adversary in.

Alternative ways to implement (iii), such as using timestamps from the user's side as a proof of freshness do not work either since LS stands in the middle and can compromise those messages. For all this follows our conclusion that if there must be a "synchronization" between users and the HC, it must be happening over a channel that is not under the control on any module of the Honeywords System nor of the adversary.

6 THE NEW PROTOCOL

One way to realize requirement's items (i)-(iii) in agreement with the Honeywords System solution, is to empower the user (i.e., the user's browser) with the ability to hash his password w with g_n^r using the same r_n that is generated by the HC. It is (almost) equivalent to let the user play the role of KR.

However, letting HC send r directly to the user over the Internet leaves the channel exposed to man-in-the-middle attacks and introduces other issues such as that of ensuring authentication of the user. The channel through which the HC "communicates" with the user must be a second channel and not in the Internet. We already justified this choice in the previous section.

The solution that we are about to discuss now and prove secure in the next section requires that the HC and the user share an OTP device. This is employed to generate a new seed r each time that the OTP is used, a seed which is also the same for the user and the HC. The protocol message sequence diagram is detailed in Figure 3.

The OTP serves as pseudo-random generator but also as proof of freshness, since what it generates is synchronized with what the OTP generates by the HC. Here we talk of an OTP that generates a new seed each time that it is pressed.

In Figure 3, we have indicated with $\mathtt{OTP}(n)$ the action of using the OTP for the n^{th} time (step **1**). The user sends to the LS, the username u and the hashed version of its password, $h^{r_n}(w)$, where the hashing takes the n^{th} OTP-generated number r_n as parameter (step **2**).

Then, the protocol follows as expected: the LS searches for an index in the password file (step **3**); the file has been reshuffled and re-hashed in a previous session by the HC, which has used in anticipation the same OTP number that the user has now used to hash the password (we will discuss in §6 how to handle when a user "burns" a generated number by pressing the OTP accidentally outside the login). The found index j is submitted together with the username and the row of the password file that LS has just used in the search (step **4**).

The HC checks first j against c_u (i.e., the index of the user's password) to determine whether to grant access or not (step **5**), then shuffles and re-hashes the password file's row. It also updates the c_u considering the index's re-ordering (steps **6**). The shuffled and re-hashed file is returned to the LS (step **7**) and LS notifies the user (step **8**).

Informal Security Analysis. We argue that there is no corruption of the LS that under our assumptions can lead to a successful attack. In particular, even if the LS learns that a particular $h^{r_n}(w)$ is a valid password, LS cannot make any use of it to anticipate the index that w will have in the new reshuffled and re-hashed password file. LS could retain an old file, but the index retrieved from it is not the new c'_u that the HC now holds. It could send to the HC the username and sweetwords file's row of another user and so have this later reshuffled and re-hashed. The only gain is that LS will likely have the request rejected without never get to know whether that hashed honeyword (and consequently the j calculated) were good for access. Note that even if two users use the same password, it is very unlikely that the hashes are the same if we assume that each user has its own OTP. LS can send the username u and password file's row of another user to know the answer about the correctness of j without having the file's row of u reshuffled and re-hashed. But then, HC changes c_u and so the LS will not be able to take advantage of what he has learned; besides, the effect seems to be disastrous in terms of compromising the integrity of a future check, when u logs in again. This counts as a Denial-of-Service (DoS) but not as an attack according to Definition 1 since it does not increase the probability of the adversary to gain access, which remains $1/k$.

Finally, our protocol is secure even under a relaxed Assumption 2. Even if the LS, learned that a particular $h^{r_n}(w)$ is a valid password, sends it back to the adversary which in turn retrieves the w, the adversary cannot use either w or the token $h^{r_n}(w)$ to gain access. He needs the token $h^{r_{n+1}}(w)$ which he cannot generate without holding also the OTP.

Before concluding, we comment on what to do if the user accidentally burns some of the valid OTPs. A classic solution is that the HC anticipates new versions of the password file using a certain number, say m, of the next OTPs. The file's row for user u becomes a matrix where each row is ordered with the same π':

$$\begin{bmatrix} h^{r_n}(w_{u,\pi'(1)}), & \cdots & , & h^{r_n}(w_{u,\pi'(k)}) \\ & \vdots & & \\ h^{r_{n+m}}(w_{u,\pi'(1)}), & \cdots & , & h^{r_{n+m}}(w_{u,\pi'(k)}) \end{bmatrix}$$

The HC stores one c_u as before, but when shuffling and re-hashing the matrix for the new run, it discards all the rows that correspond to the OTP numbers that the user has accidentally burned, including the one used in the current submission (which HC receives from LS).

7 FORMAL ANALYSIS

We modeled the original protocol and our proposal (Fig. 3) in the *applied-π calculus* and used ProVerif (Blanchet, 2001) to formally verify their security. ProVerif is an automatic verifier for cryptographic protocols under the Dolev-Yao model. The code for and results of the analysis are available at https://github.com/codeCorruption/HoneywordsM.

Analysis of the Original System. We start by analyzing the original Honeywords System. We know already that there is an attack, but our aim is to test the proper way to model a LS that has been code corrupted according to Assumption 2. Moreover, we need to correctly interpret the results, discarding attacks originated from stronger attackers than the one defined in our threat model.

Our design is based in the following decisions. There are three parties: the User (U), the LS and the HC. The LS is an active attacker since it is able to read and send messages from and to the HC; the channel between LS and HC is thus public. In contrast, the channel between U and LS is private, otherwise the attacker can learn a correct pair of user and password from the beginning, contradicting Assumption 1. Note that this decision together with the fact that the password is never transmitted in the public channel, prevents the attacker to know the submitted password at any time. It also rules out the simplest guessing (password) attack, which is the first one that ProVerif finds in the analysis, allowing the verifier to find attacks more related to the protocol's flow. We know already that a guessing attack is always possible, since Honeywords System is not designed to avoid it.

The attack described in §4 violates the security property:

$$\begin{aligned} correctIndex(u,j) \implies & injct(indexFound(u,p,j)) \\ \&\& \quad & injct(usrLogged(u,p)) \end{aligned}$$

It expresses that, whenever the HC sends a positive answer to the LS for a submitted pair of user and index (u, j), all of these three actions occurred: (1) a user logged in with a pair of credentials (u, p) (2) the index j found by the LS corresponds to (u, p) and (3) the value stored in HC for u is equal to j. Injectivity in the expression (*injct*) captures the fact of HC processing only once each request that LS submits after events (1) and (2), to prevent interaction between LS and HC in the absence of a user.

Result. As expected, the verification indicates that the property does not hold. The attack found shows how once the attacker (in this case the LS) gets a posi-

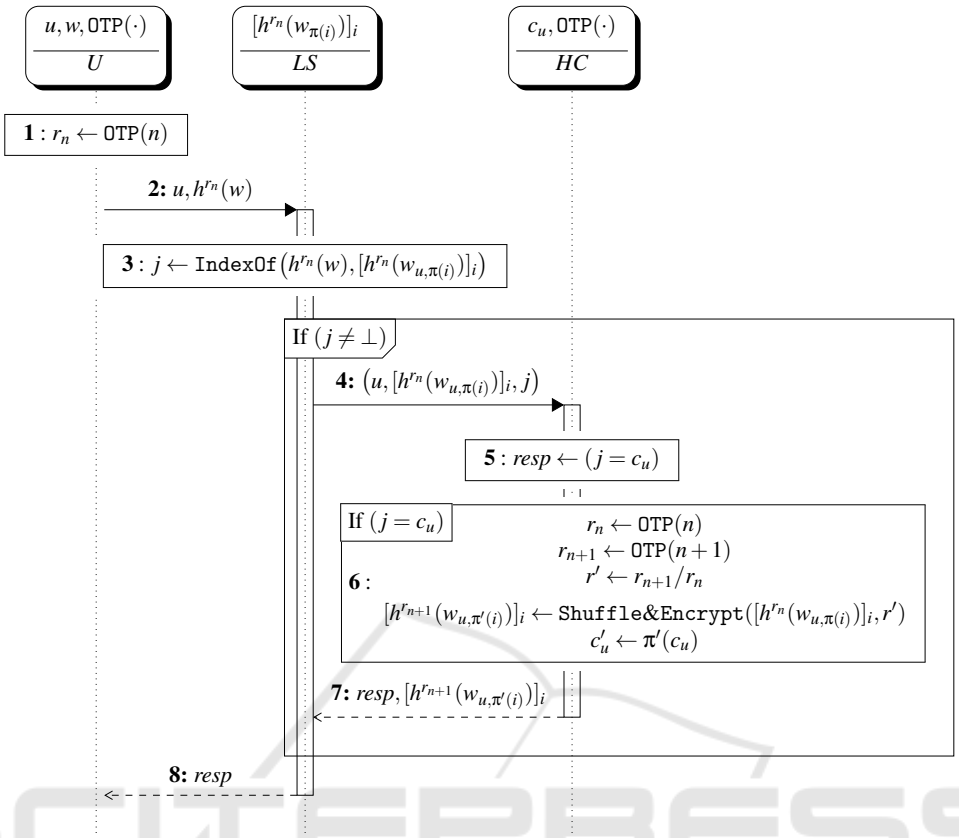


Figure 3: The new protocol.

tive answer from the HC, it is able to send a new check request to HC with the correct user and index, gaining access to the system and thus contradicting injectivity, because there was not a new $usrLogged(u,p)$ event for that second request. These observations support our model design for code-corruption and provide formal evidence that a Honeywords System resilient to the flaw must satisfy Requirement 1.

Analysis of our Solution. We are now ready to apply the analysis to the new protocol. In this ProVerif model, all channels are public since the LS can send requests at any time and can learn the inputs from U and HC. We choose this design to discover any attack using any information available. Conversely, the LS's function that retrieves the index of a sweetword is private, because LS can get information from the password's file but cannot modify it.

Unlike in the original, in this protocol each instance of U is synchronized with a HC instance by a *seed*, representing that both parts generate the same OTP at the beginning of a round; the HC knows as well the index of the password. Then, to give LS the opportunity to attempt an attack using the knowledge gained during the run of the protocol, we model the fact that HC keeps running with the updated index after reshuffling. The LS is almost as in the original protocol, except that this time it receives a hashed password parametrized by the OTP, instead of a plain password. An index is a term determined by the hashed word searched and the row of sweetwords where it is searched. Our expanded representation in ProVerif is

$$indexOfHw(hashWord(w, getOTP(n)), shuffleNhash(u,n))$$

where *hashWord* is the hash of the plain submitted word w calculated with the seed n; *shuffleNhash* is the sweetwords' row for user u hashed with seed n.

Our equational theory relies on the *checkEqual* function in the HC, which returns *true* only when all the parameters in the indexes under comparison are equal. After a successful match, the index hold by the HC is affected by the next seed value, becoming $indexOfHw(...getOTP(\mathbf{next(n)}), ...(u, \mathbf{next(n)}))$. Therefore, after this point the evaluation of *checkEqual* will be *false* for any submitted index not obtained with the new seed.

The property that we want to prove is the same as for the original Honeywords System:

$$\begin{aligned} correctIndex(u,j) \implies & injct(usrLogged(u,p)) \quad \&\& \\ & injct(indexFound(j, \\ & \quad hashWord(p,x), \\ & \quad shuffleNhash(u,y))) \end{aligned}$$

It states that every time an index j is equal to the one in the HC's database for u, then (a) the owner u of j logged in with password p and (b) j corresponds to the index of the hashed value of p in the sweetwords row for u. The conjunction ensures the execution of every step in the protocol; the injectivity ensures that each is executed only once.

In addition, we introduce the property $event(unreachable)$ to verify that LS cannot retrieve a sweetword's index of a word not submitted by a user; the event *unreachable* is triggered if the HC's check function returns *true* after shuffling and rehashing, when applied to a previously submitted hashed password.

The model also assumes, as we stated in §5, that HC must process LS's requests *atomically*, finishing a request before starting the next. Failing to implement HC this way, leads to an attack as we are going to explain in the next section, which prove that atomicity is in fact necessary.

Result. All properties were verified to be true almost immediately. It follows that even knowing that a certain $hashWord(p, getOTP(n))$ is a valid password, LS cannot use it to anticipate the new good index, since it depends on the seed value possessed only by U and HC.

The analysis also proves that event *unreachable* is actually unreachable and this implies that LS cannot get any advantage even if using HC as an oracle if using messages obtained from previous runs with U and HC.

We also verified that it is necessary for the HC to process parallel requests coming from the same user u without breaking the indivisibility of the update of passwd_u. Removing this constrain reveals an attack. The attack is as follows: let HC_1 and HC_2 be parallel runs of the HC, then (1) After a LS request, HC_1 verifies that the submitted index is correct and sends the answer to LS (2) LS submits again the correct index, HC_2 processes it, finishes the protocol and grants access (3) HC_1 continues its execution and grants access as well.

8 COMPLEXITY AND PERFORMANCE

The contribution of this research is mainly theoretical but we judged useful to test the performance of what we propose. We sketch a complexity analysis and we benchmark an implementation of our protocol both, with respect to the original system and by using different parameter for the elliptic curve (EC) multiplication which we used to execute the main operation of our protocol: exponentiation.

Complexity Analysis. The analysis assumes that an elliptic curve multiplication takes constant time $t_{\texttt{CURVE}}$ (which depends on the employed `CURVE`): this protects implementations against remote timing attacks (Brumley and Tuveri, 2011).

Let us now consider the operations that affect the performance. Once received the password, LS calls `IndexOf` to search the index of the submitted password among the sweetwords. Given that the sweetwords are not ordered and also are constantly reshuffled, this is a linear search. In the worst case it can be done in $O(k)$ time, where k is the number of sweetwords per user. In case of a match, the HC checks the validity of the index in $O(1)$ time. Next, the HC calls `Shuffle&Hash`; this function shuffles the sweetwords in $O(k)$ time and performs k times an EC multiplication in $k \cdot t_{\texttt{CURVE}}$ time. The last equation is linear in k for a fixed `CURVE`. Since each of the previous operations takes at most $O(k)$ time, the time complexity of the new protocol is $O(k)$. As well, for a fixed k, the execution time increases linearly as $t_{\texttt{CURVE}}$ grows. Moreover, EC multiplication is CPU intensive and dominates the total execution time. This is also confirmed by our empirical results (see Fig. 4(a)).

Communication Cost. In the original Honeywords system, the communication cost per login comes from messages (u, j) and *resp*. We denote the number of bytes required to encode (u, j) and *resp* by $|(u, j)|$ and $|resp|$ accordingly, and obtain the data transfer rate per login as

$$C = |(u, j)| + |resp|$$

While the data flow remains the same, our protocol brings the following communication overhead to the original Honeywords system: LS sends the sweetword hashes $[h^{r_{n+1}}(w_{u,\pi'(i)})]_{i=1}^{k}$ and receives the updated ones. The number of bytes required to encode a password hash depends on the employed curve and is denoted by $\mathtt{H}_{\texttt{CURVE}}$. Thus, LS sends $|(u, j)| + k\mathtt{H}_{\texttt{CURVE}}$ bytes and receives $|resp| + k\mathtt{H}_{\texttt{CURVE}}$ bytes per login. As a result, the total data transfer rate per login between LS and HC is computed as $C + 2k\mathtt{H}_{\texttt{CURVE}}$ bytes.

Since k, the number of sweetwords, is a constant defined by the system, and $\mathtt{H}_{\mathtt{CURVE}}$ is constant too, the overload in communication is bounded. We have not simulated nor evaluated how much this may affect a server's ability to process a great number of log-in attempts per unit of time, but we are inclined to believe that this loss in performance is not so dramatic. Of course one may will to discuss whether the solution that emerges from our analysis by fitting our requirements is not actually an overkill in itself. This is a legitimate question which we discuss in § 9.

Implementation. We implemented our solution in `C#` atop the Microsoft .NET framework.[2] Elliptic curve operations are performed using Bouncy Castle Cryptographic Library, although a faster version may be obtained by native language implementations or libraries.

In our implementation, u, j and *resp* are implemented as integers, hence C equals 12 bytes and $\mathtt{H}_{\mathtt{CURVE}}$ takes 57, 65, 97, and 133 bytes for `P-224`, `P-256`, `P-384` and `P-521` accordingly. Fig. 4(c) compares data transfer rates with different settings.

Performance Analysis. We measured the efficiency of our proposed protocol with two questions in mind: *How does number of verifications per second correlates with the number of honeywords? What is the impact of the selected curve on verification speed?* The results presented have been performed on notebooks with Intel Core i7 CPU and 8GB of RAM over an idle network. We measured the total execution time on server side computations and communication over the network separately. Roughly speaking, our prototype reaches a decision for each login request below 9 ms. Table 1 summarizes the overall performance with different settings.

Another performance consideration is the cost of avoiding login failures due to out-of-synchronization of OTPs. System policies may follow the strategy discussed in Section 6. The computational overhead of both, Login Server and Honeychecker, increases linearly on the number of copies in the password file.

It is reasonable to expect that the time required for re-encryption directly depend on the number of honeywords for a user. Fig. 4 illustrates the time measurements. It can be seen that the time required for verifying a single user increases linearly with the number of honeywords per user. The Honeychecker performs one EC multiplication for each honeyword, which is the most expensive part of its function, and the result is aligned with our theoretical expectations. Our solution preserves the computational characteristics of the original honeywords protocol: performance is linearly dependent on the number of honeywords. On the other hand, we can see from Fig. 4 (and from Table 1) that the time to run the employed curves increases with the number of honeywords.

[2]Source code is available under GPLv3 at https:// github.com/codeCorruption/HoneywordsM.

Table 1: Performance results of our implementation. Login Server and Honeychecker columns display the time in milliseconds for a single authentication on LS and HC, respectively. Throughput column shows the maximum number of verifications per second. Round-Trip Time (RTT) is the network delay during the experiments.

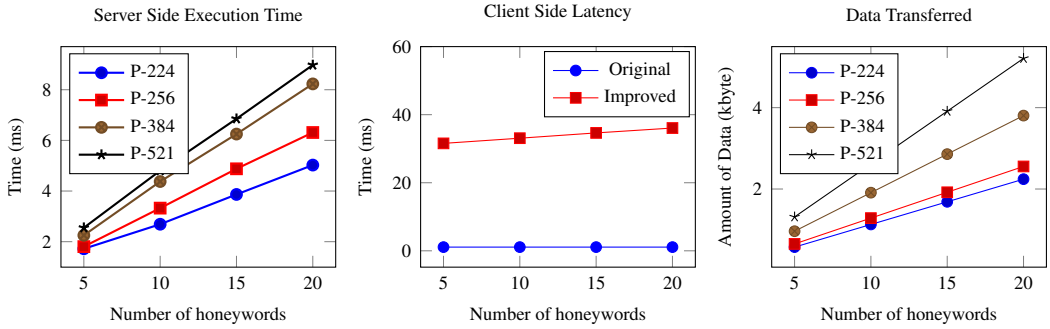
k	Curve	Login Server (ms)	Honeychecker (ms)	Throughput (login/s)	RTT (ms)
5	P-224	0.011	1.709	581	24.446
5	P-256	0.009	1.796	554	28.917
5	P-384	0.009	2.242	444	31.502
5	P-521	0.010	2.541	392	30.812
10	P-224	0.009	2.680	372	24.534
10	P-256	0.009	3.317	301	29.885
10	P-384	0.010	4.365	229	34.918
10	P-521	0.010	4.793	208	29.414
15	P-224	0.009	3.856	259	27.063
15	P-256	0.010	4.868	205	30.896
15	P-384	0.009	6.240	160	36.253
15	P-521	0.010	6.842	146	31.445
20	P-224	0.009	5.016	199	26.867
20	P-256	0.010	6.301	158	29.355
20	P-384	0.010	8.220	122	32.724
20	P-521	0.011	8.965	111	31.944

Figure 4(b) compares our protocol with the reference implementation. The client side latency of both, original and improved protocols stays almost constant. Considering the delays caused by the network, the computational overhead of our protocol is relatively small. It might not be even noticed by the clients.

9 DISCUSSION

This paper takes inspiration from a challenge left open in (Juels and Rivest, 2013). There, Juels and Rivest propose a password-based authentication system, called Honeywords System, meant to detect when a password file has been stolen. User passwords are hidden among a list of honeywords and an attacker that knows all of them cannot do better than guessing which one is the rightful password. This reduces its probability of success while revealing the leak when the attacker types one of the supposed secret honeywords instead. The open problem is how to make this concept work even when a key component of the Honeywords System, the Login Server (LS), has its code corrupted by an adversary.

We defined rigorously the notion of code-corruption, which is too powerful if taken literally. Constrained to become tractable, the adversary model results to be a less powerful version than a Dolev-



(a) (b) (c)

Figure 4: (a) CPU time required to verify a user depending on the number of honeywords and employed curve. (b) Client side latency comparison between original protocol and our proposal with NIST Curve P-256. (c) The amount of the data (in kilobytes) transferred between the Login Server and the Honeychecker.

Yao, but such that gives the attacker a better probability of success than guessing the password from the set of honeywords. The root cause of such attacks lays in the LS knowing eventually a user's valid (hashed) password. The solution that we propose avoids that, but at a price that seems unavoidable. It prevents the LS to make, off-session, any good use of what he knows, but the new protocol, according to the requirements that we elicited from studying attacks on the original Honeywords System, consists in shuffling and rehashing the password (plus honeywords) after any user's attempt to log in. The new solution also avoids that the LS can receive a token with which it can search in the password file at any moment distinct from when a legitimate user is logging in, but this last requirement implies that the user and the Honeychecker (HC) somehow get synchronized by using a second channel that is not controlled by the LS or by a man-in-the-middle. We propose One-Time-Passwords (OTPs) for this purpose. The solution is secure as we proved formally in ProVerif.

Although our result has meaning mainly for its theoretical insights, it performs reasonably well as we show in a benchmark analysis we did on a prototype that we have implemented in `C#`.

Our protocol works in the original Juels and Rivest's intention to let an attacker steal a password file, run an off-line dictionary attack on it, and have some chance to get into the system by *guessing* the rightful password. However, our solution seems making this attack useless. The intruder does not gain anything from knowing a user's password because however he does not possess the OTP with which to create the authentication token (i.e., the hash of the password). This is the credential that let the system grant access. At the light of this last observation we further comment that even if the adversary communicates with the LS and gets to know the user password, (as we explained in §3), the adversary cannot manage to log in. Our fix, at least for the new Honeywords System, nullifies the adversary's possibility to exploit the password usefully to log in, although of course leaking a password is still a serious weakness because users may reuse the same password across different sites. Still the strategy that we proposed for our new protocol suggests a completely new direction for password authentication, a procedure that is resilient even if a password is lost. Thus, at this point, one may want to go one step ahead and rethink a new system afresh where an intruder could not take any advantage after knowing the right password. This is an interesting question that goes beyond what we think was the proposal of Juels and Rivest, since it would render a Honeywords System approach completely superfluous. Instead, it suggests a wholly reviewed password-based authentication process where users still type their passwords but where the token that the LS checks in the password file is one-time-valid. If a solution exists, still it differs from current OTP-based solutions that are used today e.g., in home-banking, because of the assumption that it must work even when the LS has been code-corrupted. This is for us an interesting future work and an open problem in password-base authentication.

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