

Problems with PAKE protocols

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Abstract—In the last years data breaches in websites have become fairly common. This happens

Index Terms—

I. INTRODUCTION

notes

- normal password auth Vulnerable to offline Attacks
- motivation for development of pake protocols
- standardization
- Upcomming Questions, why not standard today only a few
- Topics of paper:
- Short Introduction to PAKE Protocols and their cryptography behind them
- The Usage of PAKE in applications today
- Attacks on PAKE
- Some other reasons PAKE isnt used widely

II. RELATED WORK

As PAKE protocols have a long history in somputer science terms, there is a lot of research already being done. There are a lot of different approaches on the topic and different ideas to solve different problems. The first appearance of Encrypted Key Exchange was 1992 in a paper which described a basic protocol secure against dictionary Attacks. The first standardization of PAKE Protocols came with IEEE P1363.2. This project was formed because of huge interest in Industry and Science in the theme During this first so called period of PAKE protocols these protocols where revised and reworked multiple times which extended the working period to 2008. However after the standardization was finisied it didnt lead to huge adoption in the industry as it was hoped. In the second phase of PAKE development some services adopted the PAKE protocol such as Apple Icloud or Mozzila Firefox. In 2018 WPA3 the replacement for WPA2, the protocol to secure wifi networks, was announced by the WIFI Alliance. It includes an PAKE protocol called Dragonfly to authenticate with the wifi router. The huge amount of PAKE protocols followed the problem

III. BACKGROUND

A. The basic security principls of PAKE

PAKE basicly allow 2 parties to establish a secure channel inwhich they can communicate without the fear of a 3rd partie to listen. The Requirements are the following

- Resistance against Dictionary Attacks:
The communittication between the two parties must not be

decryptable. This means that there is not data obtainable which allows an attacker to find the private secret. Especially if the guesses on the secret are run offline by a dictionary or another password-decryption like attack.

- On Password guess per Conection:
When establishing a new connection between two parties only one guess on the secret is possible. It isnt possible for an attacker to send for example 100 password in one connection attempt, the attacker needs 100 to try them out. Additionally these attempts should be visible and blockable to prevent further guessing the secret.
- forward secrecy:
Alice and Bob have established a protected session with their pre-shared secret, they both a session-secret which allows them to communicate securly. Eve gets to known the pre-shared secret. She can establish a new session with either Alice or Bob and impersonate the other, however she does not know the session-secret and can therefore not listen to what Bob and Alice are doing in their already established session.
- session-key security:
Additionally to the session of Alice and Bob there is another session between Alice and Charlie. Eve is now able to obtain the session-secret from Alice-Bob, this means she can listen to their communitication. The session between Alice and Charlie is still not compromised. This is the case for every other session.

A PAKE is a two stage protocol.

B. Basics of encrypted Communication

1) *Hashing*: A hash function takes a key as input. The output is a fixed size hashcode. These functions are used to map data to make it indexable That would be the case if the hashfunction was perfect which is physically not possible. Hashfunctions follow three principles to withstand different types of attacks

- Pre-Image resistance
It is difficult to find a corresponding message M to a given hash h , $h = \text{hash}(M)$. The function is a one-way function.
- Second Pre-Image resistance
It is difficult to find another message $M2$ getting the same hash as the first message $M1$. $\text{hash}(M1) = \text{hash}(M2)$.
- Collision resistance
Similar to second pre-image resistance, it should be difficult to find two message $M1, M2$ that have the same hash. $\text{hash}(M1) = \text{hash}(M2)$.

2) *Zero-Knowledge-Proof*: The Zero-Knowledge-Proof describes a way to prove someone else that you know a secret without ever telling the person the secret. The verifying person knows the secret as well. The verifier can ask you different questions which are conducted from the secret, which you can answer correct if you know the secret. This can be repeated until the verifier is convinced that you know the secret. An Abstract example would be Alice is colorblind and Bob is not. Bob has a red and a green ball. They seem identical to Alice so she is not sure if Bob is telling her the truth and they are different. She wants to prove Bob and holds one ball in her left hand the other in her right hand. Bob knows in which hand they are currently. Alice decides, without Bob looking, if she wants to switch the balls or not after she's done that she asks Bob if she switched or not. Bob answers, if both balls have the same color Bob will eventually choose the wrong option. If they are differently colored Bob should be able to tell Alice if she switched or not. Like a lot of concepts in cryptography the zero-knowledge-proof has some properties which define it.

- completeness
if the proof is correct, the prover will convince the verifier that he is correct
- Soundness
if the proof is wrong, the verifier will not be convinced by the prover, however there is a small probability for error
- Zero-Knowledge
There is no secret leaked by proofing.

A famous Zero-Knowledge-Proof would be the Schnorr-Signature

- Group G of prime order q with generator g
- Hash function $H : \{0, 1\}^* \leftarrow \mathbb{Z}_q$
- ALICE
- Pick private random key a
- get public key $A = g^a$
- Sign Message $M : \{0, 1\}^*$
- 1. Pick Random number r
- 2. Compute $R = g^r$
- 3. Signature $E = H(M, R)$
- 4. Signature $S = r - a \cdot E$
- Send Bob Public Key A , Message M and Signature E, S
- Bob verifies $M : \{0, 1\}^*$
- derive $R' = g^S \cdot A^E = g^{r-aE} \cdot (g^a)^E = g^r$
- derive $E' = H(M, R')$
- Check $E' = E$

C. PAKE Handshake

1) *Balanced PAKE: DH-EKE*:

- Pre Shared Secret
- A gen. RNR(private key)- i public key - i encrypted with PSK
- A send $\text{Enc}[\text{PSK}](\text{public key})$
- B decrypt $\text{Enc}(A)$ with $\text{PSK}-i$
- B gen RNR(private key) - i public key
- B gen Sessionkey, random Challenge
- B send $\text{Enc}[\text{PSK}](\text{public key, Enc}[\text{Sessionkey}](\text{Challenge}))$

- A decrypt, receives bob pub key
- A gen. Sessionkey with her private key and bobs public key
- A decrypts 2nd part of message with sessionkey
- A generates challenge
- A sends $\text{Enc}[\text{Sessionkey}](\text{challengeA, challengeB})$
- B decrypts checks if challengeB is the same (if no session is dropped)
- B sends $\text{Enc}[\text{Sessionkey}](\text{challengeA})$
- A decrypts, checks if challengeA is the same as her
- Can send messages encrypted with sessionkey now

2) *Augmented PAKE: SRP*: SRP is probably the most used protocol of the PAKE protocols. It is used by the mail provider ProtonMail and in the smart home solution of Apple, Apple HomeKit. Another protocol which will probably be used in the future a lot is the Dragonfly protocol used in the new WIFI security standard WPA3.

D. Problems with PAKE

IV. ATTACKS ON PAKE

To explain the attacks and some of their corresponding protocols it is needed to define some variables. Let G denote a subgroup of \mathbb{Z}_p^* of prime order q where p is prime and q is big enough for intractability of the Decisional Logarithm Problem. Let $g \in G$ be a generator. The hash or the value of the password are in the interval $[1, p-1]$.

A. Dictionary attack

A pretty basic attack which is pretty common in Public-Key-Infrastructure as well. To perform a dictionary attack you need a dictionary with common passwords, it is possible to create a dictionary based on information from the user. A lot of times dictionaries are also generated from leaked passwords on the internet (haveibeenpwned.com). Next you need an encrypted message or hash which you want to decrypt or find the corresponding message to. The last thing you need is the used encryption/hash function to cipher the message.

Now it is possible to try out as many different passwords as you have in your dictionary, only limited by time and available resources. Even if one security principle of PAKE is that it is protected against offline dictionary attacks some protocols are vulnerable to these attacks. An augmented PAKE like SRP, is not storing the password on the server. Only a verifier is saved, which is a one-way-function of the password hash. This means if the database is breached it would allow an attacker to start an offline dictionary attack on the verifier. This is pretty similar to today's mostly used Public Key Infrastructure, where only a password hash is stored on the server. Nonetheless this does not mean that the SRP protocol is completely secure against dictionary attacks, it is only secure against server data leaks. For example

B. pre-computation attacks

Pre-Communication attacks are a form of dictionary attack, which is like the dictionary attack not limited to PAKE protocols. It works by pre-computing password hashes with

a salt. After a data breach on the server-side or another way that leaks the password hash it is possible to look up the corresponding password instantly. Even though an augmented PAKE isn't directly vulnerable to such attacks, it is sometimes still possible. An example would be the Secure Remote Password (SRP) protocol. It is a rather famous protocol because it is used by some applications, therefore there are a lot of different implementations for it. This protocol does not store the password on the server only a verifier to verify the password. But it is possible to pre-compute verifiers for passwords if it is known that the target server is using the SRP protocol. Let's continue with the example of the dictionary attack

C. side-channel attack

This is a group of attacks, which try to find secrets by gathering information from the target. They do not aim on the design of the protocol, they target the implementation. These informations can be of physical nature like power consumption, electro magnetic radiation. Measuring the time it needs to compute a cryptographic function and then relaying information on the secret is also a sidechannel attack. As well as watching the access of the cache used by some victim.

D. PARASITE

While we explained some theory based attacks now we will focus on an attack on the OpenSSL implementation of SRP. This attack could lead to a password leak and is called PARASITE (Password Recovery Attack against Srp implementations in the wild) and is a cache based side channel attack. In this attack the target is the password of a victim which is saved on the memory. Especially the Flush+Reload and Performance Degradation Attack (PDA) is used. It monitors the memory addresses and finds the used ones by the victim. This is achieved by flushing and reloading the cache and measuring the time needed for the victim to receive the data. If the memory is flushed at the point of access the data needs to be looked up from the memory directly which subsequently takes longer. In the OpenSSL implementation of the modular exponentiation, they use a special variable to speed up the square and multiplication process. However the variable overflows, after that a new bigger variable with the Montgomery representation is used. The Montgomery representation is an elliptic curve used to speed up the process of modular exponentiation. Hence this part of the implementation allows an attacker to distinguish every iteration on it, as the first part of the implementation was too fast. This makes the amount of iterations guessable and you therefore guess some bit patterns. The chosen generator is 5, because it is the most convenient one to use. With knowing the generator we can identify on which bits the accumulated variable is overflowing and how many iterations are needed until the overflow occurs. Through FLUSH+RELOAD attacks it is possible to deduct some bits of the password while others remain unknown however due to known positions of said bits it is possible to reduce the remaining possibilities. If it is not possible to find the password with one run of the Protocol, it can be run more

times, with another salt, to get different bit patterns of the same password. Because we know some parts of the password it is possible to start a dictionary attack on the password even a pre-computation attack as we know the used salt. With knowing the password we can impersonate both parties. We know the password to tell the server we are the user he expects as well as telling the user we are the server because we could calculate the verifier stored on the server. These types of attacks happen and are partly possible on different cryptographic protocols. Also it is important to mention that the threat model of the attack. It needs access to the memory and the cache of the processor. This is possible through a spy program on the pc or a java-script injection in the browser. The OpenSSL library is one of the most used crypto libraries and therefore used as reference in other implementations. This is also the case on other implementations of the srp protocol which made them vulnerable as well. To make the attack a bit more clear

E. Impersonation attack

The first EKE protocols as well as the SPEKE protocol is suffering from this attack. EKE and SPEKE are balanced PAKEs. Like the name suggests the attacker poses as a user in the impersonation attack to obtain private information. The impersonation attack is applicable if two users have multiple sessions in parallel with each other. Alice and Bob share a common password. Now Alice starts a session with Bob (Session 1) by sending him a random selected number $g^x \bmod p$ (p is a safe prime number). This randomly selected number generated by a generator provided a function which takes the shared password as input. After the stage Alice and Bob get their session keys k which is generated from $g^{ab} \bmod p$. For the key verification Alice sends her first key confirmation challenge $H(H(k))$, where h is a hash function. The prime number g^x and the first key confirmation challenge are intercepted by Eve. Eve raises the prime number by the power of z , a random selected number. Eve now initiates another session (Session 2) with Alice using g^{xz} . Alice replies with another random prime number g^y . Eve does the same as before and raises this number by the power of z to g^{yz} and sends it back to Alice. In the next step Eve sends the intercepted key confirmation challenge to Alice which will be answered by Alice with $H(k)$. Now Eve has intercepted Session 1 while owning Session 2 completely which opens up for different scenarios

F. Replay-Attack

This is an attack on the J-PAKE protocol, which was used in the Mozilla Firefox synchronisation feature. It is related to the impersonation attack, because it replays eavesdropped messages and impersonates the other party. This attack is limited by the fact that the session key cannot be computed from the eavesdropped messages without the password of a session member. It means, that attackers are only authenticated but they cannot encrypt or decrypt messages from the other participant. Basically this is a variation of the impersonation attack on augmented PAKEs. J-PAKE consists of 4 messages

which can be denoted into two independent parts. The Authentication Part is independent from the key exchange part. The second part of J-PAKE which allows to run a replay-attack on it is that the function to generate a session-key doesn't include some session-specific information. We assume an Attacker Eve intercepted an earlier run of the protocol and he wants to impersonate Alice. E sends a derived message to B . B proceeds to start his part of the J-PAKE by selecting random numbers and computing Zero-Knowledge-Proofs to them. E answers with the next eavesdropped and derived message. B now verifies the numbers of E with his own and generates a session key k , using values from the first message and his own random generations. Bob thinks Eve is Alice but Eve cannot compute the session key because she doesn't have the password of Alice and x_2 . x_2 is the second random generated value of Alice which is never sent to Bob because it was only used as exponent of a safe prime number.

G. Dragonblood

Is a series of Vulnerabilities on the balanced PAKE Dragonfly. This PAKE is used in WPA3 as Handshake.

V. EVALUATION & DISCUSSION

Despite their long history PAKE protocols have not yet made the jump to be a well known solution to the common problem of authenticating a user to a server. The current standard is involving a TLS connection which prevents man-in-the-middle attacks, as well as saving the password of the user on the server. In the best case password is saved on the server as a salted hash. Worst case would be that it is saved or even logged somewhere in clear text. This flaw can also be found in a lot of balanced PAKEs, because they share the same password with each other. With Balanced PAKEs having the problem to rely on saved passwords on server side, augmented PAKEs entered the display. Another important issue with PAKE not used widely, is that most PAKE protocols used to have a patent and that stopped them from being used at all. Nowadays most patents are expired. J-PAKE was the first protocol that was publicly available and therefore used in some applications. Especially Mozilla tried to integrate it into their browsers sync feature, but it got removed shortly after. The same happened with an OpenSSL implementation of J-PAKE it got removed. J-PAKE was a balanced PAKE, it did not provide any advantage over the established methods. These advantages are while the PAKE protocols were under the protection of patents other solutions were developed. The most famous and used other solutions are SSL and their, now standard, successor TLS. Implementing these protocols in today's services would not change much for the user as he is still required to choose a password. One important factor however is the strength of the used password as the most actual versions (OPAQUE) of PAKE protocols provide enough protection from brute-force attacks in case of a server breach. This is a good thing as users tend to use simple passwords for their logins which provides a huge security risk for them. So implementing these protocols would not change anything for the user but it will help strengthen the security of

the user of a potential password leak. With implementing these protocols the next problem occurs: There could be attacks found on the implementation, like the PARASITE attack on the SRP protocol. On the other hand today's standard protocols are not immune to attacks either, like the Heartbleed attack on the TLS protocol showed in 2014. Implementing a PAKE in your login flow has the side effect of being resource intensive on the user device. It is easier to compute a salted hash of a password on the device than to compute several hashes combined with multiple additional exponential modular calculations. Some PAKE protocols already found their way in the most used crypto library called OpenSSL. When optimized it should be possible that today's used devices are able to handle the additional workload provided by using a PAKE protocol. These protocols make a pretty strong case for them nowadays especially combined with the already established TLS protocol they are a good and more secure alternative to established methods of authenticating a user. That PAKE protocols can be used in wireless networks is also showed in by Apple by using the SRP Protocol in their smart home solution.

VI. CONCLUSION

With WPA3 there is a PAKE underway to come to every wifi network, while it still has some flaws it is nowadays a better solution than WPA2. With a new generation of PAKE there is a possibility that more services and devices will adapt these protocols and be therefore more secure. The past showed that there are a lot of possible threats on PAKE protocols. These threats and vulnerabilities can be exploited as it was shown by the PARASITE and Dragonblood attacks. Our contribution was to get a short introduction to PAKE protocols and show their weakness and strengths. As well as providing some history on why PAKE protocols are not adapted by industry despite being a superior solution. We showed that PAKE protocols are not immune to attacks they say they should be, like the SPEKE or EKE protocol against dictionary attacks. As implementations of PAKE protocols becoming standardized in other protocols it is important for them to be secure. It was important for them to be performant which opened them up for side-channel attacks. While still important with today's availability of computing power it should be possible to implement PAKEs performant and secure. As a final thought, while still not standard PAKEs are on a good way to become more famous as the topic gets more traction. We wanted to contribute to that possible traction by giving the people some insight on why PAKEs are not widely used. Being a superior idea but still having some child troubles PAKEs still have a long way to go until they are a standard.

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