Security Analysis of MD5 algorithm in Password Storage

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Abstract— **Hashing algorithms are commonly used to convert passwords into hashes which theoretically cannot be deciphered. This paper analyses the security risks of the hashing algorithm MD5 in password storage and discusses different solutions, such as salts and iterative hashing. We propose a new approach to using MD5 in password storage by using external information, a calculated salt and a random key to encrypt the password before the MD5 calculation. We suggest using key stretching to make the hash calculation slower and using XOR cipher to make the final hash value impossible to find in any standard rainbow table.**

Keywords-component; MD5; Password Storage Security; Data Security; Dictionary attacks; Rainbow Tables

I. Introduction

With the advent of computer technology, it became more productive to store information in databases instead of storing in paper documents. Web applications, needing user authentication, typically validate the input passwords by comparing them to the real passwords, which are commonly stored in the company's private databases. If the database and hence these passwords were to become compromised, the attackers would have unlimited access to these users' personal. Nowadays, databases use a hash algorithm to secure the stored passwords but there are still security breaches. Recently in 2012, Russian hackers released a big list of cracked passwords from the well-known social networking sites including LinkedIn. These attacks were found to be successful due to the use of a weak hashing algorithm.

II. Hash function

A hash function is a one-way encryption function that takes a variable-size input plaintext m and generates a fixed-size hash output. It is computationally hard to decipher the hash and any attempt to crack it is practically infeasible. A "secure" hash function should be able to resist pre-image attacks and collision attacks. Due to the pigeonhole principle and birthday paradox, there will be some inputs that will produce the same hash result. The output length is of fixed size 128 bits, making a total of 2128 possible output hash values. This value, as big as it may seem, is not infinite, hence resulting in collisions.

A. MD5 algorithm

MD5 (Message Digest Algorithm 5) was designed by Ron Rivest in 1991. MD5 processes a variable-length message into a fixed-length output of 128 bits. MD5 is a popular hash function. It works on blocks of 512-bits, and processes each block through 4 rounds, where each round in turn processes 16 sub-blocks (each 32-bits). The 512-bit message is divided into 16 sub-blocks before processing. If a message block is not up to 512-bits, it is padded as shown in Fig. 1. A detailed explanation of the algorithm can be found at [1].

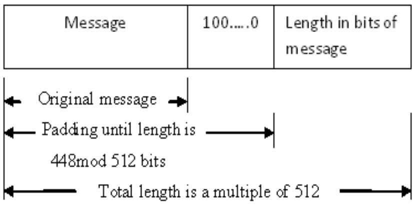
Message
100.....0
Length in bits of message
Original message
Padding until length is 448mod 512 bits
Total length is a multiple of 512

Figure 1. Length of message after padding (in bits)

III. Application of MD5 algorithm in password storage security

It is highly insecure to store passwords in plaintext in the database. In order to increase the security of passwords, MD5 algorithms can be used to hash the original passwords and the hash values, instead of the plaintext are stored in the database. During authentication, the input password is also hashed by MD5 in a similar way, and the result hash value is compared with the hash value in the database for that particular user.

IV. Security analysis of MD5

MD5 algorithm is prone to two main types of attack: dictionary attacks and rainbow tables.

A. Dictionary Attacks

In dictionary attacks, an attacker tries all the possible passwords in an exhaustive list called a dictionary. The attacker hashes each password from the dictionary and performs a binary search on the compromised hashed passwords. This method can be made much quicker by pre-computing the hash values of these possible passwords and storing them in a hash table.

B. Rainbow Tables

Rainbow tables are made up of hash chains and are more

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efficient than hash tables as they optimize the storage requirements, although the lookup is made slightly slower. Rainbow tables differ from hash tables in that they are created using both reduction and hash functions. Reduction functions convert a hash value to a plaintext. The plaintext is not the original plaintext from which the hash value was generated, but another one. By alternating the hash function with the reduction function, chains of alternating passwords and hash values are formed. Only the first (chain's start point) and last plaintext (chain's end point) generated are stored in the table. To decipher a hashed password, we first process the hashed password through reduction functions until we find a match to a chain's end point. We then take that chain's corresponding start point and regenerate the hash chain and find the original plaintext to the hashed password. Rainbow tables are very easily available online now. There are many password cracking systems and websites that use rainbow tables also, for example, OphCrack. Of course, using rainbow tables do not guarantee a 100% success rate of cracking password systems. However, the bigger the character set used for creating the rainbow table and the longer the hash chain length, the bigger will the rainbow table be.

V. COUNTERMEASURES RESEARCH

A. *Information Entropy*

Password strength is usually measured in terms of information entropy. In simple terms, the higher the information entropy, the stronger the password and hence the more difficult it is to crack it. A password of 6 characters would require only 2^6 attempts to exhaust all possibilities in a brute-force attack, while a password with 42 characters would need 2^{42} attempts. As can be seen, the longer the password and the larger the character set from which it is derived, the stronger the password. As best practice and preliminary requirement, the application should insist that the user uses a strong password during the registration process. Strong passwords run less risk of existing in dictionaries. Common simple passwords like "123456" have already been banned by Microsoft Hotmail.

B. *Salting*

One of the most common reasons to successful password cracking attacks like the one against LinkedIn was because they were using unsalted hashes. This makes it much easier for hackers to crack the system by using rainbow tables, especially given the fact that many users use very common, simple passwords and these similar passwords result in similar hashes. A salt is a secondary piece of information made of a string of characters which are appended to the plaintext and then hashed. Salting makes passwords more resistant to rainbow tables as the salted hashed password will have higher information entropy and hence much less likely to exist in pre-computed rainbow tables. Typically, a salt should be at least 48 bits. Salting can be implemented using the following ways:

1) Single salt for all passwords: Given that the salt is sufficiently long and complex, a standard rainbow table, cannot be used to decipher the salted hashes. However, two same passwords will still produce the same hash.

2) Different random salt for each password and storing the salt within the database itself: If we use different salts for each password, two same passwords will have different hashes. The attacker has to generate different rainbow tables for each individual user, making it computationally harder for an attacker to crack the hashes. These salts can be stored in plaintext in the database. The purpose of the salt is not to be secret, but to be random enough to defeat the use of rainbow tables.

3) Use an existing column value: An existing column value like username can be used as salt. This solution is similar to the second solution discussed above. It defeats the use of a standard rainbow table, but a hacker might generate a rainbow table for a specific username, for example, "root" or "admin".

4) Use a variably located calculated salt: The salt location can be prefix (salt appended in front of password), infix (salt appended within the password) or postfix (salt appended at the end of the password). If the salt's location is made random, then cracking the passwords is made harder. For example, we can set the salt location to be equal to the password's length modulo 3. The salt can be calculated by using a random character sequence (stored in the database) and using other characters (embedded within the code). For example, the salt can be made to be a combination of the first two letters of username, random sequence of characters and the last 2 letters of username.

5) Use a variably located calculated salt including information outside the database and the application code: The hacker now has to break into the database and the server containing the application code. He also needs to obtain the additional information needed to crack the password.

C. *Improvement on MD5 processing*

The following methods can be used to improve the MD5 processing:

1) Improved hash function: The hash computation function is altered, for example using one of the following functions as shown in (1), (2) and (3):

$$\text{hash} = \text{Hash (password + salt)} \tag{1}$$

$$\text{hash} = \text{Hash (Hash (password) + salt)} \tag{2}$$

$$\text{hash} = \text{Hash (password + salt + key)} \tag{3}$$

2) Iterative hashing: The password is hashed a number of times. MD5 is a fast hashing function, that is, it is computationally fast to calculate. Iterative hashing makes the calculation slower, hence computationally slower and more difficult to crack. The number of iterations can typically be made to be equal to 1000.

3) Key stretching: This makes a password more resistant to pre-computation attacks by making the attack workload bigger. Iterative hashing is used, where a weak key is fed into the hash algorithm and the output results in a stronger key. There are 3 key stretching methods depending on the input used for the iterative hashing:

a) Simple Key stretching: Only the key is hashed iteratively, as in (4). No salt is involved.

$$\text{key} = \text{Hash (key)} \tag{4}$$

b) Password Key stretching: The password along with the key are both used in the loop.

c) Salted Key Stretching: The key, password and salt are used in the loop. This method is the best of the three key stretching methods.

4) Transform the password before hashing: Before calculating the MD5 hash for the password, the latter is transformed using a simple cipher method.

5) Chaining method and XOR(Exclusive OR) cipher: If iterative hashing is used, the hash output from the current iteration is used in the input for the next iteration. We use a simple XOR cipher to compute the final hash by "XORing" the hash output value from all iterations. A simple XOR cipher is typically of the form shown in (5). If the key is made random enough, the ciphertext will be almost impossible to crack.

$$\text{plaintext XOR key} = \text{ciphertext} \tag{5}$$

D. Example of an improved MD5 processing

We will now demonstrate how we can hash passwords in databases using an improved version of MD5. There are five main steps involved.

First, a random key string of random length is first generated. Its character set is {0-9, a-z, A-Z}.This random key string is used to generate the complex password and is also stored in the database for later use during password authentication.

Secondly, the password is transformed into a complex password through columnar transposition cipher. Assuming that the random key is "YDCiA" and the password is "crazyrichard", the password is first converted into a matrix of 5 columns (same as length of random key) and the blank cells are alternately filled with "*" and "@", as shown in Fig.2. Using columnar transposition cipher, the complex password generated is "ya*ac*ridcrrzh@".

Thirdly, the salt is calculated by finding the XOR value of the random key string with the complex password, row by row. In our example, the salt is " %i\b\"s6*\r\"".

4	3	2	5	1
Y	D	C	i	A
c	r	a	z	y
r	i	c	h	a
r	d	*	@	*

Figure 2. Generate complex password through columnar transposition

Fourthly, an additional random information string of 128 bits is generated for each user and stored in an external file, e.g. in a flash drive.

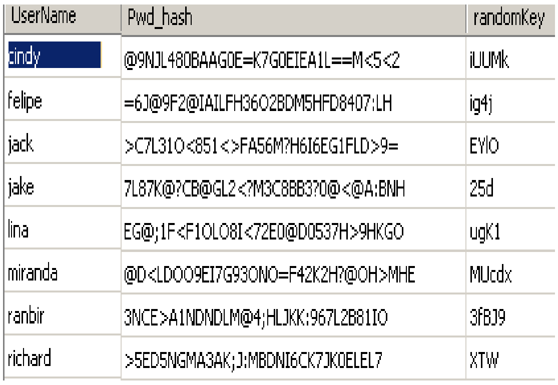
Finally, the password is hashed using a formula based on key stretching. The hashing process is similar to a cipher block chaining method, where the output of one round is used in the input of the other round, as shown in Fig. 3. By calculating the XOR result of the hash value at one round with the one at the previous round, the resulting hashed value is made impossible to find in any standard rainbow table.

The final hashed password is then stored in the database. The system authenticates a user by calculating the hash value (the random key is retrieved from the database for use), which is then compared to the stored hashed password. An example of how the hashed passwords will appear in the database is shown in Fig. 4.

$\text{finalHash} = HV_0$ ^ HV_1 ^ ……^ HV_N ,

HV_0 = Hash (CpxPassword, additionalInfo);
HV_1 = Hash (CpxPassword, HV_0, salt);
HV_N= Hash (CpxPassword, HV_{N-1}, salt);
N is the number of iterations and ^ is XOR.
HV: Hash Value and
CpxPassword: Complex Password

Figure 3. Example of hashed passwords in a database using the improved MD5



UserName	Pwd_hash	randomKey
cindy	@9NJL480BAAG0E=K7G0EIEA1L==M<5<2	iUUMk
felipe	=6J@9F2@IAILFH36O2BDM5HFD8407:LH	ig4j
jack	>C7L31O<851<>FA56M?H6I6EG1FLD>9=	EYlO
jake	7L87K@?CB@GL2<?M3C8BB3?0@<@A:BNH	25d
lina	EG@;1F<F1OLO8I<72E0@D0537H>9HKGO	ugK1
miranda	@D<LDOO9EI7G93ONO=F42K2H?@OH>MHE	MUcdx
ranbir	3NCE>A1NDNDLM@4;HLJKK:967L2B81IO	3fBJ9
richard	>5ED5NGMA3AK;J:MBDNI6CK7JK0ELEL7	XTW

Figure 4. Example of hashed passwords in a database using the improved MD5

The overall algorithm can be summarized in Fig. 5. The initialization vector used here is the additional information,

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which is a random string of 128 bits. Each user has a different initialization vector value.

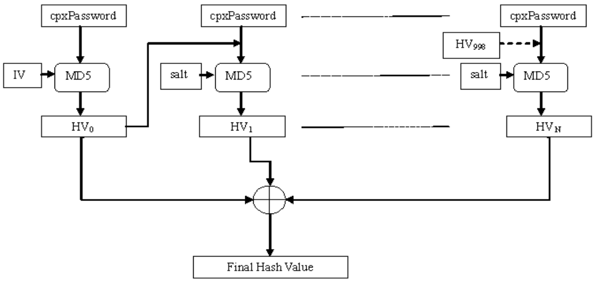
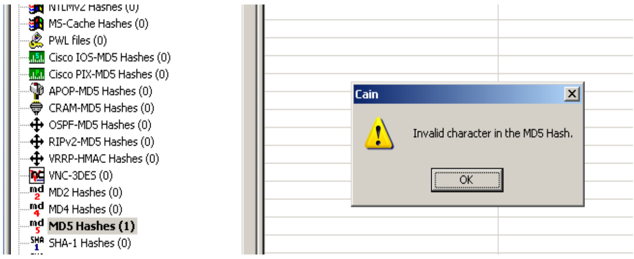


Figure 5. Improved MD5 processing (IV: Initialization Vector)

VI. Performance Analysis

First of all, an attack using a standard rainbow table would fail because the hashed password stored in the database is not of hexadecimal form and hence would not exist in any standard rainbow table. We tried a few online MD5 decryption tools like http://www.md5decrypter.co.uk/ and downloaded software tools like Cain and Abel. But, since all of them use rainbow tables where the MD5 hashes are in hex form and our stored hash value is in ASCII, the attacks would already fail from the beginning, as shown in Fig. 6.

Also, by XORing the output hash values from each iteration makes it almost impossible to find out the original hash output at the first round. Generally, if we XOR the plaintext with a key to calculate the cipher text, we can get back the plaintext simply by using XORing the cipher text with the key. However, if the key is random, then it is almost impossible to get back the plaintext. In our example, the key is totally random as we are hashing intermediate hash output values and hence given the final hash value, it is impossible to decipher it**.**



Invalid character in the MD5 Hash.

Figure 6. Invalid character in the MD5 Hash in Cain and Abel

Also, even if two users have two same passwords, the random key used to encrypt the passwords will be different, resulting in different complex passwords. Furthermore, the initialization vectors and salt are different for each user. For two users with the same passwords, the final hash value will be completely different.

VII. Conclusion

Password storage security is one important aspect of data security as most systems nowadays require an authentication method using passwords. Hashing algorithms such as MD5 are commonly used for encrypting plaintext passwords into strings that theoretically cannot be deciphered by hackers due to their one-way encryption feature. However, with time, attacks became possible through the use of dictionary tables and rainbow tables. In this paper, we discussed different methods to thwart these attacks: (1) the use of a strong password to reduce the probability of it existing in a dictionary, (2) using salts, (3) key stretching and iteration hashing to make the MD5 computation slower, (4) chaining method, where the output of one iteration is used in the input of the next iteration and the use of a different initialization vector for each password, (5) encrypting the password before hashing and (6) XOR cipher to make the final hash value impossible to find in any rainbow table. An implementation of the proposed approach is carried out using C# as programming language and Microsoft SQL Server as database. With our proposed approach, the attacker will now have to hack into the database, the server containing the application code as well as the external file.

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