PAKE-based mutual HTTP authentication 
for preventing phishing attacks

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Abstract
This paper describes a new password-based mutual authentication protocol for Web systems which prevents various kinds of phishing attacks. This protocol provides a protection of user’s passwords against any phishers even if dictionary attack is employed, and prevents phishers from imitating a false sense of successful authentication to users. The protocol is designed considering interoperability with many recent Web applications which requires many features which current HTTP authentication does not provide. The protocol is proposed as an Internet Draft submitted to IETF, and implemented in both server side (as an Apache extension) and client side (as a Mozilla-based browser and an IE-based one). The paper also proposes a new user-interface for this protocol which is always distinguishable from fake dialogs provided by phishers.

1 Introduction

1.1 Summary of this paper
This paper describes a new password-based mutual authentication protocol for Web systems which prevents various kinds of phishing attacks. Currently, initial design of the protocol is finished, an extension for Apache Web server and an Mozilla-based extended browser supporting the new protocol are implemented, and the specification is submitted to IETF as an Internet Draft [12] for standardization. This paper describes the criteria and decisions behind the protocol design, and the difference from previous work, which are not discussed in the specification document.

Recently, phishing attacks are getting more and more sophisticated. Phishers not only steal user’s password directly, but also imitate successful authentication to steal user’s private information, check the password validity by forwarding the password to the legitimate server, or employ a man-in-the-middle style attack to hijack user’s login session. Existing countermeasures such as one-time passwords can not completely solve these problems.

The new protocol prevents such attacks by providing users a way to discriminate between true and fake web servers using their own passwords. Even when a user inputs his/her password to a fake website, using this authentication method, any information about the password does not leak to the phisher, and the user certainly notices that the mutual authentication has failed. Phishers cannot make such authentication attempt succeed, even if they forward received data from a user to the legitimate server or vice versa. Users can safely enter private data to the web forms after confirming that the mutual authentication has succeeded.

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To achieve this goal, we use a mechanism in ISO/IEC 11770-4, a kind of PAKE (Password-Authenticated Key Exchange) authentication algorithms as a basis. The use of a PAKE mechanism allows users to use familiar ID/password based accesses, without fear of leaking any password information to the communication peer. The protocol, as a whole, is designed as a natural extension to the current HTTP authentication schema such as Basic and Digest access authentication [7]. To use PAKE mechanism for such a purpose, we had to modify it to prevent credential forwarding attacks (man-in-the-middle attacks). The protocol copes with HTTPS to provide encryption, and it also supports the use of load balancers and SSL accelerators for easy deployment on real systems.

There are some existing work (e.g. TLS-SRP extensions) which uses a kind of PAKE algorithm in the transport layer. Those protocols can be used for closed applications like VPN or IPP. However, we have considered that it is not suitable for general web systems which perform authentication in the application layer.

This paper also proposes new user-interface for this authentication system. To prevent phishing attacks, it is important to make users easily check whether the server authentication has been succeeded or not. This information must not be forged by phishers, otherwise phishers deliberately circumvent users that the mutual authentication is established so that users input private information to the phishing sites. We have implemented an extension for Mozilla Firefox which uses the address-bar area for password input instead of using dialogs, and introduces an indicator for displaying the result of authentication. When a user wants to input private information, he/she just needs to check that this indicator has good (green) indication with the user’s ID. This indication ensures that the document displayed in the content area is not from any phishing sites.

### 1.2 Phishing attacks

Throughout this paper, we define phishing as to make a false web service which runs on its own host and imitates itself as an existing legitimate service running on another host, in order to steal (or alter) some information which users intend to send to the legitimate service. This kind of attack is easy to be done on the Internet: everyone including a rogue person can start running their own web server, and make a visual imitation of any legitimate servers by simply copying their visual elements such as logotypes. It is a inherent weakness of the Internet which comes from the openness of it: we can not prevent such servers from running. This is also true for HTTPS services in general (see also the discussion in Section 2.2.1).

The fundamental way of defense against phishing is to check the hostname displayed on the address bar (or other identities such as the subjects of server certificates under HTTPS protocol) service just before sending critical information to the server. However, phishers often use social attack techniques so that users mistakenly send information to the phishing host without noticing that the hostname is different from the genuine host. The purpose of the protocol is to provide a secure alternative way to check host’s identity.

In the above definition, we ignored some transport-level attacks, such as DNS spoofing or transport-level man-in-the-middle attacks, because the TLS (HTTPS) protocol works well against such attacks.

### 1.3 The structure of this paper

The rest of this paper is organized as follows: in Section 2, we will investigate current phishing attacks and existing countermeasures for it. Section 3 describes the design goals and features of the protocol. Section 4 contains a brief view of the protocol, and Section 5 shows our user interface design which is an important part of our proposal. Section 6 describes our extension to HTTP authentication protocol to make it friendly with existing web applications. Our implementation and public experiments are briefly introduced in Section 7. Section 8 has discussions on the proposal, and examine previous work in Section 9. Section 10 concludes this paper and shows future direction of our research.
2 Background

2.1 Categorization of phishing attacks

Phishing attacks are very common in recent days, and its method is getting tricky. Many users including novice and even experienced users are still trapped with kind of attacks. Examining existing phishing sites, we can find several patterns for how the phishing sites handled users’ passwords which are mistakenly inputted by users. Common patterns can be categorized as follows:

**Pattern I (simple forgery without password):** Do not use and acquire passwords at all. Instead, acquire other private information such as credit card numbers.

**Pattern II (simple password stealing):** Ask users’ password and does nothing else.

**Pattern III (blind authentication acceptance):** Ask users’ passwords, always accept it and continue to forge users.

**Pattern IV (credential forwarding):** Ask users’ passwords, then use genuine sites
to check their validity.

**Pattern V (full transaction forwarding):** Forward all communications (including passwords) to genuine sites, possibly altering part of these (e.g., altering bank account number for money transfers to steal money).

Figure 1 summarizes those patterns.

A **pattern I attack** is simple: first instance of phishing in the early days was to simply show imitated web forms to let victim users input private information such as credit card numbers and PINs, without any authentication attempts. These simple attack scheme are still in use, however, as users are getting accustomed to phishing attacks, more sophisticated attacks appeared to forge users.

A **pattern II attack**, another instance in the early days was to steal user’s password. After acquiring passwords from form inputs, phishers simply show either communication errors, authentication errors, or just a “thanks” message. We categorize this as a “password-stealing attack.”

Later, there was new **pattern III attack**, which was an extension of pattern I with fake password authentication added to it. Possible background of this phishing pattern might be that phishing was getting popular and people start to feel unnatural for the pattern II phishing sites. When users entered the password and get no meaningful response, they begin feeling something unusual and change their password immediately. New kinds of phishing sites first show a fake authentication requests, and when a user enters a password, they show another form to input private information like pattern I attacks regardless of the inputted passwords. Because victim users have been inputted passwords, they believe in that they are communicating with genuine sites. We call these “blind authentication acceptance attacks”.

When the blind acceptance attacks became common, users began to take a countermeasure to them. To detect such attacks, users first input wrong passwords to every site they are visiting and see the responses from the server. As phishing sites do not know the true passwords, their response to wrong passwords will be “login succeeded”. However, this countermeasure was not perfect: some phishing sites started sending the inputted passwords to the genuine sites to see whether they are correct ones. These attacks are hereafter named “credential forwarding attacks”, or “pattern IV attacks”.

Another sophisticated phishing sites ever seen are to forward almost all web traffic to the genuine sites and to steal or hijack the web session of the user. When a user sent a critical information such as a bank account number for money transfer, they alter it to make false request (e.g. redirect bank money transfer to their own accounts). We name it a “full-transaction forwarding (pattern V) attack”. This attack works even when there are additional (two-factor) authentication present.

Note that the last pattern is completely different from transport-level man-in-the-middle attacks. In transport-level man-in-the-middle attacks, the client software is forged to communicate with false servers. In phishing cases, however, the client user is forged, and the client software is directed by user to communicate with phishing hosts. This makes some cryptographic solution for man-in-the-middle attacks (such as TLS) ineffective against phishing attacks.

**2.2 Existing countermeasures against phishing**

There are many proposed countermeasures against phishing attacks. However, none of them are satisfactory and complete. Table 1 summarizes the comparison in this section. It shows, for each countermeasures, whether the measure is effective for various patterns of phishing attacks shown in the previous section.

**2.2.1 Global whitelists and blacklists**

Most common approaches against phishing attacks are to maintain a list of either good or bad sites by trusted third-party. The common problem of those approaches are that such methods cannot be
Table 1: Comparison of Phishing countermeasures

|                | I  | II       | III      | IV       | V       | Applicable for all genuine sites<sup>†1</sup> | Detecting all phishing sites<sup>†2</sup> | Portable (no local storage)<sup>†3</sup> |
|----------------|----|----------|----------|----------|---------|-----------------------------------------------|---------------------------------------------|------------------------------------------|
| Global whitelist | yes | yes      | yes      | yes      | yes     | NO                                            | –                                           | yes                                      |
| Global blacklist | yes | yes      | yes      | yes      | yes     | NO                                            | –                                           | yes                                      |
| Local whitelist | yes | yes      | yes      | yes      | yes     | NO                                            | –                                           | NO                                       |
| SSL with client key | NO | yes      | NO       | yes      | yes     | yes?                                          | NO                                           | NO                                       |
| Digest authentication | ?   | Weak<sup>†3</sup> | NO       | NO       | NO      | yes?                                          | NO                                           | yes                                      |
| PwdHash        | ?   | Weak<sup>†3</sup> | NO       | yes      | yes     | yes?                                          | NO                                           | yes                                      |
| Our proposal   | yes | yes      | yes      | yes      | yes     | yes?                                          | yes?                                         | yes                                      |

<sup>†1</sup> Every sites, including both large-scale and small-scale (e.g., personal) sites, have opportunity to use the protocol without any social requirements (e.g., third-party screening or auditing).

<sup>†2</sup> This means that whether phishing sites fails to imitate the behavior associated to genuine sites under each countermeasure (e.g., successful authentication), social requirements (e.g., third-party screening or auditing).

<sup>†3</sup> Whether users are free from managing information (such as private keys) stored in client software.

<sup>†4</sup> “Weak” means cryptographically weak against off-line dictionary attacks.

Complete by the Internet’s nature. Especially for whitelist approaches, there is always a tradeoff between rejection of legitimate servers (false positive) and false acceptance of phishing servers (false negative), and it seems to be impossible to give an appropriate rights for every “good” or “genuine” website on the Internet while keeping all phishing sites away.

In former days, SSL server certificates are thought to be providing some kind of trusts over commerce web sites, as a kind of whitelist. Valid SSL certificates are only issued by designated certificate authorities (CAs) which are trusted by Web browser vendors. However, the validation for issuing SSL certificates is too easy for phishers in fact. Moreover, many CAs recently started to issue so-called “class-1 SSL server certificates” or “domain-validated certificates” which can be obtained without any evidence of real-world identities. In the reality, there are phishing sites which runs HTTPS sites with valid SSL server certificates. Although SSL server certificates still provide an important role for transport security<sup>1</sup>, it is now almost useless for protecting casual (careless) users against phishing<sup>2</sup>.

To overcome the problem of SSL server certificates and phishing attacks, CAs and browser vendors introduced a special kind of SSL server certificates called “EV (extended-validation)-SSL certificates”<sup>2</sup>. CAs has introduced much stricter criteria for issuing EV SSL certificates, which can almost never be satisfied by phishers. When web browsers connect to HTTPS servers with EV-SSL certificates installed, the address bar regions are illuminated green to indicate that the site is most likely to be a genuine one. However, as a consequence of the stricter validation criteria, it can not be introduced for every genuine web sites. Their intention seems to prevent phishing against some of very high-profile services such as banking, and not to prevent all phishing attacks.

The opposite to those whitelist approaches are to create and continuously maintain a up-to-date list of known phishing websites so that users will not visit those websites. Most of the today’s web browsers, such as Internet Explorer and Mozilla Firefox has built-in supports for such “anti-phishing” functionalities. However, such blacklist can never be complete. For an instance, according to the documents which is issued by Microsoft and Mozilla<sup>10, 3</sup>, at least 10% of known phishing sites can not be prevented by those filters.

<sup>1</sup> With server certificates issued by trusted CAs, TLS ensures that the client software is communicating to some server who are allowed to use the hostname the software intend to communicate. However, as long as there is a valid server certificate presented, even if the software-recognized hostname is not the user’s intention, TLS will simply accept it.

<sup>2</sup> If users were careful and paranoid enough so that they check certificates for every accesses, they can simply protect themselves from phishing by checking the domain part of the URL to be accessed.
2.2.2 Local whitelists

Another kind of approaches is to maintain a user-specific whitelist of known genuine hosts by each users.

Petname tool is a Mozilla Firefox extension for providing local whitelist functionality. It allows users to “name” each website they visit. When the users visit the same site for the second time, it shows the user-given name with a green background, showing that the site seems to be the intended one.

Alternatively, most browsers have a built-in support for password managers, which can be used for this purpose. When users let browsers to remember a password for a genuine site, the browsers will automatically input the password only when the user visits the same site. The browsers will not input the password for the phishing sites with a different URI from the genuine sites, thus users can notice when they visit phishing sites.

Another related approach is to customize login screen for each user by using HTTP cookies stored in the browser. An identifier cookie is stored into each browser, and when a user accesses a login page, the server customizes the part of the screen using the identifier sent as a cookie. As an access to phishing sites does not contain that identifier cookie, it can only send an uncustomized login screen to the users.

The common problem of those approaches are that these requires local storages, which hardens users for using several computers alternately. In addition, users have to maintain the list appropriately and carefully.

2.2.3 Existing cryptographic solutions

There are some cryptographic approaches for hardening web authentication. SSL client authentication introduces public-key cryptography for authenticating clients to servers. Users installs a client certificate and the corresponding secret key to browsers, and when the server requests the browser authenticates themselves using the secret key, in the way it is cryptographically secure against secret stealing and credential forwarding attacks (Patterns II and IV). The server will be authenticated by using server certificates as usual. Sometimes it is called a mutual authentication for SSL. However, in the context of Web browsers, these two authentication attempts are not tied together: the server only needs to show any valid SSL server certificate to be authenticated by the client, and the client will not know whether the client certificate has been verified by the server or not. As a result, the client authentication can not prevent blind acceptance (pattern III) phishing attacks which is previously mentioned.

Digest web authentication algorithm uses MD5 hash function and a challenge-response style protocol to let clients authenticated by the servers without sending a plain-text password, intending to prevent password stealing attacks (Pattern II). However, when the client sends the MD5-hashed response to a phishing website, the phisher can send that value to the genuine site to make a successful authentication, thus it is vulnerable for credential-forwarding attacks (pattern IV). It is also vulnerable for blind acceptance attacks (pattern III). Furthermore, as long as users use passwords with a memorable entropy, recent computers can easily reverse the hash function by a simple off-line brute-force dictionary attacks to regain the plain-text password. According to a NIST publication Appendix A, user-inputted passwords of 40 characters only have about 62 bits of entropy, which is considered insecure against off-line attacks nowadays. It means that the Digest authentication can not actually prevent plain-text password to be obtained by phishers and eavesdroppers.

PwdHash overcome the credential-forwarding attacks by generating a distinct hashed temporary password for each websites from a single passphrase. When user input a passphrase preceded by two @ characters to any password entry form field, PwdHash traps the keystrokes and inserts a temporary password generated by hashing the input passphrase with the hostname of the...
form’s target. When user unwittingly inputted a passphrase to a phishing site (with @@-prefix),
the generated temporary password will be different from the one valid for the genuine site, thus
preventing password stealing (pattern II) and forwarding (patterns IV & V) attacks.

However, PwdHash can not provide mutual authentication, thus it can not prevent blindly-
accepting (Pattern III) attacks. In addition, the off-line attack can regain the user’s password in
the same way as for the Digest authentication, which makes it ineffective against attacks in pattern
II.

3 Our proposal

3.1 Design goals and criteria

Considering the weakness of existing countermeasures against phishing, we designed a new au-
thentication protocol which can easily prevent all kinds of phishing attacks. The design of the
protocol considers future replacement of HTML form-based authentication mechanisms imple-
mented in Web-application layer as well as Basic and Digest authentication mechanisms defined
in [7]. To realize this goal, the design must be carefully considered so that it does not make
existing web applications difficult to adopt the new protocol.

While designing the protocol, we have settled several goals and criteria for it.

Password-based authentication without local storage  Novice users are well accustomed to the
password-based authentication, and it is difficult for them to manage local secrets (such as
private keys) stored in the local hard-disk in the correct way. In addition, the existence of lo-
cal secret also makes difficult for users to use more than one computer simultaneously. The
protocol avoid requirements for any long-term local secret storages and/or local whitelists.

Secure mutual authentication  Of course, the protocol must be secure enough to prevent phish-
ing attacks. Especially, we focus on that it provides mutual authentication to prevent blind
acceptance attacks (Pattern III), which was not achieved in the above-presented existing
countermeasures. Of course, it should be secure against other types of attacks including
forwarding attacks (Patterns IV and V).

The design also considers that the protocol should secure against off-line attacks even after
the client has been started communication with phishing websites, because normal users is
unlikely to be able to set up a password which is resistant to off-line dictionary attack.

There is an Internet-draft proposing introduction of Mutual authentication for preventing
phishing attacks as mentioned in [8], but none of proposed/widely-accepted countermea-
sures provide this feature for HTTP.

Generic (equal opportunity)  The protocol should be usable to any web services who want to
provide user authentication, including personal websites. Current EV-SSL scheme does
not provide this criteria: EV-SSL certificates can only be acquired by parties having long-

enough credit as a commercial entity.

Compatibility with real Web applications and systems  The protocol should be designed so
that it can be easily deployed for many real Web application with complex needs and heavy
loads. Many existing solutions, including Digest authentication fails in this criteria.

In more detail, we focused on the following topics.

Per-URL authentication configuration, Multiple authentication realms on one server
In real web systems, authentication is defined for sets of web resources specified
by URIs. For example, most Web applications have both public contents (e.g. blog
contents) and private, authenticated contents (e.g. blog editing interfaces). The
protocol should be able to set up authentication only for the part of the resources on
one Web server, unlike TLS client authentication.
In addition to the above, there are web applications which have multiple set of authentication “realms” (groups of resources which share same setting of the authentication) on one server.

For example, the mail interface of the “Google Apps” sets up an independent authentication realm for each domains hosted: The main Gmail service has the URI \texttt{http://mail.google.com/} while the hosted service for example.com domain has the URI \texttt{http://mail.google.com/a/example.com/}. Other examples are the customization interface for hosted mailing lists, a hosted environment for wikis, etc. When multiple realms are not supported, such services must set up individual host names for every realms, which is so cumbersome that unlikely to be deployed.

**Sufficient support for recent Web application designs** One strong motivation for current web application designers/implementors to use form-based authentication instead of HTTP Basic authentication is the flexibility of authorization. When authentication is implemented using forms and HTTP cookies, the Web application can control various aspect of authentication/authorization. For example, such applications can provide both unauthenticated (guest) contents and user-customized contents on the same URI depending on the status of authentication, set timeout for user’s inactivity or total login time and force logout, and implement explicit “logout” UI to forget authentication status so that the same terminal can be used for multiple user identities (including unauthenticated guests).

However, form-based authentication is inherently vulnerable for phishing attacks, because the behavior of the forms is fully controlled by the web contents. To the purpose of the security, we have to avoid use of form authentication as well as existing HTTP authentication. To replace form-based authentication with our new protocol, the protocol provides several functionalities for implementing such applications on the top of this protocol.

**Compatibility with load-reducing equipments** Many web services with heavy loads uses several existing equipments for reducing the server loads. For example, many services uses SSL accelerators, which are reverse-proxies dedicated for talking TLS protocol and forward traffics to the back-end servers. They also uses a load-balancing reverseproxies with multiple back-end servers for the same contents.

We designed the protocol so that most of the these facilities can be used with our authentication protocol as much as possible. Some example configuration for deploying our protocol in large systems are shown in Section 8.2.

### 3.2 Designing Policies

Given the above criteria, we have designed the protocol having the following properties.

#### 3.2.1 Use of password authenticated key exchange (PAKE)

To prevent password to be revealed to the phishing sites even with off-line attacks, we have chosen a variant of PAKE (Password-based Authentication and Key Exchange) protocols as an underlying cryptographic protocol. PAKE protocols enable mutual authentication between clients and servers by using only a shared “weak secret” (such as passwords), while keeping weak secrets not known to the both party on the failed authentication. By this property, when users have been connected to the wrong server (possibly a phishing server), and when they try to authenticate themselves using this protocol, the users’ passwords are kept secret to the server, unlike Basic/form authentication (passwords are sent in plaintext) or Digest authentication (vulnerable against simple blute-force attacks) mechanisms. This prevents password stealing attacks (Pattern II) completely. Furthermore, the protocol benefits from PAKE to detect blind acceptance attacks (Pattern III). Mutual
authentication provided by PAKE protocols will never succeed when the server does not know about user’s password. The protocol, unlike previous ones, checks successful authentication on both client and server side to detect and prevent such attacks.

3.2.2 Detection of credential forwarding attacks

PAKE is actually a key-exchange protocol which is usually used for both authentication and encryption. Under such use case a man-in-the-middle attack (MITM) is impossible, because the encryption key established by the key exchange is known only to the both peers of the PAKE negotiation. However, because the protocol implements authentication in the HTTP communication layer, we use established secret shared key only for the authentication. In this setting, PAKE itself can not provide security against MITM, thus we need another mechanism to prevent credential forwarding attacks.

Our solution is to modify PAKE protocol to check that intended host-name is matched at both authenticating endpoints. This check is sufficient for preventing phishing, because forwarding phishing sites uses hostnames which is different from the genuine servers. When a client talks to a phishing websites which forwards the received messages to another website, the authentication will fail because the weak secret and/or confirmation materials does not match, preventing pattern IV (and V) attacks. The secret password will not be revealed to the phishing servers also in this case, by the virtue of the behavior of PAKE protocol in secret mismatch case.

3.2.3 Extending HTTP-layer authentication architecture

To achieve authentication handling depending on the requests, we have designed the whole protocol as an extension to the current HTTP protocol [5] and HTTP authentication mechanisms [7] in the HTTP message layer. The protocol is naturally designed using existing architectures of HTTP authentication as far as possible, so that it can be easily integrated to existing HTTP implementations.

One problem of authentication tied to the connection layer, such as TLS client authentication, is that the authentication runs before the client send the request to the server, therefore server can not know what resource the client is accessing to. There is also a gap between connection layer authentication and the HTTP keep-alive architecture. The proposed protocol avoids such deficiencies.

On the other hand, there is several weaknesses on applicability of both HTTP-based and connection-based authentication for web applications as described above. We are solving those weaknesses by slightly extending the HTTP authentication architecture (see Section 6).

4 The protocol

This section describes the overview of the proposed protocol in this section. The authentication is based on a PAKE variant called the “Key Agreement Method 3 (KAM3)”, originally proposed by Kwon, defined in the ISO standard ISO-10770-4:2006 [6]. In this section, only a typical conversation for the protocol using discrete-logarithm-based settings is described: the full specification is available as an IETF Internet Draft [12].

An example session trace for the whole process of the protocol negotiation will be shown in Appendix A.

Notations

In this section, we let $q$ be a prime number defining a finite group, $g$ be a generator inside the “mod $q$” group, and $r$ be a rank of the subgroup generated by $g$. The generator $g$ must be carefully chosen so that $r$ becomes a large-enough prime (in the specification we set the parameters to satisfy $r = (q - 1)/2$). $H(\tilde{x})$ is a hash value generated from elements of list $\tilde{x}$. 
4.1 Preprocessing (registration phase)

Before authentication starts, there are some things to be set up. The authentication is performed using a username and a secret password. A pair of a username and a password is valid for one “authentication realm”, a group of Web pages on which the same set of users and passwords are valid.

In the protocol, each authentication realm is defined as follows: a parameter “auth-domain” specifies the range of the hosts using the same set of usernames and passwords (authentication domain). It can be a single host (FQDN, e.g. \\
\texttt{www.example.com}), or it can be limited a specific protocol and port of the host (e.g. \\
\texttt{https://www.example.com:443}). It also supports a realm which is a set of hosts in the same domain (e.g., \\
\texttt{*.example.com}) to support single-sign-on services. Another parameter “realm” is a simple string which is used as a label inside each authentication domain. Each pair of auth-domain and the realm defines one authentication realm.

For each authentication realm, a set of valid username-password pairs is defined. The user has one pair of the username and the password in plaintext. The weak secret $\pi$ used by the client for PAKE-based authentication is extended from the ISO specification to include the authentication domain, the realm and the user-name, defined as

$$\pi = H(\text{algorithm}, \text{auth-domain}, \text{realm}, \text{username}, \text{password}).$$

The server will only need its specially encrypted version $J(\pi)$ defined as

$$J(\pi) = g^\pi \mod q.$$ 

The retrieval of the password from $J(\pi)$ needs brute-force searching.

4.2 Message Exchanges

For the first access to the authenticated contents, the protocol requires three round-trips of HTTP messages. First, as a response to a client’s request (without any authentication credentials), the server sends a usual HTTP 401 response to request authentication. This is very similar to the Basic and Digest HTTP authentication. The response from the server specifies an “algorithm” which defines the parameters $(g, p, r)$, an authentication realm and a realm to be used.

The client asks the user for the username and password. When the password is available from a user input, the client constructs a cryptographic value $w_a$, which is generated from a random number $s_a$ as

$$w_a = g^{s_a} \mod q,$$

and sends the second HTTP request along with the user-name.

The intermediate 401 response from the server contains another cryptographic value $w_b$, which is generated from $J(\pi)$ stored in the server-side password database and another random number $(s_b)$ as

$$w_b = (J(\pi) \times w_a^{H(1,w_a)})^{s_b} \mod q.$$ 

Because this value have randomness from $s_b$ which is larger than the entropy of $J(\pi)$, $w_b$ can not be distinguished from a random number by any other party. This means that the value of $J(\pi)$ can not be extracted from $w_b$ in any way unless one knows $\pi$. The equations for $w_a$ and $w_b$, are directly derived from the ISO specification.

At this time, both the client and the server compute a shared secret $z$ using different set of known values. The client calculates it from $s_a, w_a, w_b$ and $\pi$ as

$$z = w_b^{(s_a+H(2,w_a,w_b))}/(s_a+H(1,w_a)+\pi) \mod q,$$

and the server calculates it from $w_a, s_b, w_b$ as

$$z = (w_a \times g^{H(2,w_a,w_b)})^{s_b} \mod q.$$
If and only if a correct pair of $\pi$ and $J(\pi)$ is used, the two $z$ calculated at both sides will match. As long as eavesdroppers do not know either $s_a$ or $s_b$, $z$ cannot be reconstructed because this key exchange is a modification of Diffie-Hellman key exchange protocol.

The final step of the protocol is to check whether mutual authentication is succeeded by confirming the value of $z$ at each side. The client sends a third request containing value of $o_a$. The value $o_a$ is a hash value defined as

$$o_a = H(4, w_a, w_b, z, nc, v),$$

where $v$ is the host verification element defined in Section 4.3 and $nc$ is the value of nonce counter. The server calculates the same value by its own value of $z$ and verifies the equality. If they matches, the server grants the access to the resource and sends the final response with the value $o_b$, which is generated in the similar way as

$$o_b = H(3, w_a, w_b, z, nc, v).$$

The receiving client must verify the value $o_b$ to check whether the server is genuine. Without knowing the true value of $J(\pi)$, the server can not construct the correct value of $o_b$. This means that phishers can not forge clients by blindly accepting authentication requests, thus Pattern III attacks are prevented. The equations for $o_a$ and $o_b$ are also extended from the ISO specification to include various additional values to be verified, such as $nc$ and $v$.

When a second request to the same host is sent, the client can reuse the shared secret $z$ by directly sending the third message to the server using the same session identifier and $z$, incrementing the nonce counter. In this case, both clients and servers only need to perform a lightweight hash operation but no public-key operations.

### 4.3 Host verification element

Host verification element $v$ ensures that the client is directly communicating to the server on which the genuine web service intended to do so, and no credential forwarding attacks are employed. The value to be used for such verification must have the following properties: (1) it is shared between the client and the server, and (2) when talked to the phishing site, it will be different from what will be used for the genuine site. This protocol uses the following values, chosen by the “validation” field in the response header, for that purpose.

- “Host” verification: the string $v$ will specify the scheme-host-port triple, for example, http://www.example.com:80.
- “Tls-cert” verification: $v$ will be the hash of the server public-key certificate which the HTTPS server uses.
- “Tls-key” verification: $v$ will be the master secret of the underlying TLS sessions.

For HTTP services the Host verification is used, as in this case transport-level security is not intended. For HTTPS services, we can use any of the above three methods safely, although we recommend tls-cert mainly for applicability. See Section 8.1 for some discussions.

### 5 User Interface

A possible attack to this protocol is to forge the user interface asking a password. Existing Basic and Digest authentication usually uses a modal dialog box for asking usernames and passwords. However, it can be easily imitated by using either a stylized HTML, an HTML pop-up window or even a picture of a pop-up dialog box. In general, any region inside the content area is always

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5The protocol allows services to safely introduce a relaying facility on their intention, while preventing unwanted relaying attacks. See Section 8.2 for some examples.
vulnerable for forging by phishers. In this context, the weakness of the forms inside the document is needless to say. If plaintext passwords are sent to the phishers outside of this proposed protocol, we can not prevent any patterns of phishing attacks.

To prevent such kind of attacks, we propose to use the “chrome area” (the area where an address bar and other browser UI components are exist) for the new authentication protocol. Our implementation of the Mozilla Firefox extension uses address-bar area (where web-pages do not have any access to) for password input instead of using pop-up dialog windows. Note that the chrome area is considered to be a secure region, and if there were a method to overwrite there, it shall be considered to be a vulnerability of the browsers. Inside the address bar we put input boxes for a username and a password, and also an indicator for displaying the authentication status.

In our implementation, the input boxes are initially not displayed. When users visit a website which requires mutual authentication, two input boxes for a username and a password automatically appear on the right of the address bar (Figure 2(a)). When the user enters the user-name and the password the authentication begins, and after the authentication success has been recognized by the client (by checking the final $o_b$ value in the response message), it displays a mutually-authenticated user-name with a green background on the right of the address bar (Figure 2(b)), showing that the identity of the host is verified by the password.

By using this protocol and the UI, users can prevent all patterns of phishing attacks which involve passwords (see patterns II–V in Section 2.1) by following two simple rules:

- Users must enter password only to the text-box provided by this UI.

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6It is extremely important that the proposed UI is only used for this protocol (and more secure protocols, if any) and not for weaker authentication mechanisms such as Basic and Digest authentications, so that to it is ensured that the password entered to this UI is not sent in an insecure way.

7In the past, there was such implementation problems to allow forgery of browser security indications, but now all known problems are considered as security vulnerabilities and fixed.
• Users must enter private information such as credit-card numbers only when the indicator becomes green.

If a user sees the green indicator, user can trust that the communicating service is the genuine one (whom the user has told his/her password before). Furthermore, if this protocol is widely accepted and introduced to many commercial websites, we can expect that the above rules prevents even phishing attacks without passwords involved (Pattern I attacks), because when users are well trained to always use Mutual authentication, they will find that such phishing sites are requiring an unsafe authentication which is not the usual.

The only exception to the above rules is the initial enrollment to the web services. In the current design, users must input a plaintext password to somewhere in which it is sent in raw password (possibly) over the TLS secured channel. Future version of the protocol may support sending encrypted password token \( J(\pi) \) to the server, but it does not completely solve the problems in such situation. In the time of initial enrollment, users must always be very careful to determine whether they should continue to access the web services, because they need not only to check the connection integrity, but also to check the service’s social trustworthiness which is completely outside of the scope of authentication protocols.

6 Additional features for Web applications

We have designed the protocol as it is almost upper-compatible with existing HTTP authentication mechanism. If websites are using Basic or Digest authentication, it is easy to migrate to the new protocol by reconstructing the password database from plaintext passwords.

However, most existing websites are using form-based password authentication implemented in web application level instead of HTTP-layer authentication. There may be many reasons to do so including UI design flexibility, but we think that the strongest reason is the lack of flexibility in HTTP Basic and Digest authentication. We have extended a base mechanism of HTTP authentication in several ways to overcome these problems with the mutual authentication protocol.

6.1 Optional authentication

Today’s typical web services often accept guest users and authenticated users simultaneously. Such a service shows a default contents for the guests when a user accesses it for the first time, and when the user authenticates themselves it shows a content customized for each user. For example, in a commercial auction website, summaries of exhibited items are displayed for all users including unauthenticated guests, but a form asking a bid price is displayed only for authenticated users. It is easy to implement this kind of services by using form-based authentication, but it is tricky to implement with HTTP Basic/Digest authentication.

The specification of the new protocol introduces a direct support for such services. Web servers can ask clients to optionally start mutual authentication while sending contents for guest users by using a newly-introduced \( \text{Optional-WWW-Authenticate} \) header.

In websites using optional authentications, Web servers will send normal “200 OK” responses with a newly-defined \( \text{Optional-WWW-Authenticate} \) header. The browser will render the response body (containing a page for guest users) in a usual way, and at the same time it enables the input fields for authentications. If users wish to visit the website as a guest user, they can just continue browsing as usual. On the contrary, if they want to use website as authenticated users, the browser will simply send a Mutual authentication request by the users’ requests, and servers

\[8\] Of course, it does not mean that the peer will use the credit-card numbers righteously. If users use “untrustful” services as their intention, it is up to their responsibility. Our protocol’s responsibility is to prevent communicating with untrustful services without the users’ intention.

\[9\] For Digest authentication, the protocol even provides a backward compatibility feature so that the database can be directly converted for the new mutual-authentication protocol.
will respond as usual. Our new UI design for this authentication protocol (Section 5) is well suited for this use, because it is implemented as non-modal input fields.

Implementation for this additional feature will not be difficult: In the server side, semantics for a “200 OK” response with an Optional-WWW-Authenticate is almost similar to a “401 Authentication Required” response with a Optional-WWW-Authenticate header. Also in the client side, the effort for implementing optional authentication will be almost as same as that for implementing the Mutual Authentication itself. Our implementations already support this in both sides.

6.2 Application-level control for login/logout behavior

Many web applications have their own policies for handling the authentications. For example, many applications implements a forced time-out for login sessions for either user’s inactivity time or the time from the beginning. In some cases applications want to forcibly terminate an user’s authentication sessions. Some application forces entry-point of the authenticated pages to on location.

However, such control was one of the weak points of existing HTTP authentication mechanisms. In current HTTP authentication mechanism, once a user inputs the user-name and the password to a browser, it continues to send them to the website until the user closes all browser windows, and there was no way for servers to specify that the current log-in session is to be terminated, except for requesting a new credential by sending a false “login failed” response. In addition, users are also difficult to switch to another account without closing the browser once.

The proposed protocol introduces a new header for a finer control of the browser’s behavior related to an authentication. Using the new header, named Authentication Control, servers can specify that the client should forget login passwords after a given time period. It also allows servers to specify a conditional redirects to another URL based on a current status of authentications, e.g. a redirect only for a user not starting an authentication. By using this header, applications can use many of current designs of webpage structures (such as fixed log-in page or log-out page) as is, along with our new authentication mechanism with little modifications. Our UI implementation also allows users to logout the service by their own.

6.3 Domain-level single sign-on (SSO) support

Recent large-scale websites such as Yahoo! or Google use several hosts for serving a group of services. In the HTTP Basic authentication, however, the realm of the authentication (the area that shares the same user-name and the password) is defined by the pair of the host-name and the realm value specified in the response header, which means that the same password must be reentered for every host even in the same domain.

The current version of the protocol supports this kind of websites by allowing a wild-card for the authentication domain. If the authentication domain is set to “*.example.com”, for example, the same user-name and password will be automatically used for any host inside the domain example.com when the same realm value is used. While passwords are shared, each servers inside the authentication domain will need an access to valid password databases, because the host verification element v still differs between servers. This forbids credential forwarding even within the same authentication domain. As a result, phishing will be impossible even when there is a less-trusted host inside the domain as long as the password database is kept secret.

7 Implementation

We already have several implementations of the protocol, most of which are published as open-source software. These software can be downloaded from our project homepage.

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Project Homepage URL: [https://www.rcis.aist.go.jp/special/MutualAuth/](https://www.rcis.aist.go.jp/special/MutualAuth/)
For the server side, we implemented an extension module for the Apache 2.2 Web server. The module, `mod_auth_mutual`, supports basic functionality of the Mutual authentication protocol. It can be used almost in the same way as existing authentication modules such as `mod_auth_basic` and `mod_auth_digest`. We have also implemented a preliminary module for the WEBRick server written in the Ruby language.

For client side, we have two implementations: our `MutualTestFox` (shown in Figure 2), which is a modified version of open-source Mozilla Firefox, implements both back-end protocol and proposed UI design. We also have an Internet Explorer-based implementation based on Lunascape,

There are two experiment Web sites which are open to public. Especially, Yahoo! Japan Auction have deployed in the last year a special experimental trial site on which users can log onto the trial site using their existing Yahoo! ID and passwords, using both client implementations.

7.1 Performance

We designed the protocol carefully so that the computation resources required for server side will be as low as possible. If an authentication session takes its first place, there will be three HTTP round-trips (request-response pairs). There is one round-trips more than the Basic or Digest authentication methods, but unlike Digest method, there is no need to generate any random numbers until the client really need to authenticate itself to the server.

There will be two computations similar to RSA secret-key operation (a power-modulus with large exponents), and two cryptographic-hash computations. This overhead is similar to the SSL client authentications.

Once an authentication has succeeded, a “cryptographic session” associated with a cryptographic secret is shared between a server and a client. For the second (or later) request, authentication can be done in a very light-method way with only one hash operation (no public-key cryptography operations). These sessions are designed to be implemented in a constant memory (including nonce duplication checks), and can be discarded in any time under the server’s decisions.

On the real web server we’re currently using (a server with 1.73GHz Intel Pentium M processor and 512MB memory), an authentication request without pre-shared secrets takes only about 132 milliseconds for processing (using 2048-bit discrete-logarithm and SHA-256 setting). After a secret has been shared between peers, processing the second request only requires 0.4 milliseconds.

8 Discussions

8.1 Choice of host verification elements

As described in Section 4.3, we provide three possible values used for host verifications. Strictly speaking, the strength of the verification is `tls-key` the strongest, `tls-cert` the next, and `host` the weakest. `tls-cert` verification assumes the secrecy of the secret key associated with the certificate, and `host` verification assumes correct operation of the CA and PKI even for applications outside the Web.

The reason for us to provide the solutions other than `tls-key` is the difficulty of the implementation of the `tls-key` verification. If every details of the TLS protocol implementation is available, it is possible to implement the strongest `tls-key` method. However, for the most black-box implementation of TLS protocols, it is not possible to acquire the shared secret key of

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111http://www.lunascape.jp/
121HTTP Digest authentication needs random nonces for every responses from servers, even if the client do not want to start authentication.
131We measured a time consumed in our authentication handlers inside Apache web server, without network and other overheads.
the underlying connections. 

8.2 Possible deployments

The protocol design enables several flexible ways of deployment for existing web system with minimal modifications.

1. Single-server setting
   For the small services, the server-side authenticator can simply be installed in the web server (Figure 3A). We have implemented an extension module for the Apache web server, which can be used almost in the same way as other authentication modules such as mod_auth_basic. The simpler one of our experiment websites uses this setting.

2. Authenticating reverse-proxy
   If there are web servers which are difficult to modify its setting, we can implement authentication in reverse proxies (Figure 3B). The reverse-proxy selectively adds mutual authentication requests into the responses from the back-end server, and when authentication has been succeed, the proxy passes the authentication results to the back-end server using additional headers. This reverse proxy can also work as a load-balancer for several back-end servers.
   Our large-scale experiment on the Yahoo! Auction trial site uses this scheme, since the existing service servers are not possible to implement Mutual authentication directly.

3. TLS accelerators
   Many existing web services uses dedicated, single-function SSL accelerators to reduce SSL encryption overhead on the application servers. The proposed protocol can cope with such...
systems (Figure 3-C). When TLS accelerators are used, TLS encryption negotiations are done between clients and the accelerator, and the requests sent encrypted from the client are forwarded to the back-end web server in plain-text form. In this case, it is impossible to perform user authentication in the TLS-level, because such accelerators do not have anything but simple TLS negotiation functions. However, our protocol works under such deployment, as long as the back-end server knows that the accelerators are used and the tls-cert host verification is used. The back-end server speaks plaintext HTTP protocol and negotiates the Mutual authentication as if it is using the HTTPS protocol. As long as the accelerators forward only responses from the genuine servers, phishing attacks are correctly prevented.

9 Related work

Several related works are presented in Section 2.2. In this section we describe about TLS-SRP, recently proposed extension to TLS.

TLS-SRP [14] is an extension to the TLS encryption protocol which uses SRP, another variant of PAKE protocols, both for authentication and key exchange. TLS-SRP can be used either with or without a server certificate issued by PKI certificate providers, and performs SRP key exchange during the negotiation phase. It may be suited with several TLS applications which basically use one connection per client, such as IMAPS, POPS, and TLS-based VPNs, because all of these protocols perform authentication and application-specific operations sequentially on one TCP/TLS connection, so that TLS-SRP can naturally replace the first authentication phase.

While we designed the proposed protocol, we have examined the use of TLS-SRP for preventing phishing against Web application systems along with the current HTTPS protocol, and we have concluded that it is not well suited for Web uses for several reasons. While TLS-SRP’s authentication is strongly bound to the underlying TCP connection, HTTP transport is not used in such way: in HTTP, concurrent HTTP requests to several applications in the same web server are sent sharing one or several TCP or TLS connections intermixed. Furthermore, the keep-alive feature implemented in HTTP/1.1 allows several requests to hosts sharing the same IP address to be streamlined in one underlying connection, either TCP or TLS. When TLS-SRP is used for Web application authentication, two requests for different web applications with separate authentication and authorization may be sent on the same TLS-SRP connection authenticated with a single identity, which is conceptually undesirable.

Moreover, because TLS-SRP negotiation is performed before establishment of TLS encrypted channel (i.e. before the detail of requests are sent), there is no way to negotiate any detail of the authentication (such as realms) before investigating the request. It forces all contents on one server to share one authentication realm, which sometimes requires large-scale redesign of the application. For those reasons, we abandoned to use TLS-SRP and have implemented PAKE-based authentication inside the HTTP protocol.

10 Conclusion and future directions

We have designed a new secure password-based Web mutual authentication protocol which prevents various kinds of phishing attacks. The protocol design considers various aspects of existing web systems, such as additional requirements from applications, systems with multiple hosts, and various ways of system deployments. We also propose new browser UI design to securely use this protocol.

Our implementation of the browser extension and the web server module are available as open-source software. We are also performing demonstration and experiments in a part of the "Yahoo! Auction" website, which is the largest auction website in Japan. During the experiment
we will examine applicability of this protocol to the existing Web applications, examine the user experiences, and use these results to improve the protocol specification for standardization.

We currently consider to extend the protocol to support various existing authentication applications. For example, supporting secure one-time password tokens and inter-domain single sign-on protocols may be desirable. We hope this protocol to be widely-accepted and deployed in many websites to defeat phishing attacks.

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A An example session log

This appendix shows an example log for a session performing a Mutual authentication. Large cryptographic values and other undetermined values unrelated to the protocol is replaced to placeholders like . . . .

Like existing HTTP authentication, the client first sends a request without any authorization credentials, and server requests an authentication in a 401 response.

GET / HTTP/1.1
Host: www.example.com

HTTP/1.1 401 Authentication required
WWW-Authenticate: Mutual version=draft05, algorithm=iso11770-4-dl-2048,
  validation=host, auth-domain=www.example.com,
  realm="Protected Contents", stale=0
Content-Type: text/html; charset="ISO-8859-1"
Content-Length: ...

In the second round-trip messages, the peers performs a password-based key-exchange.

GET / HTTP/1.1
Host: www.example.com
Authorization: Mutual version=draft05, algorithm=iso11770-4-dl-2048,
  validation=host, auth-domain=www.example.com,
  user="foobar", wa="0EeAHPu4Izqrag4vusMs036...VhGBTrdS0YUd1AE7+J2=="

HTTP/1.1 401 Authentication required
WWW-Authenticate: Mutual version=draft05, sid=d0ea626480044abd,
  wb="RUF+v07/uSQ+6uzsV3mKL5/6...TE2w+9HyB6c88+Npptedy==",
  nc-max=256, nc-window=64, time=300, path="/"
Content-Length: 0

The third, final exchange for the first request confirms whether the authentication has been succeeded. Not only the server, but also the client confirms the mutual authentication using the value ob returned from the server in the Authentication-Info header. The Authentication-Control header specifies the browser should terminate the log-in session 300 seconds later.

GET / HTTP/1.1
Host: www.example.com
Authorization: Mutual version=draft05, algorithm=iso11770-4-dl-2048,
  validation=host, auth-domain=www.example.com,
  user="foobar", sid=d0ea626480044abd, nc=0,
  oa="S3aVf+9Vgtdjh7S...S6NnleE/IFy="

HTTP/1.1 200 OK
Authentication-Info: Mutual version=draft05,
  sid=d0ea626480044abd, ob="K6FrV4gFy+XLh...Ow9gAAVhYkSg="
Authentication-Control: logout-timeout=300
Content-Type: text/html; charset="ISO-8859-1"
Content-Length: ...

Once a key-exchange has been succeeded, the shared key is reused for several HTTP requests within the browsing session. The client uses the same session ID (sid) with an incremented nonce count (nc) to request the authentication using the previously-shared secret. The Authentication-Control header in the response reset a log-out timer set by the previous response to 300 seconds again.
