Thesis Dissertation

AUTH.JS: ADVANCED AUTHENTICATION FOR THE WEB

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May 2020

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Thesis submitted in partial fulfilment of the requirements for the award of degree of Bachelor in Computer Science at University of Cyprus

May 2020

Acknowledgments

I would like to express my gratitude to my diploma project supervisor, Dr. Elias Athanasopoulos, for his guidance and help for the completion of this diploma project. He offered all the support necessary for my to successfully overcome any obstacles and complete this research.

Summary

Several research works attempt to replace simple authentication schemes, where the cryptographic digest of a plaintext password is stored at the server. Those proposals are based on more elaborate schemes, such as PAKE-based protocols. However, in practice, only a very limited amount of applications in the web use such schemes. The reason for this limited deployment is perhaps their complexity as far as the cryptography involved is concerned. Today, even the most successful web applications use text-based passwords, which are simply hashed and stored at the server. This has broad implications for both the service and the user. Essentially, the users are forced to reveal their plain passwords for both registering and authenticating with a service.

In this thesis, we attempt to make it easier for any web service to a) enable easily advanced authentication schemes, and b) switch from one scheme to another. More precisely, we design and realize `auth.js`, a framework that allows a web application to offer advanced authentication that leverages sophisticated techniques compared to typical cryptographically hashed text-based passwords. In fact, `auth.js` can be easily enabled in all web applications and supports traditional passwords – however, once enabled, switching to a more elaborate scheme is straight forward. `auth.js` leverages advanced cryptographic primitives, which can be used for implementing strong authentication, such as PAKE and similar solutions, by ensuring that all cryptographic primitives are trusted and executed using the browser's engine. For this, we extend Mozilla Crypto with more cryptographic primitives, such as `scrypt` and the edwards25519 elliptic curve. Finally, we evaluate `auth.js` with real web applications, such as WordPress.

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Chapter 1

Introduction

Contents

1.1 Overview

Authentication is vital for the majority of on-line web applications. Through the process of authentication, services can distinguish their users and offer dynamically generated and personalised content. Unfortunately, the authentication process is often an attractive target for attackers. The goal of attackers is to impersonate users by stealing their credentials and therefore gain access to their data. Notice that, beyond accessing sensitive data, the attacker can also *generate* information on behalf of the compromised user [20] [6].

Several attacks exist depending on the way authentication is implemented. In the case of text-based passwords, it is common to salt, cryptographically hash, and store them at the server. The mechanics of the password protection, which is based on storing the password hashed at the server, coerces the user to *reveal* their plain password to the server each time they log in, which is very likely to already be used in other services, as well. A malicious server could then use the user's plain password to try to take control of another account of the same user in another service. This can be dramatically augmented due to password reuse [14], where users recycle passwords among different services.

On the other hand, advances in cryptography have developed all necessary tools for realizing protocols that do more than simply sending a string to be salted and hashed. For instance, several protocols for Password Authentication Key Agreement (PAKE) [10] permit a password to act as a seed for generating cryptographic keys. Regardless of the actual implementation, such schemes allow users to send a secret to the server for authenticating instead of the password in plain. The secret is cryptographically connected

with the password and, therefore, even non-trusted servers must perform cracking attacks for revealing a user's password.

Despite the availability of such protocols, most services continue to base their authentication on hashing plain passwords. An exception to this rule is Keybase [1], a service which offers cryptographic functions to users (for instance encrypted chat, filesystem and version control). Keybase assumes that the password (or *passphrase*, as they call it) of the user serves as a seed for generating a pair of keys that belong to an elliptic curve [11]. The private key is generated on the fly by the browser and allows the user to sign a message that is validated using the public key stored at the Keybase server. Thus, the password of the user is never revealed to Keybase, while complex handling of cryptographic keys is not an issue; the keys can be re-generated from the passphrase every time the user logs in (from any device).

Unfortunately, Keybase implements all this functionality, including the cryptographic operations, using its own code and does not use the browser's engine to do so. A web site may advertise that it supports a Keybase-like authentication process, where the password of the user is never revealed to the server, in order to convince users to register with it. However, unless the cryptographic primitives are executed in a secure context, it is unclear whether the aforementioned web site implements the authentication algorithm correctly or deliberately violates it in order to read the user's password.

In this thesis, we build a framework for allowing any web site to offer advanced authentication, where plain passwords are used but are never exposed to any server. In particular, we design, implement and evaluate `auth.js`, an authentication framework with a JavaScript interface, which allows developers to enable any PAKE-like protocol in their apps. As a proof-of-concept, we use `auth.js` to enable Keybase-like authentication to WordPress with just a few code modifications. `auth.js` can be used through JavaScript, however, all cryptographic primitives are enforced by the browser engine, which we assume trusted. For this, we extend Mozilla Crypto with more cryptographic primitives, such as `scrypt` and the edwards25519 elliptic curve. As long as the browser can be extended to support all the cryptographic primitives required for an authentication scheme, `auth.js` can be extended to support the use of such a scheme.

1.2 Contributions

To summarize, this thesis contributes:

- we extend Mozilla Crypto with more cryptographic primitives, such as `scrypt` and the edwards25519 elliptic curve –although this is a solely engineering task, we consider it important for enabling new cryptographic capabilities for web applications;

- we design and realize `auth.js`, a framework that allows a web application to offer advanced authentication that leverages sophisticated techniques compared to typical cryptographically hashed text-based passwords;
- `auth.js` can be easily enabled in all web applications and supports traditional passwords – however, once enabled, switching to a more elaborate scheme is straight forward;
- we evaluate `auth.js` with real web applications, such as WordPress. Enabling auth.js in WordPress requires modifying about 50 LoCs of the main authentication code and adding 50 LoCs for enabling password recovery and signature validation.

Chapter 2

Background

Contents

2.1 Overview

In this section, we briefly discuss some basic crytographic primitives which are required for implementing the Keybase-like authentication scheme. We also mention some common authentication schemes supported by most web applications. auth.js can easily support all mentioned schemes, as well as more elaborate ones, such as PAKE protocols [10].

2.2 Cryptographic hash functions

A *hash function* is defined as a function which takes as input some data of any size and maps the data to some fixed-size output, called the hash of the data. Given the same data as input, the hash function will produce the same hash. *Cryptographic hash functions* are a special category of hash functions, which have the extra required property of being *one-way functions*, which means it is not possible to guess what the input data of the function was by only observing the output hash. Cryptographic hash functions are widely used in

cryptography. One of the most common uses of cryptographic hash functions is password storing. A server which stores users' password in a database, does not typically store the passwords in plain text. Instead, it calculates the cryptographic hash of a user's password and stores that instead of the actual password. This offers an extra layer of protection in case the contents of the database are leaked, since an attacker cannot guess the original users' passwords by only having the hashes.

2.3 The scrypt cryptographic hash function

Depending on the use case of a cryptographic hash function, we may require the function to have some extra properties. For example, when the hash function is used to create HMACs for packets in a TLS connection, we would like that to be done as fast as possible. However, fast computation is not always desired. As mentioned above, when a hash function is used to store a user's password in a database, we want it to be as difficult as possible for an attacker with access to the database to find the original value of the password. Even though the attacker does not directly know the password, he can try to brute force it, which means he can try to hash all possible passwords until he gets a hash that matches the stored hash of the user's password. In order to make this process as slow as possible for the attacker, the cryptographic hash function used for storing the passwords should ideally be relatively slow to compute. A way of doing that is by using a *CPU-intensive* or *memory intensive* hash function, which is a function that needs a lot of CPU or memory resources to compute the hash.

One memory intensive hash function is the `scrypt` [8] cryptographic hash function. Specifically, `scrypt` is a key derivation function and its purpose is to derive secret keys given a password as input, and can make the process of deriving the hash more memory-intensive and difficult to compute by tuning some input parameters. Apart from the user's password and a salt, `scrypt` also takes the following parameters, which help increase the expense of generating the hash:

- **N:** the CPU/memory cost parameter
- **P:** the parallelization parameter
- **r:** the blocksize parameter, which configures the size of a memory read

These three parameters determine how costly it will be to compute the hash of the given password. Apart from these parameters, `scrypt` also takes some other parameters which can determine other features of the hash (for example its length, *etc.*).

2.4 Elliptic curve cryptography and the edwards25519 elliptic curve

Elliptic curve cryptography (ECC) is a form of public key cryptography, which makes use of elliptic curves over finite fields to create several cryptographic protocols used for key exchange, signing, *etc.* ECC algorithms are considered to be more secure than their non-ECC counterparts, as a small ECC key provides the same level of security as a long non-ECC key. For example, a 256-bit ECC key provides as much security as a 3072-bit RSA key.[1]

In traditional public key cryptographic schemes, such as RSA, the security of the scheme lies in the difficulty of factoring a very large number which is composed of two large prime numbers. The keys used in such schemes are calculated using these prime numbers. For ECC, the difficulty lies in the fact that, given a starting point on an elliptic curve and multiplying that point with itself many times, it is very difficult to compute the multipicand given the starting and resulting point. In particular, an overview of what ECC public and private keys represent is the following. For an ECC cryptographic scheme, a particular elliptic curve must be chosen. The parameters of the curve, along with a special point G, called the *generator point* are made public. An ECC private key is a randomly generated number k. The corresponding public key, A, is the point on the curve which is calculated by multiplying the private key k with the generator point G. The calculation of A when knowing k can be computed in polynomial time. However, when the elliptic curve parameters are carefully chosen, there are no known algorithms that can calculate k efficiently using only A and G.

Many cryptographic algorithms are designed based on elliptic curve cryptography. One of them is the EdDSA signature scheme, which makes use of a particular family of elliptic curves, named *twisted Edwards curves*, and is designed to be faster than other commonly used signature schemes, such as DSA, without sacrificing security. The most common elliptic curve used for EdDSA is the ed25519 twisted Edwards curve, which is birationally equivalent to a curve named *Curve25519* [11]. For short, the version of EdDSA which uses this particular curve is called Ed25519. A simplistic description of how an EdDSA signature of a message M with a private key A is calculated is the following. Firstly, a secret r is calculated by performing several cryptographic operations, such as hashing, on the private key and the message. This secret is then used to generate a new public point R, by performing scalar multiplication on a generator point G of the curve using the secret r as the scalar. Finally, another public number, s, is calculated by performing cryptographic operations involving the point R, the original public and private

[1] In this context, security means the time that would be required for an attacker to derive the secret using brute force techniques.

keys and the message m. The final signature is the resulting pair $\{R, s\}$. The signature can then be verified using the public key.

2.5 Conventional password authentication

The most common authentication scheme used in the web is text-based passwords. A general overview of how this scheme works is the following. Firstly, when a user registers a new account, they send their password over a (usually encrypted) channel to the web server. The web server uses a cryptographic hash function to compute the hash of the user's password and stores the hash, along with other information about the user, such as their username.

When the client wants to authenticate itself to the server, the user is prompted for their password and the password is sent back to the server. At the server, the hash of the password is computed again and compared against the stored hash. If the two hashes match, the authentication is successful and the user is logged in. For storing different cryptographic digests for identical passwords, the server often concatenates a random, non secret, *salt* to the plain password before hashing it.

2.6 Public key authentication

An alternative authentication method is public-key authentication. This form is often combined with keys that are derived from a password, in order to simulate the typical text-based password experience. For this authentication scheme, the client does not send their password to the server that it wants to register to. Instead, it generates a key pair consisting of a public key, which is sent to the server, and a private key, which the client stores locally.

For authentication, the client informs the server that it wants to authenticate. The server then sends a message to the client and the client uses their stored private key to sign the message, in order to prove ownership of the private key. The signed message is sent back to the server, and the server verifies the signature using the stored public key of the user. If the verification is successful, the user is logged in.

2.7 Keybase authentication

Keybase [1] is a service which offers to its users the ability to prove their identity on social media platforms by mapping their profiles to generated encryption keys. It also offers end-to-end encrypted messaging between its users, an encrypted cloud storage system

and other services. Keybase uses a public key authentication system which works as follows. When a new user tries to sign up [3], they firstly type in a password. However, the password is not directly submitted to the server. Keybase uses its signup API call to generate a random salt value and an `scrypt` hash is generated using the password and the salt. Some bytes of the generated hash value are interpreted as an EdDSA private key, which is then used as a seed to another function to generate the corresponding EdDSA public key. This public key is sent to the Keybase server and is stored as the user's credential. At the login phase [2], the EdDSA private key is recomputed similarly to the signup phase. In order to prove ownership of the key, the client recomputes the private key by prompting the user to re-type their password. Using this key, the client creates a signature which is verified by the server using the stored public key of the user.

Chapter 3

Architecture

Contents

3.1 Overview

In this chapter we provide an overview of the architecture of `auth.js`, as well as the steps needed to be taken by the web application programmer in order to use the framework. We also provide an example of a use case where a server chooses to use an advanced authentication scheme based on public-key cryptography, and specifically based on the authentication scheme of Keybase described in Chapter 2, to register and authenticate its users. This scheme is referenced as `scrypt_seed_ed25519_keypair` by the `auth.js` API. The cryptographic primitives required to be performed for authentication and registration are handled on the client side by the `auth.js` framework, which uses the client's browser engine to ensure that the cryptographic operations are performed in a secure context.

`auth.js` provides simple API calls for the programmer that wants to use advanced authentication techniques in their web application, without needing to worry about the underlying implementation. This is especially important for the various cryptographic elements, which may be leveraged during authentication. First, the programmer does not need to re-implement any cryptographic primitives and, second, all primitives are enforced by the web browser, which we consider trusted.

When a client requests a web application, the web server will direct the client to

retrieve a copy of `auth.js`. The library can be provided to the client either by the web server directly, or via a trusted third party such as a Content Distribution Network, as seen in Figure 3.1. After retrieving the library, the client is able to start the registration or authentication process. In particular, our library provides two API calls, `authenticate` and `register` that, when called, will use the client's browser Web Crypto API to perform the correct cryptographic operations depending on the chosen authentication scheme. For example, in the case of the `scrypt_seed_ed25519_keypair` scheme, the library will use the implemented `scrypt` hash function and the `Ed25519` key generation to create a key pair using the user's password. For authentication, it will use the generated private key to sign a nonce sent by the server using the `Ed25519` signature scheme, to prove ownership of the private key. The implementation of the two API calls is presented in Appendix A.

Our library currently supports traditional plain password authentication, as well as the more advanced public key authentication scheme based on the Keybase authentication. It can be extended to support any authentication scheme, as long as the browser supports the corresponding cryptographic primitives.

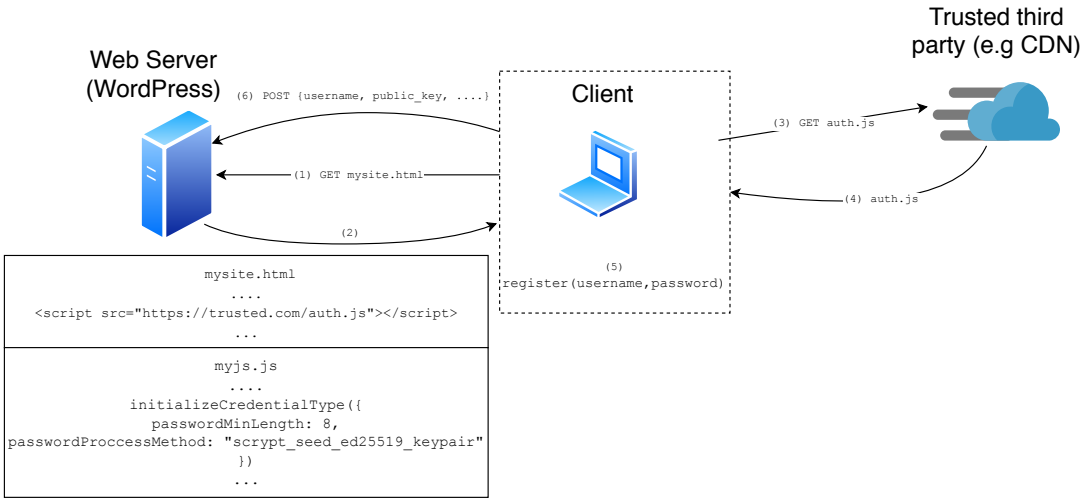

Figure 3.1: Overview of the architecture of `auth.js`.

3.2 auth.js API

3.2.1 Usage

Our JavaScript library provides an easy-to-use API that can be used by the web application programmer with minimal effort. The library will be used as follows:

- The server that wants to use our library includes `auth.js` in the web application's source.

- The desired authentication options must be initialized by the web programmer using the `initializeCredentialType` API call in the main web application (e.g. in the JavaScript file served by the web server), as depicted in Figure 3.3. This call takes as an argument a JSON object describing the authentication options. The library currently supports two options. First, the `passwordMinLength` option allows the server to choose the minimum password length it can accept. The second option, `passwordProcessMethod`, enforces the use of one of the supported authentication schemes. The currently supported schemes are `plain`, which is the traditional text-based password and `scrypt_seed_ed25519_keypair`. If the `initializeCredentialType` call is not used, the library will use the default values of no minimum password length and the `plain` authentication scheme.

- After initializing the options, the `authenticate` and `register` calls can be used. Those calls are placed in the web application's JavaScript source by the web programmer, to be called when the user tries to perform a authentication or registration action. The `register` function takes as an argument the password which the user typed and returns the corresponding credential based on the chosen authentication scheme, to be sent to the server. The `authenticate` function also takes as an argument the user's password and, in the case where an advanced public-key based authentication scheme is used, the optional message argument, which is the nonce that should be signed using the user's private key. The function generates the private key based on the password, signs the message if needed, and returns the signed message. In the case of the plain authentication scheme, the two functions simply return the user's password.

- The web application sends the generated credential to the server. If the authentication or registration is successful, the user can continue using the web application as usual.

3.2.2 Example

In the following example, we depict how a server chooses to use the `auth.js` API to perform registration and authentication using the `scrypt_seed_ed25519_keypair` authentication scheme, with a minimum of 8 characters for the password. The web application HTML code directs the user to retrieve `auth.js` from a trusted source, as seen in Figure 3.2. The API calls `register` and `authenticate`, are then used to generate the correct credentials that the web application can now send to the server. In this particular case, for the registration process, the credential will be the user's public key, generated using the user's password as a seed. For the authentication process, the credential will

again be the user's public key, concatenated with an Ed25519 signature over the nonce attached on the page.

Figure 3.2: Web application html file.

```
<html>
<head>
...
<script type = "text/javascript" src = "https://trusted.com/auth.js"></script>
<script type = "text/javascript" src = "myjs.js"></script>
...
</head>
<body>
/* Registration and login form */
</body>
</html>
```

Figure 3.3: Web application JavaScript file.

```
  ...
  initializeCredentialType({
    passwordMinLength: 8,
    passwordProccessMethod: "scrypt_seed_ed25519_keypair",
  });
  ...
    let password = document.getElementById("password");
  ...
      /* On registration action */
    let credential = register(password);
  ...
      /* On login action */
    let message = document.getElementById("nonce");
    let credential = authenticate(password, message);
  ...
  /* Send credential and other necessary information to the server */
```

Chapter 4

Implementation

Contents

4.1 Overview

Since modern web browsers do not yet provide support for the cryptographic primitives needed for offering advanced cryptographic capabilities, we extended Mozilla's Network Security Services, which is the set of cryptographic libraries used by Mozilla, to support the use of the `scrypt` cryptographic hash function, the creation of `Ed25519` public and private keys and the use of the `Ed25519` signature scheme. Firefox's Web Crypto API also needed to be extended, so as to enable the option to make use of the new cryptographic primitives through the browser. By adding those capabilities, the client does not need to rely on untrusted external sources to perform the aforementioned cryptographic operations, since their own browser's engine executes the cryptographic primitives in a secure context.

Figure 4.1: sha512.c in Mozilla's NSS implementation

```
1  ...
2  void
3  SHA256_End(SHA256Context *ctx, unsigned char *digest,
4             unsigned int *digestLen, unsigned int maxDigestLen)
5  {
6      unsigned int inBuf = ctx->sizeLo & 0x3f;
7      unsigned int padLen = (inBuf < 56) ? (56 - inBuf) : (56 + 64 - inBuf);
8      ...
9      /* SHA256 implementation */
10     ...
11 }
12 ...
13 void
14 SCRYPT_End(SCRYPTContext *ctx, unsigned char *digest,
15             unsigned int *digestLen, unsigned int maxDigestLen)
16 {
17     /* Set scrypt parameters */
18     ...
19     _crypto_scrypt(...);
20 }
21 ...
```

4.2 Extending Mozilla's Network Security Services

4.2.1 Adding the `scrypt` cryptographic hash function

We added a new cryptographic hash function based on the implementation of `scrypt` taken from Tarsnap [5] into the NSS. The new function is added in NSS similarly to other existing cryptographic hash functions, such as the implementation of `SHA256`. An example of how the new `scrypt` works, along with the existing `SHA256`, is depicted in Figure 4.1.

4.2.2 Adding the `Ed25519` EdDSA signature scheme

In a similar fashion, we added support for the Ed25519 signature scheme. In particular, we added the functionality to create a public-private key pair based on a given seed, as well as the signing functionality of the scheme. For this cryptographic primitive, we used parts of the SUPERCOP benchmarking tool's implementation of Ed25519 [4].

Adding the whole functionality of the Ed25519 signature scheme proved to be a rather complicated process and, since we only wanted the functionality as a proof-of-concept for the `auth.js` API, we decided to only add the necessary functionalities (create a keypair based on a seed and sign a message using a private key). Firefox already supports the X25519 key exchange scheme, which uses a curve which is birationally equivalent to the one used in Ed25519 scheme, but we could not find an Ed25519 implementation in the

NSS library.

We decided to add these two functionalities of the Ed25519 scheme as two different digest functions. Note that this is merely a proof-of-concept and should not be used in an official browser release. Rather, we expect that, at some point, new cryptographic primitives such as the `scrypt` hash function and the Ed25519 signature scheme will be correctly implemented in browsers.

Since the Ed25519 scheme needs more than one argument to produce a signature (the private key and the message to be signed) but digest functions only take one argument (the text to hash), we modified the function to take a single argument and then parse it to get both the private key and the message to be signed. Specifically, the function takes the keypair concatenated with the message, and splits it to get both the private key and the message.

4.3 Extending Mozilla's `Web Crypto API`

Apart from extending the NSS library, we also needed to extend Mozilla's Web Crypto API, in order to enable the use of the newly added cryptographic primitives through JavaScript API calls. Similarly to the NSS extension, we located the files containing the calls to other cryptographic primitives and extended them to also provide calls to the newly added operations. With this addition, the client's browser can use the Web Crypto API to perform password hashing using the `scrypt` hash function, as shown in Figure 4.2, generate `Ed25519` keys and sign messages using those keys.

Figure 4.2: `scrypt` hash function called from Firefox using Mozilla's Web Crypto API.

```
1 const encoder = new TextEncoder();
2 //Get scrypt hash of password
3 const passwordEncoded = encoder.encode(password);
4 const hashScrypt = crypto.subtle.digest("SCRYPT",passwordEncoded);
```

As mentioned in the previous subsection, the two latter functionalities were added in the form of hash functions. Specifically, we added the functionality to create an Ed25519 keypair as a hash function called `CURVE25519`, and the functionality to sign a message using a private key as a hash function called `ED25519SIGN`. The first function, `CURVE25519`, takes as an argument the seed produced by the `SCRYPT` hash function in the form of an Ed25519 private key, and outputs the corresponding public key in the form of a digest. The `ED25519SIGN` function takes as an argument the keypair to be used for signing, concatenated with the message to be signed, and returns the signed message.

Both functions can be called using the `crypto.subtle.digest` method of the Web Crypto API. Parts of the `auth.js` implementation where the functions are called can be

found in Appendix D.

More code samples of the Mozilla Firefox code extension are presented in Appendix C.

4.4 WordPress

WordPress is one of the most popular open-source web management systems. It is written in PHP and is widely used for building various websites, ranging from simple blog spots to professional websites. Since it is open-source, we modified the source code to incorporate our authentication and registration system, by extending the current WordPress functionality.

The current default login and registration system of WordPress works as follows. When users wish to register to the website, they provide their user name and email. The user then receives an email with what is essentially link to a reset password form, where they can set their first password. After the user chooses a password, it is sent to the server, where it is salted and hashed with the MD5 hash function and stored.

At the login phase, the user fills in their user name or email and their password in the login form, which is submitted to the server. There, the hash of the submitted password is checked against the stored hashed password and, if they match, the user is logged in.

A web developer that wishes to use `auth.js` in a WordPress site can do so by making minor tweaks to the WordPress source code. The number of changes needed to be made depend on the authentication scheme that is chosen to be used. Simply adding `auth.js` in a WordPress website that wishes to continue using its current authentication system is as simple as adding a few lines of code, while switching to the public key authentication scheme requires some extra steps, such as the addition of a few more functions using the hooks provided by WordPress, in order to extend the functionality of the authentication system. Both of the aforementioned additions are demonstrated below.

4.4.1 Using `auth.js` with the current WordPress authentication system

A web developer can choose to add `auth.js` to a WordPress website without wishing to change the default authentication scheme. To do so, the following steps are required:

- Include `auth.js` in the list of the scripts which are loaded along the log in and reset password pages. Note that as discussed in Chapter 3, this could also be done by loading the file from a trusted third party, such as a CDN.
- Modify the log in and reset password form to make `auth.js` intervene before the form submission, in order to change the typed user password to the corresponding

Figure 4.3: Using the `login_enqueue_scripts` hook to enqueue auth.js.

```
1  add_action( 'login_enqueue_scripts', 'enqueue_authjs' );
2
3  function enqueue_authjs( $page ) {
4        wp_enqueue_script( 'auth', home_url() . '/wp-includes/js/auth.js', null, null,
             true );
5  }
6  do_action( 'login_enqueue_scripts' );
```

credential for the chosen authentication method. Even though no modification will be made on the password field when the `plain` (default) authentication scheme is chosen, adding this will make it easier to switch between authentication schemes in case the web developer wishes to change to a more advanced authentication scheme in the future.

Adding the `auth.js` file can easily be done using the `login_enqueue_scripts` hook provided by WordPress, as shown in Figure 4.3. This should be added in the `wp-login.php` file, which handles the login, reset password and registration forms. This hook allows us to load any script during the loading of the log in page.

To modify the reset password form, a script that temporarily stops the form submission must be added. We demonstrate how this can be done using JQuery in Figure 4.4. The minimum password length and authentication scheme must be initialized using the `initializeCredentialType` call. Before eventually submitting the form, the script uses the `auth.js` API to generate the correct credential and change the credential value which will be submitted. Similarly to the reset password form, a script can be added to change the submitted password value on the login form. In the case of the `plain` authentication scheme, the typed password length is checked and the password is submitted as is.

Both the reset password and log in form scripts can be saved in the site's resources in the `wp-includes/js` folder and enqueued in the same way the `auth.js` file is enqueued, using the `login_enqueue_scripts` hook in the `wp-login.php` file.

4.4.2 Using `auth.js` with the public key authentication scheme

In order to switch to the more advanced public key authentication scheme, the following additional steps must be taken, apart from the steps described above:

- Whenever the `initializeCredentialType` API call is used to set the options for the credential generation, use `scrypt_seed_ed25519_keypair` as the value for the `passwordProccessMethod` field.

Figure 4.4: JavaScript code that uses `auth.js` API to generate the credential and submit the reset password form

```
jQuery("#resetpassform").on("submit", function (e) {
    e.preventDefault(); //Stop form submission
    let self = jQuery(this);
    initializeCredentialType({
     passwordMinLength: 8,
     passwordProccessMethod: "plain",
    });
    let password = jQuery("#pass1").val();
    let public_key = register(password); //Generate the credential using auth.js
    public_key.then( (pk) => {
        console.log(pk);
        jQuery("#pass1").val(pk); //Set the new credential value to be submitted
        jQuery("#pass2").val(pk);
        jQuery("#resetpassform").off("submit");
        self.submit();//Submit the form
    })
});
```

- Modify the login form to include a random token that will be utilized as a nonce and get signed with the user's private key in order to perform authentication.
- Add the same nonce as a cookie that will be submitted along with the form, in order for the server to have the original value of the nonce and be able to verify the signature.
- Modify the default authentication check of WordPress to make it verify the submitted signed nonce using the stored public key.

As mentioned above, to use the public key authentication scheme in the log in and reset password forms, the `passwordProccessMethod` field seen in Figure 4.4 needs to be changed to `scrypt_seed_ed25519_keypair`. When this authentication scheme is chosen, the `register` API call of `auth.js` will use the browser's Web Crypto API and perform the necessary cryptographic operations to change the value of the typed password to the correspoding Ed25519 public key, which is generated using the `scrypt` hash of the password as a seed. The log in script will use the `authenticate` API call to sign the nonce placed in the login form using the private key correspoding to the public key mentioned earlier. The submitted value will be the public key concatenated with the generated signature. Note that the server must have a way to get the original value of the cookie, in order to be able to verify the signature.

Next, the nonce that will be utilized as a message and get signed using the user's private key needs to be added. A simple way to do so is to generate a nonce on the server and attach this nonce in a hidden field in the login form and also add the same value as

a cookie. This way, the server does not need to keep the state of each session, since the original value of the nonce before it was signed can be retrieved from the cookie. This addition is demonstrated in Figure 4.5 and should again be made in the `wp-login.php` file. Adding a random nonce could be implemented in a number of different ways, but most of them would need to keep a state of each connection, so we decided to implement it in a way that would not require the server to do so. WordPress also provides certain functions which generate and verify random nonces, but they could not be used for our purpose, since they do not provide direct access to the value of the nonce, which would be necessary in order to verify the signature.

Figure 4.5: Add a nonce as a cookie, as well as in the log in form as a hidden field

```
1 # Create nonce and set it as a cookie
2 $token = bin2hex(openssl_random_pseudo_bytes(16));
3 setcookie("nonce-message", $token, time() + 60 * 60 * 24);
4 ...
5 # Add the nonce as a hidden field in the login form
6 <input type="hidden" id="nonce-message" name="nonce-message" value="<?= $token ?>" />
```

Finally, the authentication check in the WordPress server side needs to be extended to support authenticating users using their public keys. To do this, the `authenticate` hook can be used to add a new function to authenticate the user. This hook should be added in the `default-filters.php` file, in the `wp-includes` folder. We added the new user authentication function, called `authjs_authenticate`, in the `user.php` file. `authjs_authenticate` functions similarly to the default authentication functions[1] used by WordPress, except that, for checking the user's credentials, it does not call the default `wp_authenticate_email_password` function. Instead, it calls a new function called `check_public_key`. The differences between the two functions can be seen in Figures 4.6 and 4.7.

The `check_public_key` function is added in the `pluggable.php` file. Figure 4.8 shows how `check_public_key` verifies that the submitted signature is correct. In particular, it parses the received credentials to get the public key and signature values and checks if the hash of the public key submitted by the user matches the stored public key hash. Then, it uses the submitted signature along with the Ed25519 public key and the original nonce value to verify the signature. We implemented this signature verification as an external Python script, which uses the PyNaCl library to verify that the given signature is correct. The script is presented in Appendix B. After the signature is verified, the user is successfully logged in. Note that the signature verification does not need to implemented externally, but could also be implemented in PHP, in the `pluggable.php`

[1] To be precise, WordPress has three default authentication methods: one using username and password, one using email and password and one using a cookie.

Figure 4.6: wp_authenticate_username_password, one of the default authentication functions used in WordPress

```
function wp_authenticate_username_password( $user, $username, $password ) {

  if ( ! wp_check_password( $password, $user->user_pass, $user->ID ) ) {
    return new WP_Error(
      'incorrect_password',
      sprintf(
        /* translators: %s: User name. */
        __( '<strong>ERROR</strong>: The password you entered for the username %s is
            incorrect.' ),
                '<strong>' . $username . '</strong>'))
                ...
    }
...
}
```

Figure 4.7: The `authjs_authenticate` function which is used in place of the default authentication function of WordPress

```
function authjs_authenticate( $user, $username, $password ) {
...

  if ( ! check_public_key( $password, $user->user_pass, $user->ID ) ) {
    return new WP_Error(
      'incorrect_public_key',
      sprintf(
        /* translators: %s: User name. */
                __( '<strong>ERROR</strong>: Wrong public key' ),
                ))
    ...
    }
...
}
```

file itself, as is the case for the rest of the authentication functions. The only requirement for this would be a PHP module which supports the necessary cryptographic operations for verifying EdDSA signatures.

If a web developer wishes to switch back to the old WordPress authentication system or to another potentially supported authentication system, he can do so easily. To change the server side authentication he can simply change the `authenticate` hook to point to another authentication function. To change the value which is submitted during login or registration, he can change the value of `passwordProccessMethod` in the `initializeCredentialType` API call to the corresponding authentication scheme. Of course, the users of the web application would then need to reset their credentials to match the new authentication scheme. For example, switching from the current WordPress authentication scheme to the public key scheme would require the credentials to be changed

Figure 4.8: The `check_public_key` function that verifies the submitted signature using the user's stored public key

```
1         // Get the original value of the nonce from the cookie, so we can verify the
              signature
2         $message = $_COOKIE["nonce-message"];
3         // Extract the public key an signature
4         $public_key = substr($credentials, 0, 64);
5         $signature = substr($credentials, 64);
6         ...
7         // Check if the hash of the sent public key matches the stored hash
8         $check = hash_equals( $stored_pk, md5( $public_key ) );
9         ...
10        // Run python script to verify signature //
11        ...
12        return apply_filters( 'check_password', $check, $credentials, $stored_pk,
              $user_id );
13        }
```

from plain passwords to public keys.

Chapter 5

Evaluation

Contents

5.1 Overview

In this chapter we evaluate the performance of `auth.js` and particularly the overhead that the public key authentication system adds over the traditional password authentication method.

5.2 Setup

For the following measurements, we used two Linux machines running Ubuntu 18.04 LTS. The first machine run a dummy server with minimal functionality. The second machine run a fork of Mozilla Firefox Nightly 73.0a1, compiled with the disable optimizations and enable debug options.

5.3 Average time for posting credentials on the server and getting a reply

We measured the average time for generating and posting a user's credentials using the two authentication methods, traditional password authentication and public key authen-

tication, from the machine running Firefox to the machine running the dummy server. For checking the password, the dummy server simply checked if the posted password matched the user's stored password in its database. For checking the posted signature, the server run the Python script mentioned in Chapter 4, which uses the PyNaCl library to verify the signature. Table 5.3 presents the average time for 1,000 repetitions. The timing includes the time needed for the client to receive the reply from the server that either the authentication is successful or not, which varies due to network latencies. The signature was produced on the same message, with the same key pair for all 1,000 repetitions.

Table 5.1: Average time for posting key pairs and signatures.

Credential posted	Average time
Password	260 ms
Signature	328 ms

5.4 Average time for key pair and signature generation

We measured the performance of `auth.js` for creating Ed25519 key pairs and signing messages using the private key of the pair. We split the measurement in 3 parts: the time for only generating key pairs with a given password, the time for only signing a given message with a given key pair, and the time for both generating a key pair using a given password and signing a given message with the generated private key. Table 5.4 presents the average time for these three measurements for 10 thousand repetitions. For these measurements we used a fixed seed for the key pair generation and a fixed key pair and message for the signing process.

Table 5.2: Average time for generating key pairs and signatures.

	Average time
Generate key pair	30.9 ms
Sign message	29.5 ms
Generate key pair + sign message	59.3 ms

As can be seen from the evaluation, switching to the public key authentication scheme would add around 60 ms of overhead compared to simply submitting the user's password as is. These timings were taken on the browser which was compiled without optimizations for debugging reasons, resulting in its performance being several times worse than an average browser. As a result, the 60 ms of overhead would translate to much less in an

average user's browser, so it would be unnoticeable. Also, the time needed for the server to verify the signature is not significantly more than the current time needed to verify a password.

Chapter 6

Related Work

Contents

6.1 Advanced authentication schemes

Apart from the public key authentication scheme we presented, various more authentication methods exist. PAKE protocols such as SRP [21] allow clients to authenticate themselves to a server and exchange a secret securely, without needing to send their actual password. Even though certain PAKE protocols have seen some adoption, many of them have not been successfully deployed yet. Other password-based authentication mechanisms which are based on PAKE protocols, such as [22], are also starting to get proposed. `auth.js` can serve as a single framework from which such protocols can be deployed. As long as the cryptographic primitives needed for a protocol are implemented in the client's browser, `auth.js` can securely enforce their usage, assuming of course that the browser is not compromised. A web programmer who wishes to use another scheme for authenticating users can do so simply by changing the `passwordProccessMethod` field in their forms to the authentication scheme of their choosing and transparently switch to a new authentication method, assuming that the server also supports the use of a chosen protocol. The autentication scheme mentioned in this thesis is based on the authentication scheme used by Keybase [1]. The major difference is that Keybase uses its own source code to perform the cryptographic operations, while `auth.js` uses the cryptographic primitives that are built in the user's browser, ensuring that the operations will be performed securely.

6.2 Cryptographic primitives

In the recent years, many improvements have been made and many new cryptographic primitives have been introduced, which are not yet implemented by the major web browsers. For our work, we added the scrypt [17] hash function as well as the Curve25519 elliptic curve [11] to Mozilla Firefox and specifically in the Web Crypto API, in order to use them for our authentication scheme. We expect that those cryptographic primitives, as well as more primitives such as the bcrypt [18], Argon2 [12] and blake2 [9] hash functions or new elliptic curves such as the FourQ curve [13] will eventually be implemented in the major web browsers and will be available to use. As more and more cryptographic primitives are added, `auth.js` can be modified to support the usage of these primitives to create new authentication schemes. Other projects have also explored the extension of the Web Crypto API functionality to add support for other operations, such as document signing [15]. New types of cryptographic primitives are also starting to get implemented. For example, Microsoft's SEAL [19] provides an API that can be used to perform homomorphic encryption.

6.3 Cryptography frameworks

Other frameworks have also tried making advanced cryptography more accessible and easier to use. For example, Let's Encrypt [7], [16] makes it easy to obtain a TLS certificate without the need of human intervention. Keybase is another web service that offers advanced cryptography to simple users, such as an advanced authentication scheme, end-to-end encryption, public identity verification and encrypted storage.

Chapter 7

Conclusion

Contents

7.1 Overview

In this thesis we designed, implemented and evaluated auth.js, a framework that allows web developers to integrate any authentication scheme in their applications. auth.js allows a developer to express the authentication policy in JavaScript and realize complex schemes, that leverage modern cryptographic primitives, in the browser environment. Moreover, the framework makes sure that cryptographic operations are not implemented in JavaScript, but are instead carried out using the browser's internal engine, which is considered trusted. For this, we extended Mozilla Crypto with the `scrypt` hash function and the edwards25519 elliptic curve in order to easily implement the authentication used in Keybase. In the same fashion, auth.js can support other cryptographic-based authentication schemes, such as PAKE. Enabling auth.js in existing web application is trivial and, once the framework is in place, switching from one authentication to another is straight forward. For demonstrating this, we enabled auth.js in a popular open-source web application, namely WordPress. Our modifications do not exceed 50 LoCs for the main authentication code in WordPress and require additionally 50 LoCs for enabling password recovery and signature validation.

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Appendix A

auth.js implementation

Figure A.1: JavaScript implementation of the authenticate API call

```
async function authenticate(password, message = "") {
    let retVal;
    // Get the chosen authentication method
    if (CredentialType.passwordProccessMethod === "plain") {
        // If the plain scheme is used, simply return the password
        retVal = password;
    } else if(CredentialType.passwordProccessMethod === "scrypt_seed_ed25519_keypair"){
        // If scrypt_seed_ed25519_keypair is used create the keypair using the password
            as a seed
        let keypair = await createKeyPairFromPassword(password);
        // Get the public key part of the key pair
        let public_key = keypair.substr(64, 128);
        // Sign the message
        let signedMessageBytes = await signMessage(keypair, message);
        let signedMessageArray = Array.from(new Uint8Array(signedMessageBytes));
        let signature = signedMessageArray.map((b) => b.toString(16).padStart(2, "0")).
            join("");
        // Return the public key concatenated with the signature
        retVal = public_key.concat(signature);
    }
    return Promise.resolve(retVal);
}
```

Figure A.2: JavaScript implementation of the register API call

```
async function register(password) {
    let retVal;
    // Check that the password is longer than passwordMinLength
    if (!(CredentialType.passwordMinLength === null)) {
        if (password.length < CredentialType.passwordMinLength) {
            let errorMessage = "Password must be at least " + CredentialType.
                passwordMinLength + " characters long";
            throw errorMessage;
        }
    }
    if (CredentialType.passwordProccessMethod === "plain") {
        // If the plain scheme is used, simply return the password
        retVal = password;
    } else if(CredentialType.passwordProccessMethod === "scrypt_seed_ed25519_keypair"){
        // If scrypt_seed_ed25519_keypair is used create the keypair using the password
             as a seed and return the public key
        let keypair = await createKeyPairFromPassword(password);
        let public_key = keypair.substr(64, 128);
        retVal = public_key;
    }
    return Promise.resolve(retVal);
}
```

Appendix B

Signature verification

Figure B.1: Python script which checks the validity of the signature

```
...
SIGNATURE = bytearray.fromhex(SIGNATURE_STR)
MESSAGE = bytearray.fromhex(MESSAGE_STR)
# Create a VerifyKey object from a hex serialized public key
VERIFY_KEY = nacl.signing.VerifyKey(PUBLIC_KEY_STR, encoder=nacl.encoding.HexEncoder)
# Check the validity of a message's signature
try:
    VERIFIED = VERIFY_KEY.verify(MESSAGE_STR, SIGNATURE_STR, encoder=nacl.encoding.
        HexEncoder)
    print("1")
    # print ("".join("{:02x}".format(ord(c)) for c in verified))
except nacl.exceptions.BadSignatureError:
    print("0")
```

Appendix C

Mozilla Firefox extension

Figure C.1: Adding new cryptographic primitives in the WebCrypto API

```
1  ...
2  if (algName.EqualsLiteral(WEBCRYPTO_ALG_SHA1) ||
3      algName.EqualsLiteral(WEBCRYPTO_ALG_SHA256) ||
4      algName.EqualsLiteral(WEBCRYPTO_ALG_SHA384) ||
5      algName.EqualsLiteral(WEBCRYPTO_ALG_SCRYPT) ||
6      algName.EqualsLiteral(WEBCRYPTO_ALG_CURVE25519) ||
7      algName.EqualsLiteral(WEBCRYPTO_ALG_ED25519SIGN) ||
8      ...
9  return new DigestTask(aCx, aAlgorithm, aData);
10 }
11 return new FailureTask(NS_ERROR_DOM_NOT_SUPPORTED_ERR);
```

Figure C.2: Adding new cryptographic primitives in various files in the NSS library

```
/* secoidt.h */
...
typedef enum {
    SEC_OID_UNKNOWN = 0,
    SEC_OID_MD2 = 1,
    SEC_OID_MD4 = 2,
    SEC_OID_MD5 = 3,
    SEC_OID_SHA1 = 4,
    ...
    SEC_OID_SCRYPT = 364,
    ...
    SEC_OID_ED25519SIGN = 367,

/* utilmodt.h */
#define SECMOD_SHA256_FLAG 0x00004000L    /* also for SHA224 */
#define SECMOD_SHA512_FLAG 0x00008000L    /* also for SHA384 */
...
#define SECMOD_SCRYPT_FLAG 0x00080000L
#define SECMOD_CURVE25519_FLAG 0x00200000L
#define SECMOD_ED25519SIGN_FLAG 0x00400000L
...

/* secdig.c */
...
SGNDigestInfo *
SGN_CreateDigestInfo(SECOidTag algorithm, const unsigned char *sig,
                     unsigned len)
{
...
    switch (algorithm) {
        ...
        case SEC_OID_SHA256:
        case SEC_OID_SHA384:
        case SEC_OID_SHA512:
        case SEC_OID_SCRYPT:
        case SEC_OID_CURVE25519:
        case SEC_OID_ED25519SIGN:
        ...
            break;
...
```

Appendix D

Using the EdDSA signature scheme through the WebCrypto API

Figure D.1: Calling the ED25519SIGN and CURVE25519 digest functions in the auth.js implementation

```
...
  const privateKeyEnc = hexToBytes(privateKey);
  const privateKeyBytes = new Uint8Array(privateKeyEnc);
  //Curve25519 scalar mult lower 32 bytes of scrypt hash to get public key
  const publicKeyPromise = await crypto.subtle.digest("CURVE25519", privateKeyBytes);
  const publicKeyByteArray = Array.from(new Uint8Array(publicKeyPromise)); // convert
      buffer to byte array
  const publicKey = publicKeyByteArray.map((b) => b.toString(16).padStart(2, "0")).join
      ("");
  return privateKey.concat(publicKey);
};
  ...
let signMessage = async function (keypair, message) {
  const input = keypair.concat(message);
  const inputBuf = hexToBytes(input);
  const inputArray = new Uint8Array(inputBuf);
  return crypto.subtle.digest("ED25519SIGN", inputArray);
};
...
```