

Hochschule Wismar

University of Applied Sciences

Technology, Business and Design

Faculty of Engineering, Department EE & CS

Course of studies: IT-security and forensics



Master's Thesis

for the Attainment of the Academic Degree

Master of Engineering (M. Eng.)

Security Evaluation of Multi-Factor Authentication in Comparison with the Web Authentication API

Submitted by: August 25, 2019

From: Tim Brust
born 03/31/1995
in Hamburg, Germany

Matriculation number: 246565

First supervisor: Prof. Dr.-Ing. habil. Andreas Ahrens
Second supervisor: Prof. Dr. rer. nat. Nils Gruschka

Purpose of this thesis

The purpose of this master's thesis is to introduce, analyze and evaluate existing multi-factor authentication solutions in regards to their technical functionality, usability in web projects and potential security risk.

Those multi-factor authentication solutions are compared to the Web Authentication API in order to identify if the Web Authentication API is a suitable replacement or complementary addition to the multi-factor authentication solutions.

Abstract

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special contents, but the length of words should match the language.

Kurzfassung

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special contents, but the length of words should match the language.

Contents

1	Introduction	1
1.1	Problem statement and motivation	1
1.2	Goals of this thesis	2
1.3	Target audience	3
1.4	Delimitation of this thesis	3
1.5	Approach and methodology	3
2	Basics of authentication	5
2.1	Methods of authentication	5
2.1.1	Knowledge	5
2.1.2	Possession	6
2.1.3	Biometrics	7
2.1.4	Further methods of authentication	9
2.2	Processes of authentication	9
2.2.1	Active authentication	10
2.2.2	Passive authentication	10
2.2.3	Continuous authentication	10
2.3	Wording differences between multi-factor, multi-step, authentication, and verification	11
3	Single-factor authentication	12
3.1	Threats	12
3.1.1	What you know (Password)	12
3.1.2	Possession	12
3.1.3	Biometrics	13
3.1.4	Further methods	14
3.1.5	General threats	14
4	Multi-factor authentication	16
4.1	OTP	16
4.1.1	HMAC	16
4.2	Smart Cards	17
4.3	Hardware Tokens	17
5	Security of multi-factor authentication	18
5.1	Introduction	18
5.2	HOTP and TOTP	19
5.2.1	Algorithm	19
5.2.2	Transportation	19

6	Introduction to the Web Authentication API	23
6.1	History and evolution	23
6.2	Technical implementation and details	23
6.2.1	Browser support	24
6.2.2	Usability	27
6.3	Security aspects	27
6.3.1	Problems	27
7	Comparison	28
8	Conclusion and Outlook	29
	Bibliography	VI
	Internet sources	X
	List of Figures	XII
	Listings	XIII
	List of Tables	XIV
	Glossary	XV
	Acronyms	XVI
A	Appendix	XVIII
A.1	Test	XVIII
B	Annex	XIX
B.1	Table of Content of the CD-Rom	XIX
	Declaration of academic integrity	XXI

1 Introduction

1.1 Problem statement and motivation

»Usernames and passwords are an idea that came out of 1970s mainframe architectures. They were not built for 2016.«¹

Alex Stamos

Passwords, in the way they are currently used, are not suited for the twenty-first-century, like Alex Stamos, the former Chief Security Officer (CSO) of Facebook and Yahoo!, stated. The secure handling of passwords is a problem for many users. Passwords are re-used between different websites and often shared across private and work environments. This renders the (private) user data, but also business secrets at high risk.

To make things worse, very few people are using multi-factor authentication (MFA) nor a password manager in 2019. The majority of the users are either remembering their passwords or writing them down on a piece of paper – in cleartext.² At the same time, the recorded amount of cybercrime cases is still increasing, and, for example, phishing remains a big problem. While MFA can protect against threats such as brute force attacks or stolen credentials, but they are still affected by phishing attacks. Besides that, SMS traffic is not considered secure anymore, yet a lot of MFA solutions use it. Nevertheless, the majority of the users are not using MFA at all.³

To counter these negative trends, new application programming interfaces (APIs) are emerging, for example, the Web Authentication API. It is a standardized API supported in major browsers such as Chrome, Firefox or Edge that allows a secure registration, login and two-factor authentication (2FA) – all without the generation,

¹See Col16.

²See Kes18; See Fri19.

³See dim19; See Bun18, pp. 6–7.

storage and remembering of passwords by using asymmetric cryptography. The private keys are stored, e.g., on external devices like USB sticks, but can be stored on built-in hardware, too and, for example, a fingerprint sensor can protect these.

1.2 Goals of this thesis

The goals of this thesis are an introduction into MFA and the different authentication factors such as »knowledge, possession and biometrics« including the technical functionality, usability in web projects and respectively web browsers and their security risks alongside an introduction to the Web Authentication API. Those methods of authentication need to be mapped to actual forms of authentication such as passwords, security keys, and fingerprint sensors, that need to be again evaluated security-wise.

The Web Authentication API and its origin are being illustrated and technically in more depth explained. In this connection, the question has to be answered if the Web Authentication API can increase security and user comfort and usability. Of course, the security and potentials risks of the Web Authentication API need to be taken into account.

Finally, the thesis should answer the question if the Web Authentication API is ready to be used yet and whether it can replace passwords and existing MFA solutions or be used in conjunction. Besides that, questions such as

- What are the risks of not using MFA?
- Why are weak password and re-usage such a big issue?
- Is there a protection against the weakest link, often being humans?
- If using MFA, are there any risks, too?
- Are the architecture and algorithms used secure enough for usage in web projects and insecure connections?
- Is the Web Authentication API suitable and understandable for end-users?

are taken into account and answered.

1.3 Target audience

The target audience of this thesis are technically experienced readers that have a good understanding and interest in data security and privacy. Additionally, the reader should have a basic knowledge about the functionality and mathematics behind algorithms such as RSA, Elliptic-curve cryptography (ECC) or symmetric and asymmetric key exchange (e.g., DiffieHellman key exchange). Moreover, the reader needs to be familiar with the underlying concept(s) and techniques of MFA.

Furthermore, the thesis is tailored towards interested (web) developers. On the one hand it shall, introduce a new standardized Web API to them in detail. On the other hand, the thesis helps to understand the pros and cons of alternative registration, login, and MFA solutions using asymmetric cryptography and if the Web Authentication API suits their needs.

1.4 Delimitation of this thesis

Existing proven algorithms and concepts, as long as not required for the understanding of this thesis, are not explained in detail. It is not the goal of this thesis to perform complete cryptanalysis, but to take other factors, such as usability for the user, technical feasibility, and web browser support into account. Different, but adjacent, technologies such as OAuth (2.0), OpenID Connect or Single Sign-on (SSO) neither are a focus of this thesis. Additionally, the topic of authorization is not taken into account and not from concern for this thesis.

1.5 Approach and methodology

Initially, in Chapter 2, the reader is introduced into the basics of authentication. After that in the following chapters the areas

- Single-Factor-Authentication
- MFA

are explained, for example, their technical functionality, and analyzed regarding their security and potential risks and attacks such as phishing or Man-in-the-Middle (MITM) attacks.

Hereupon the Web Authentication API is introduced in Chapter 6 and described in detail. The technical functionality is a crucial aspect of this chapter. Additionally, the attacks the Web Authentication API can offer protection against are explained but also asserted which security risks exist, too. Where suitable example source code listings are used to highlight these analyses.

In Chapter 7, the Web Authentication API is compared with existing MFA solutions. Therefore, it's reviewed if the Web Authentication API can be used in conjunction or as a replacement for MFA.

Concluding follows an evaluation based on the gained insights from the previous chapters with a conclusion and an outlook for further research and studies.

2 Basics of authentication

2.1 Methods of authentication

There are multiple different methods or forms, respectively, that can be used to authenticate a user against someone or something. Traditionally only knowledge, possession, and trait are considered the different forms of authentication,⁴ but other sources also introduce or take new methods into account such as the location- or time-based authentication.⁵ Therefore, this thesis accounts for them, too, and describes the methods in the following sections briefly including a diagram of an example authentication flow. A detailed analysis of the security, potential risk, and threats follows in section 3.1

2.1.1 Knowledge

The most common method of authentication is knowledge, i.e., »something the user knows«. Commonly used in information technology (IT) are passwords. Other forms of knowledge are, for example, personal identification numbers (PINs), passphrases, secrets, recovery questions, or one-time passwords (OTPs). The PIN is a good example for usage, e.g., in banking (ATM's, credit cards) or telephony (SIM cards). The security relies on the fact that the knowledge method is considered a secret that only the user knows. When compromised it is relatively easy to replace the knowledge with a different secret the user knows. Unintentional side effects are that the user may have to replace the used knowledge everywhere in case of re-use.⁶

⁴See TW75, p. 299; See BB17, p. 140; And08, p. 47.

⁵ZKM12; See DRN17, p. 191.

⁶See Eck14, p. 467.

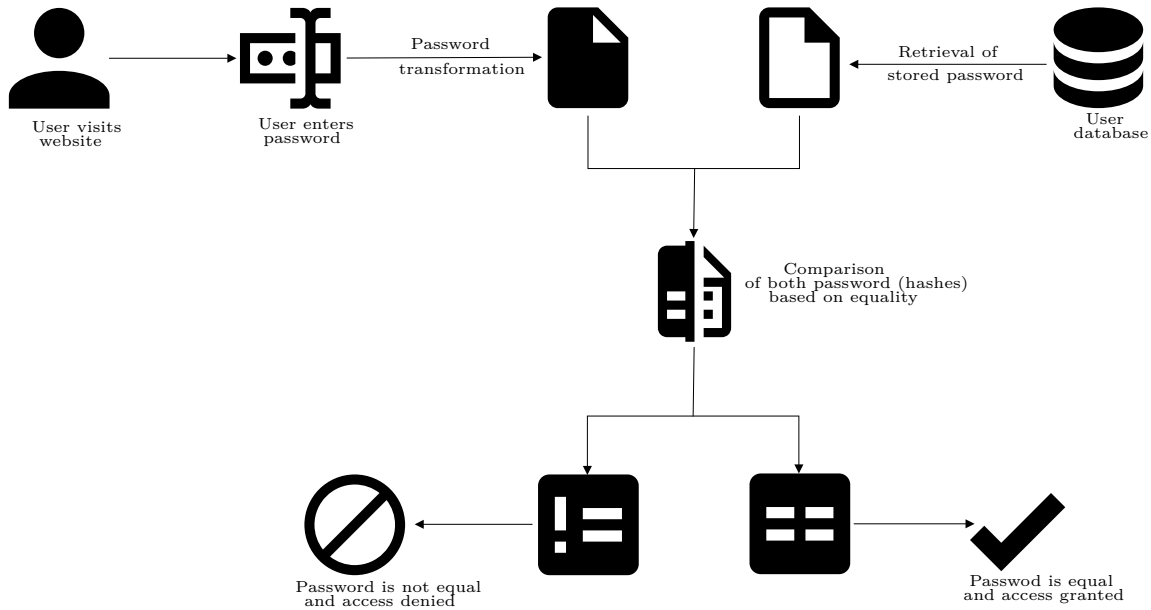


Figure 2.1: Exemplary, but simplified, authentication by knowledge flow⁷

Figure 2.1 shows a simplified authentication by knowledge flow. First, the user visits in this example a website and enters their password in the corresponding form fields. When the user submits the form, the transferred password is often transformed, e.g., hashed and salted. If the user is known in the database, then the stored (hash of) the password is retrieved and compared to the given one. Only if the hashes are identical, then the login succeeds. Otherwise, it fails. The »access denied/cancel« and »checkmark« symbols are chosen, since it cannot be verified if the authentication is made by the genuine user or an imposter that gained access to the knowledge of the attacked user, in this case, their password.

2.1.2 Possession

Another form of authentication is the possession, i.e., »something the user has« (physically). The most basic example is a key for a lock. Other forms are, for example, a bank, or ID card that can use techniques like radio-frequency identification (RFID), an onboard chip or magnetic stripes to store the information. In IT security tokens are often used, which can be a hardware (such as a YubiKey, a RSA SecurID or a smart card) or software (e.g., a smartphone application) token. They can either be disconnected, connected (e.g., via USB or as a smart card) or contactless (e.g., via near-field communication (NFC), Bluetooth Low Energy (BLE))

⁷Source: diagram by author.

or RFID). Sometimes these tokens contain a display itself that can show further information.⁸

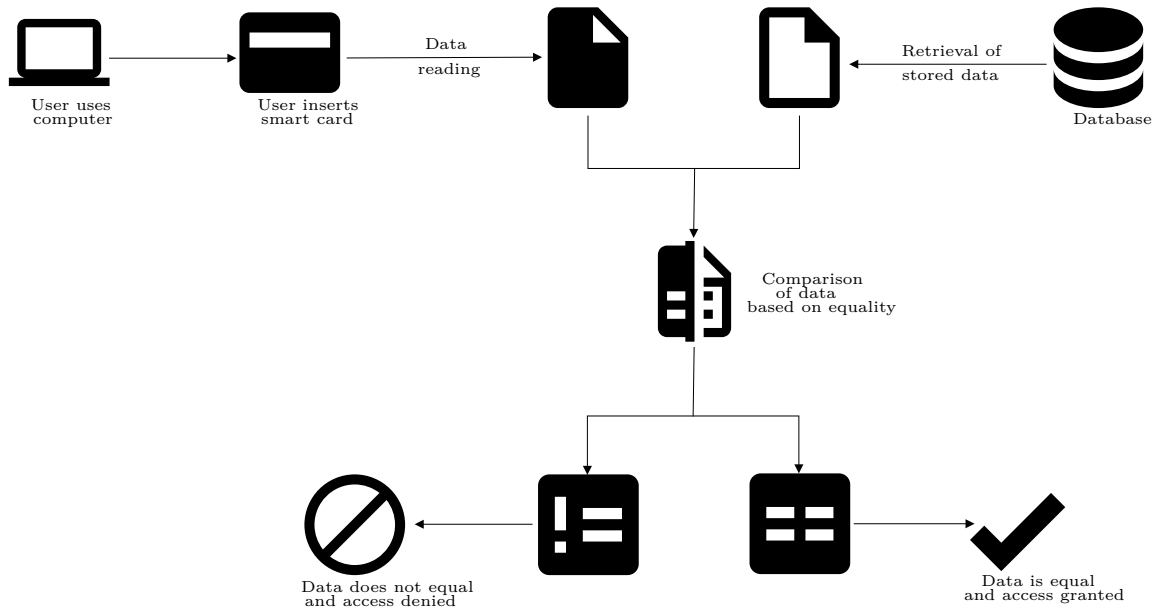


Figure 2.2: Exemplary, but simplified, authentication by possession flow⁹

Figure 2.2 shows an example of an authentication flow with a smartcard. First, the user inserts the given smartcard into their computer. The data is read subsequently. Contemporaneous the application or system reads the stored database entry and compares the data to the one stored on the smartcard. If the data is equal or matches, and the user is authorized, then the authentication succeeds. Again, any user can log on as long as they are in possession of the smartcard.

2.1.3 Biometrics

Besides the knowledge and possession factors, another one is biometrics. This factor is classified as »something the user is« and commonly includes the fingerprint, facial, or iris scan. In theory, many other characteristics like the gait, the ear, DNA, or even the human odor could be a biometric factor.¹⁰

These intrinsic factors are sometimes referred to as traits or inherit, too.¹¹

While it seems natural to authenticate a person with a biometric, it also comes with a couple of challenges. Both, the false rejection rate (FRR), i.e., the system rejects

⁸See Tod07, p. 24; DLE19; See Kei17, pp. 8–11.

⁹Source: diagram by author

¹⁰See JRN11, pp. 30–34.

¹¹See DRN17, p. 186.

a user even though it is a legitimate authentication attempt and false acceptance rate (FAR), i.e., an imposter is granted access, need to be accounted for the usage. Compared to knowledge and possession factors, the enrollment of the biometrics and the continuous update of the sample is more complicated and expensive.¹²

On the other hand, it is more complicated to steal, share, or copy this factor than the others – but also nearly impossible to replace a compromised biometrics. The usability varies because of the quality of the used biometrics module, the chosen biometrics itself, and the availability of the biometrics.

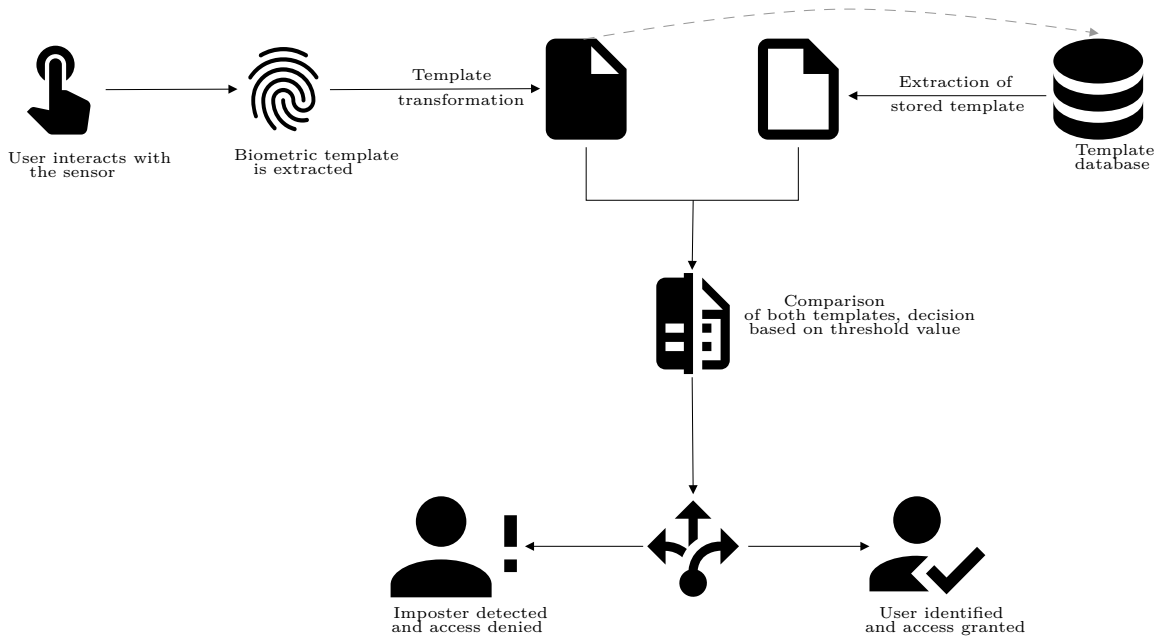


Figure 2.3: Exemplary, but simplified, authentication by biometrics flow¹³

Figure 2.3 shows an exemplary authentication flow using biometrics, in the case with a fingerprint. First, the user interacts with the sensor that reads the fingerprint and extracts the biometric template. Generally, the system or reader transforms the template into a more comparable format. For instance, fingerprints are scanned for minutiae and their direction. Simultaneously, the system retrieves the stored fingerprint or searches for it. The system now compares the stored probe to the fresh one. A threshold value that determines how much difference is tolerable decides finally if the authentication attempt can proceed or has to be aborted and access denied. If the authentication succeeds, the stored template can be updated in the database, as denoted by the dotted grey arrow.

¹²See JRN11, pp. 18–24; See Tod07, pp. 34–37.

¹³Source: diagram by author, based on JRN11, p. 11.

2.1.4 Further methods of authentication

While the mentioned authentication forms above are considered a standard in the literature, other forms exist, too. Those include, for example, the location of the user. The location-based approach grants or denies access based on the current location. The location can either be physical (e.g., via GPS) or digital with, e.g., an IP address.¹⁴

Another form is time-based authentication. A typical example is time-limited access to a banking safe, which can only be opened at specific times of the day, a time lock secures it. In IT this form of authentication helps to protect against, for instance, phishing attacks from abroad, because the access is granted or denied based on the time and usual time routines where, for instance, a user logs typically on.¹⁵

Further methods of authentication are, for example, social authentication, also referred to as »someone the user knows«. For example, Facebook uses this method to ensure that the authentication attempt is genuine by asking the user to identify a set of their friends. Of course, social authentication works in other scenarios, especially offline, too.¹⁶ Besides these methods, »something the user does« is another form of authentication. Examples range from keystrokes to online shopping behavior.¹⁷

2.2 Processes of authentication

The process of authentication can be done in three different manners that are explained in the following subsections. These are namely:

1. **Active authentication**, where a user has to initiate the process
2. **Passive authentication**, where the user does not need to interact with the system
3. **Continuous authentication**, where a system continually monitors and authenticates the user

¹⁴ZKM12; See Bis18, Chapter 13.9.

¹⁵See DRN17, p. 191.

¹⁶See Bra+06; See Sho14, pp. 278–279.

¹⁷See Shi+11; See Oud16.

2.2.1 Active authentication

The most common process of authentication is active authentication. In this process of authentication, the user has to initiate the authentication. Instances for this process can be opening a website and entering the password in the form fields, pressing a button or placing the fingerprint on the corresponding sensor.¹⁸

2.2.2 Passive authentication

In contrast to the active authentication process, the user is in the passive authentication process authenticated without action on their part. Use cases are for RFID chips that continuously send a signal in a short-range and can open a door when the user approaches it. Further examples can be the analysis of the keystroke or touch screen usage patterns. In comparison with active authentication, this process is more low-friction.¹⁹

2.2.3 Continuous authentication

Further, the process of continuous authentication exists. In this case, the user is continuously authenticated or monitored to ensure that it is still the initially authenticated user who is using the system. The authentication must happen in a non-intrusiveness way. Commonly used for continuous authentication are biometrics, such as the fingerprints, facial recognition, or keystroke patterns.²⁰

Unfortunately, the term active authentication is often used to describe continuous authentication, too. To avoid confusion, solely term continuous authentication is used to refer to this process of authentication, while any mentions of active authentication refer to the process described in subsection 2.2.1.

¹⁸See DZZ14, pp. 185–186.

¹⁹See DZZ14, p. 186; See XZL14.

²⁰See DRN17, pp. 236–238; See Fri+17.

2.3 Wording differences between multi-factor, multi-step, authentication, and verification

The naming of the chosen authentication or verification methods by companies is often confusing or difficult to understand. The terms used by companies vary from 2FA, often just calling it 2FA,²¹ to two-step-verification, sometimes written as 2-Step Verification, too.²²

One could argue that the different authentication factors can be reduced to a single one, e.g., that an OTP is »something the user knows« since it relies on a secret that *could*, in theory, be memorized, too, but practically is not memorizable.

In this case, the term MFA or 2FA is technically incorrect, since it is instead a multi-step authentication because the same factor is used multiple times. However, it has to be noted that using the same authentication factor multiple times is weaker than using different authentication factors.²³

Besides that, (user) verification is a part of the authentication process this little differentiation of verification vs. authentication and multi-step vs. multi-factor is not crucial for this thesis, and the term MFA is used throughout.

²¹Sup19a.

²²Sup19b; Pla; Goo; Mic19.

²³See Gri17, p. 117.

3 Single-factor authentication

3.1 Threats

3.1.1 What you know (Password)

Just knowledge. Often weak, re-used. Meant to be remembered. One factor only. Protection by the server often not given, user's are writing it down etc.

1. re-usage
2. phishing -> stealing in general
3. secret might be known by others, too (e.g. security questions)
4. guessing
5. brute force
6. copied

3.1.2 Possession

The primary risks of authentication by possession are that it is not tied to the user itself and can be lost or even worse stolen by an attacker. Besides, that possession factors can be shared between multiple users, allowing attacks such as a malicious insider attack. Often the possession factors are not protected itself so, e.g., a keycard to open a door can be used by the attacker, too.

Another usage implication is that it has to be carried with the user and can be forgotten which makes the authentication impossible if no access to the possession is possible and no backup or different authentication methods are available. Another risk is that possession can be damaged or destroyed. For example, carrying security keys on a keyring exposes them to damage by a fall or liquids.²⁴

²⁴See Sho14, pp. 263–264.

Especially possessions that use wireless transmissions such as BLE, NFC, or RFID can be copied even over some distances. For instance, an attacker could copy credit cards in crowded places such as trains or buses.²⁵

3.1.3 Biometrics

In contrast to possession and knowledge, the biometric trait cannot easily be stolen. While it can be copied, e.g. the fingerprint from high-resolution photographs or face models to circumvent face recognition systems.²⁶ In the recent past, researchers could copy both German Chancellor's Angela Merkel's iris and the fingerprint of Ursula von der Leyen, the now the elected President of the European Commission, from high-resolution photographs.²⁷ It has to be taken into account though, that especially the so-called latent fingerprints are nearly left everywhere, i.e., the security of biometrics heavily relies on the chosen biometric trait.²⁸

Further implications are that the biometric characteristics can change over time or be temporarily unavailable because of injuries. While some can heal over time, others, especially scars, can permanently change the biometric trait and therefore render it unusable. Also, each time the user authenticates with biometrics, a new sample of the trait is gathered and compared to the stored one. Because the recent probe will never be 100% identical compared to the stored one («intra-user variants»), a threshold needs to be defined, which allows or denies the authentication attempt. Setting the threshold to a too low value increases the risk of the FAR, while a too high value decreases the usability and increases the FRR.²⁹

Traits such as facial recognition must also be usable with different amounts of facial hair, hairstyles, with and without glasses.³⁰

Another high risk is data privacy and security. Over 50% of the users fear about data usage, both legitimate and abusive, and collection of their biometrics, yet the majority of the user states that biometrics is the most secure authentication compared to, e.g., passwords and PINs.³¹ It is crucial that the stored biometric probe is not accessible by third parties nor shared with them. For example, a theft of smartphones should not mean theft of the biometrics, e.g., fingerprint, too.

²⁵KSM14.

²⁶FKH14; FSS18.

²⁷Kre14.

²⁸See Vac17, p. 299.

²⁹See JRN11, pp. 13–17, 52.

³⁰See JRN11, p. 98.

³¹See Kes18, p. 8.

However the major threat remains the difficulty to replace a compromised biometric template. While, e.g., a password or a security key can be changed or replaced, for instance a fingerprint can't be altered, changed or replaced since it remains the same for the whole lifespan of a person. To counter this threat it is advised to use, for instance, only a hash of the fingerprint and not store the *image* of the fingerprint itself.³²

Further, it is necessary to respect the quality and availability of the sensor. If a sensor is damaged, too cheap or the surface is, for example, dirty, then the authentication and especially the usability suffers.³³

3.1.4 Further methods

A high risk of location-based authentication is the spoofing of the actual location by an attacker. An attacker can choose different attack vectors, such as spoofing the source IP address that tries to access a system. Another form of spoofing is the GPS spoofing where an attacker modifies the actual GPS by broadcasting false information. Further, the Caller ID spoofing technique can be used with VoIP to disguise the location. Besides these techniques, the most common variant remains the usage of a VPN network or DNS proxy to hide the genuine location.³⁴

For time-based authentication, an attacker could use attacks against the Network Time Protocol (NTP) in order to either gain access of the verification system or to modify the synchronized time in order to allow the login attempt to succeed.³⁵

3.1.5 General threats

General threat: security of transmission!

Initialization/Registration/Enrollment

A more general threat is the registration or initialization of the authentication. The user has to make sure that no attacker can intercept or copy the required enrollment data. For instance, if a malware comprises a users computer and installs a keylogger, then an entered password is no longer a secret and is compromised.

³²See Sho14, p. 266.

³³See Tod07, p. 37.

³⁴See Har05, pp. 138–145; See Yua05, Chapter 4.5.3.

³⁵See Mal+15.

A computer virus could also intercept a USB connection from a security key, both when registering the device and while using it. Furthermore, the user needs to make sure that his enrollment process is not observed from, e.g., a surveillance camera, a hacked webcam, or a colleague from behind.³⁶

Transmission

³⁶See Mul+13, pp. 152–153; See ULC19, p. 61.

4 Multi-factor authentication

In this chapter a list of different MFA solutions is described in detail. [Sta15]

4.1 OTP

4.1.1 HMAC

Keyed-Hashing for Message Authentication (HMAC) Code is an extension of a Message Authentication Code (MAC) and standardized in Request For Comments (RFC) and National Institute of Standards and Technology (NIST) abc. [KBC97]

HTOP

HMAC-based One-time Password algorithm, counter based. RFC 899. Configurable length (6-10). Default SHA1. Truncation of HMAC [MRa+05]

TOTP

Time based instead of counter based. RFC 123 and Initiative For Open Authentication (OATH). [MRa+11]

pros

1. Collisions in MD5 or SHA1 are no problem, already stated/analyzed in the RFC

³⁷Source: diagram by author

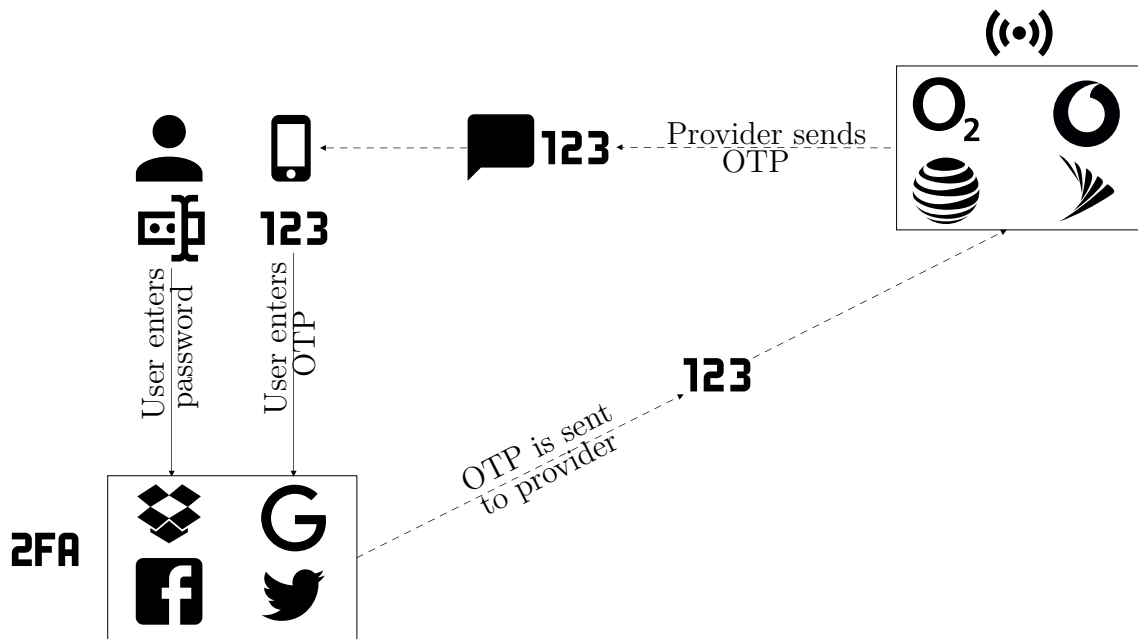


Figure 4.1: Exemplary MFA authentication flow³⁷

cons

"Just an algorithm"

1. synchronization
2. invalidation
3. nobody knows how the algorithm is implemented (RFC = no standard)
4. Differences (e.g. Steam - only 5 digits, limited Alphabet)
5. Brute Force if server does not limit
6. Not phishing resistant

4.2 Smart Cards

4.3 Hardware Tokens

5 Security of multi-factor authentication

5.1 Introduction

In this chapter the introduced MFA solutions are analyzed in regards of their security aspects, ranging from algorithms to transportation risks.

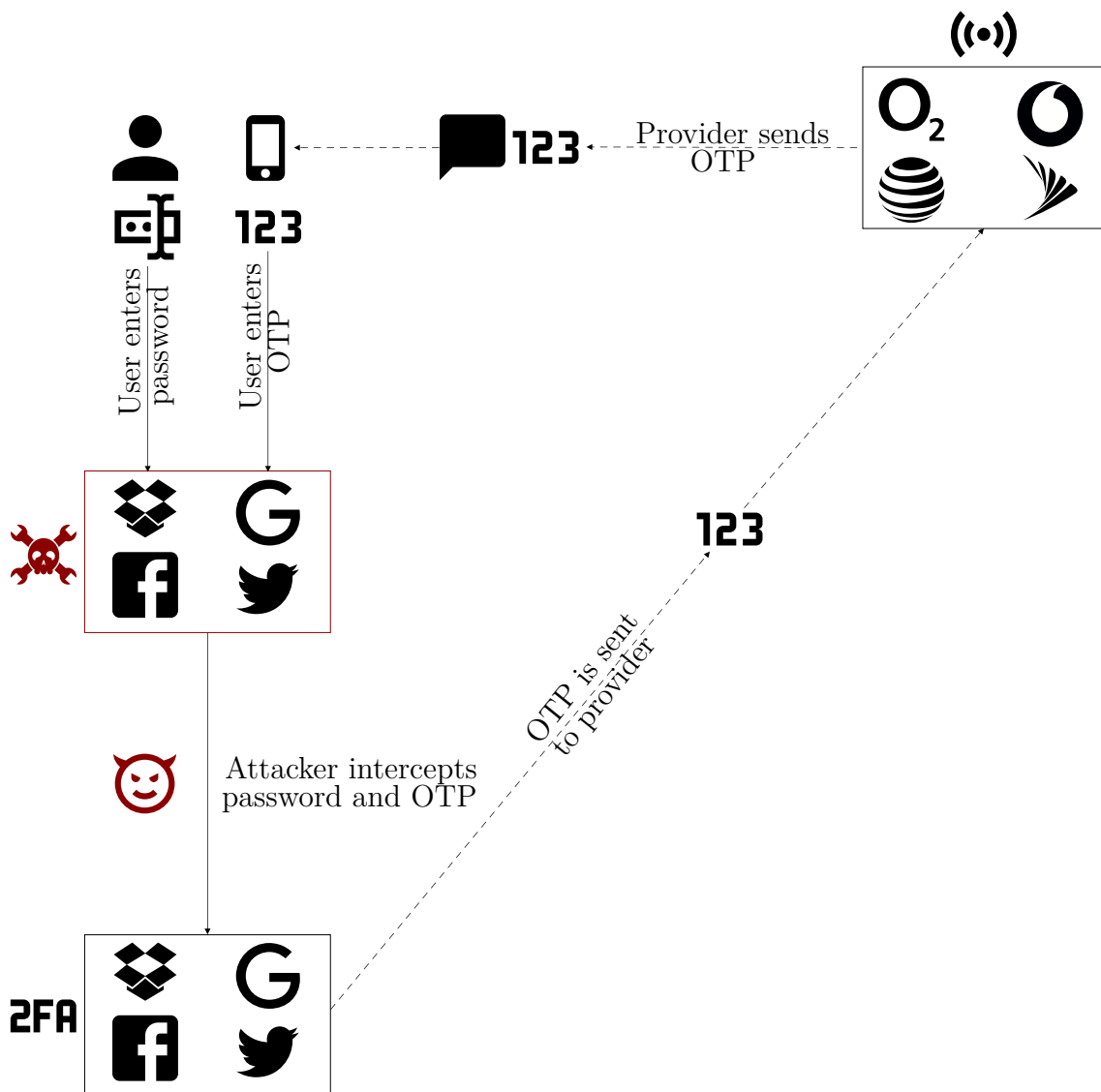


Figure 5.1: Exemplary 2FA phishing of an OTP³⁸

5.2 HOTP and TOTP

In this section the security of both HMAC-based One-time Password algorithm (HTOP) and Time-based One-Time Password algorithm (TOTP) is being analyzed.

5.2.1 Algorithm

As both the HTOP and the TOTP are based on the HMAC algorithm by building the OTP over the HMAC function of the secret key and the counter with a truncation, the underlying HMAC algorithm needs to be evaluated.

The important part here is the chosen cryptographic hash algorithm. Mostly Secure Hash Algorithm (SHA)-1 is used, since it's the default of the RFC. Given that both SHA-1 and MD5 are considered insecure one has to ask if they are still considered secure in the OTP context.

Because the collision resistance of the chosen cryptographic hash algorithm is not important for the security of the OTP generation those algorithms do not expose a threat.

The Federal Office for Information Security (BSI) lists these algorithms as secure for HMAC³⁹

Citations:⁴⁰

It is more important that the algorithm is implemented correctly, in the past e.g. Google did not issue OTP values with a leading zero. Besides that, the minimum length of the OTP values are six digits, meanwhile the RFC supports up to 10. For example Steam, decided to use a different alphabet and character length.

A theoretical vulnerability is to use the time sync offset feature because it enables an attacker to use a token that's much longer valid than it should be. (as discussed in section xx - time sync/drift)

5.2.2 Transportation

Given that the generation of the OTP is considered secure the more important region to analyze is the transportation of these OTP. In this section the transportation

³⁸Source: diagram by author

³⁹Sic19.

⁴⁰Ste+17.

mediums SMS, E-Mail and App are considered.

SMS

The biggest advantage of SMS as a transportation medium is every mobile, ranging from an old Nokia to a new iPhone XS, is capable of receiving SMS. All major mobile phone operation systems come with a SMS application pre-installed, so no external apps are required.

SMS are around 1999 and highly accepted and easy to use.

While there are some key advantages with SMS transportation it also comes with a lot of downsides. Besides the cost aspect of SMS traffic, both for the sender and potentially for the receiver due to roaming fees, too, the current state of SMS traffic is considered insecure.

The SMS traffic relies on the Signalling System No. 7 (SS7) network which was developed in the 1970s. It has multiple security flaws that allows an attacker to eavesdrop or modify the in- and out-coming traffic.⁴¹

In contrast to the web and email the user is not very aware of phishing attacks in the SMS context. Studies however show that a new technique called forward phishing is already in use. In this scenario the attacker sends the victim a (spoofed) SMS from the fakes service provider to reply with the OTP code for security measures.⁴²

Another negative aspect of SMS transportation is the routing. Many companies rely on third-party providers in order to send the SMS to the user. Often these providers like name some are using countries where SMS are very cheap, but on the other hand the SS7 security measures like SMS home routing and not enforced. This results in a higher security risk of the SMS being compromised while reaching the user. Also, the third party providers are given access to the OTP which enables the risk of a malicious insider because the security measures might be weaker than the original company.

Especially for Android there exists multiple SMS trojans which are capable of intercepting the SMS, too.

Given all these facts SMS transportation should be avoided at all costs⁴³, since there are multiple flaws in the SS7 network itself and the process how the SMS reaches

⁴¹Wel17; HO17; Puz17.

⁴²Jak18; Sia+17.

⁴³Jak18.

the user. It's also not resistant against phishing or mobile phone trojans.

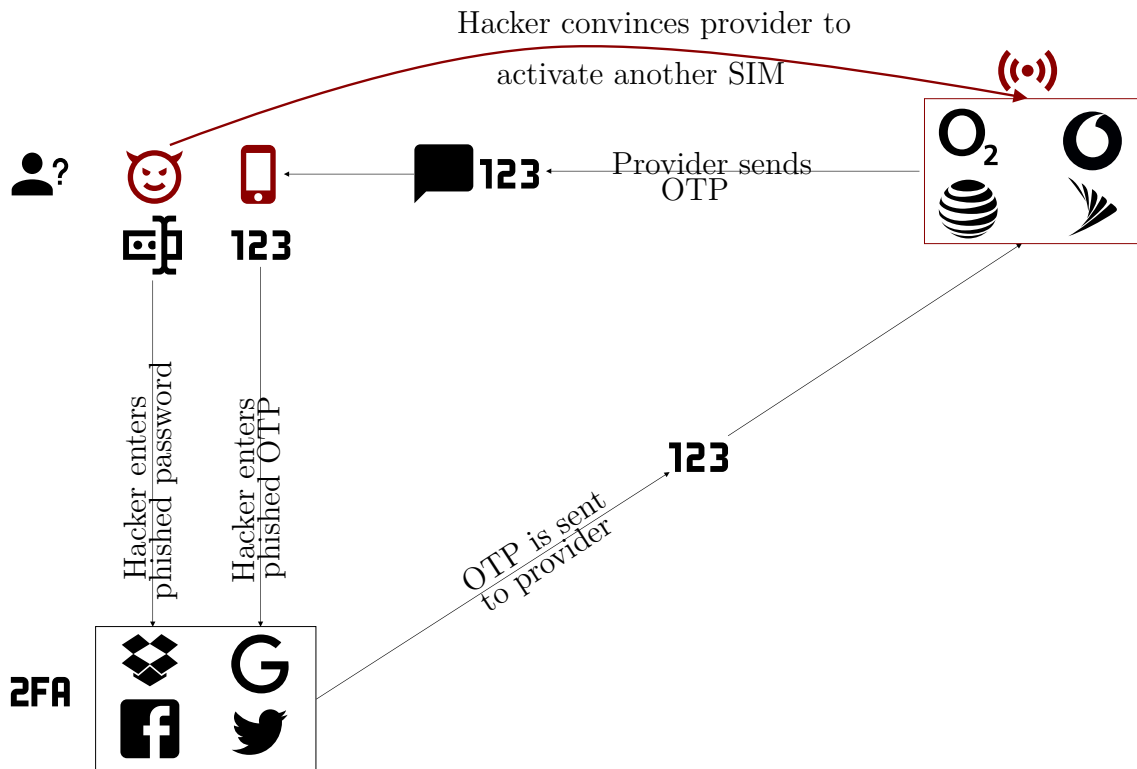


Figure 5.2: Social engineering used to phish an OTP in MFA⁴⁴

cons

1. Delivery time
2. SIM Swapping, cloning, hijacking, ...

App

pros

1. Works offline
2. cheaper

⁴⁴Source: diagram by author

⁴⁵Source: diagram by author

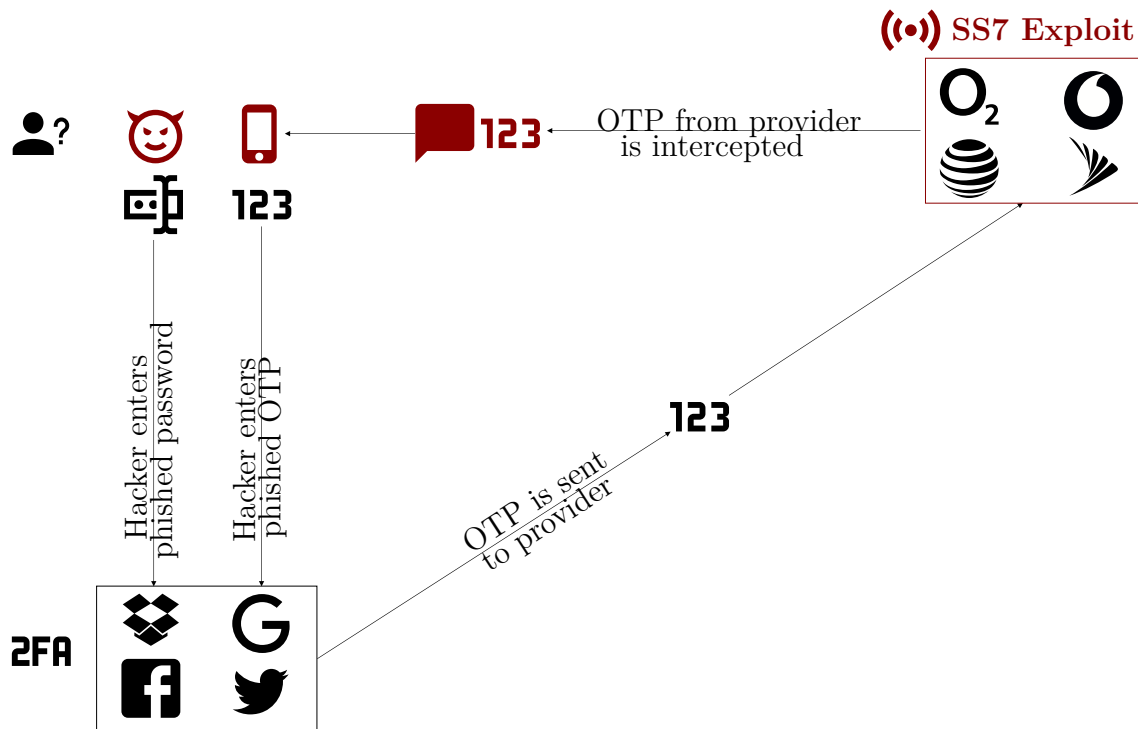


Figure 5.3: SS7 exploit to phish an OTP used in MFA⁴⁵

cons

1. Secret can be phished while setup (either on phone or computer)
2. Trusted apps? OSS?⁴⁶
3. Vulnerabilities → e.g. Authy⁴⁷

E-Mail

pros

cons

⁴⁶Ste19.

⁴⁷Hom15.

6 Introduction to the Web Authentication API

6.1 History and evolution

Fast IDentity Online (FIDO) World Wide Web Consortium (W3C) Universal Second Factor (U2F) Universal Authentication Framework (UAF) API

6.2 Technical implementation and details

6.2.1 Browser support

Table 1 shows the support status of the Web Authentication API for the most common web browsers, both desktop and mobile, and if they support the API. If so the table shows the version which initially added support for the Web Authentication API alongside with the release date. The following subsections will explain the web browser support more detailed.

The global browser support as of August 2019 is 68%.

	Web browser	Supported	Version	Release Date
Desktop	Chrome	✓	67	May 2018
	Firefox	✓	60	May 2018
	Opera	✓	54	June 2018
	Internet Explorer	✗	-	-
	Edge	✓	18	November 2018
	Safari	(✓)	(13)	-
Mobile	Opera Mobile	✗	-	-
	IE Mobile	✗	-	-
	iOS Safari	✗	-	-
	iOS Safari	✗	-	-
Android	LineageOS Stock Browser	✗	-	-
	Chrome for Android	✓	70	October 2018
	Firefox for Android	✓	68	July 2019
	Opera	✗	-	-
	Opera mini	✗	-	-
	Edge	✗	-	-
	Samsung Internet	✗	-	-
	UC Browser	✗	-	-
	Mint Browser	✗	-	-
	360 Secure Browser	✗	-	-
	QQ Browser	✗	-	-
	Yandex Browser	✗	-	-
	Brave Browser	✗	-	-

Table 1: Web browser support of the Web Authentication API⁴⁸

⁴⁸Sources: (BK18; JT18; Dav18; Ger18; Jon19). A detailed analysis of Android browsers is available on the CD in the appendix.

Desktop support

The Web Authentication API is supported from Chrome 67 onwards, which was released in May 2018. Firefox added support for the Web Authentication API in May 2018 with its version 60 as well.

Microsoft added support for the Web Authentication API in Edge 13 which was released in November 2015. However, the implementation is based on an earlier draft version of the Web Authentication API. Support for the FIDO 2.0 specification was added in Edge 14 (released in December 2016). The feature is hidden behind a configuration option though and was enabled for all users with the release of Edge 17 in November 2018.

Browsers like Opera, Vivaldi or Brave and upcoming Edge versions that are all based on Chromium, the browser and source code behind Google's Chrome browser, have support for the Web Authentication API, too.

As the development for the Internet Explorer halted, and it is only receiving security updates, no support is available for new web APIs including the Web Authentication API, even though it is still used by 5% of all desktop browser users and remains supported for the operating system Windows 7, 8.1 and 10.⁴⁹ This is an important fact to take into account when evaluating the usability of the Web Authentication API since especially enterprise users often cannot upgrade or switch their browser.

Safari added support for the Web Authentication API feature in December 2018 but only for the preview variant of the browser, called the Safari Technology Preview. It is expected to be available for all users with the release of Safari 13 in mid to end September. The support is limited to USB HID enabled authenticators though and only available for macOS Mojave and Catalina and yet unknown if older macOS version will receive an update to Safari 13.

Besides that, Windows 10 also added support for MFA by incorporating the technology described in the FIDO standard. This allows biometric authentication with, e.g., fingerprints when a reader is available or to use the facial recognition technology or iris scans. This feature is called »Windows Hello«. The credentials are only stored locally and are protected by asymmetric encryption. Besides biometric authentication Windows Hello also supports PINs. The Trusted Platform Module (TPM) stores this PIN.⁵⁰

⁴⁹See Sup19c.

⁵⁰Bio16.

Mobile support

The support for the Web Authentication API in mobile web browsers is inferior to desktop support. While Chrome for Android supports the Web Authentication API since October 2018 and Firefox since July 2019, iOS completely lacks support for the Web Authentication API. Even though in the iOS 13 beta versions the feature can be enabled in the »Experimental Features« section the API remains unsupported or at least there is no way to add an authenticator in the browser yet.

The only ray of hope is that the Brave browser for iOS incorporated support for the yet to be released security key »YubiKey 5Ci« which enables U2F and the Web Authentication API for iOS by using an Apple certified Lightning accessory. Unfortunately, due to lack of availability, this functionality could not be tested.⁵¹



Figure 6.1: Failed try to use the Web Authentication API with the Brave Browser on an iPhone 6⁵²

However, Figure 6.1 shows the try to use an existing U2F YubiKey with a lightning dongle in the Brave browser on a website that offers support for the Web Authentication API. While the U2F YubiKey has power, Brave does not recognize it; neither is it usable. Safari did not show an overlay either.

⁵¹See Bra19a; See Bra19b.

⁵²Source: author's own photograph

It has to be noted though, that other Android browser vendors need to implement the functionality themselves. Other geographic regions use a variety of different browsers, e.g., the UC Browser, 360 Security Browser, Mint Browser from Xiaomi or the QQ Browser from Tencent. Neither they nor browsers such as Samsung Internet, Opera (mini) for Android, Edge or the Android Stock browser are currently supporting the Web Authentication API.

Other mobile operating systems like Windows Phone 8, BlackBerry 10 or KaiOS do not support the Web Authentication API.

6.2.2 Usability

6.3 Security aspects

Problems:⁵³

6.3.1 Problems

The problems that are transferred to the Web Authentication API are the ones of authentication by possession already described in subsection 3.1.2. If the Web Authentication API is used with a security key then the same risk of damage, loss or theft exist. Besides that, if the security key itself is not protected (by e.g. fingerprints) an attacker can easily gain access to an account if he steals or copies the authenticator.

⁵³Sta18.

7 Comparison

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like “Huardest gefburn”? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special contents, but the length of words should match the language.

8 Conclusion and Outlook

OAuth 2.0, KERERBOS, radius based, LDAP, AD, OpenID Connect, SAML

Bibliography

- [And08] Ross J. Anderson. *Security Engineering: A Guide to Building Dependable Distributed Systems*. 2nd ed. Indianapolis, IN, USA: Wiley, 2008. ISBN: 978-0-470-06852-6.
- [BB17] Lee Brotherston and Amanda Berlin. *Defensive Security Handbook: Best Practices for Securing Infrastructure*. Sebastopol, CA, USA: O'Reilly Media, 2017. ISBN: 978-1-491-96038-7.
- [Bio16] “Microsoft Windows Hello biometric login now works with websites.” In: *Biometric Technology Today* 2016.4 (Apr. 2016), p. 12. ISSN: 0969-4765. DOI: [10.1016/S0969-4765\(16\)30071-6](https://doi.org/10.1016/S0969-4765(16)30071-6).
- [Bis18] Matthew Bishop. *Computer Security: Art and Science*. 2nd ed. Boston, MA, USA: Addison-Wesley Professional, 2018. ISBN: 978-0-13-409714-5.
- [Bra+06] John Brainard et al. “Fourth-factor Authentication: Somebody You Know.” In: *Proceedings of the 13th ACM Conference on Computer and Communications Security*. CCS '06. Alexandria, Virginia, USA: ACM, 2006, pp. 168–178. ISBN: 978-1-59593-518-2. DOI: [10.1145/1180405.1180427](https://doi.org/10.1145/1180405.1180427).
- [DLE19] Thomas Dressel, Eik List, and Florian Echtler. “SecuriCast: Zero-touch Two-factor Authentication Using WebBluetooth.” In: *Proceedings of the ACM SIGCHI Symposium on Engineering Interactive Computing Systems*. EICS '19. Valencia, Spain: ACM, June 2019, 6:1–6:6. ISBN: 978-1-4503-6745-5. DOI: [10.1145/3319499.3328225](https://doi.org/10.1145/3319499.3328225).
- [DRN17] Dipankar Dasgupta, Arunava Roy, and Abhijit Nag. *Advances in User Authentication*. Cham, Switzerland: Springer International Publishing, 2017. ISBN: 978-3-319-58808-7. DOI: [10.1007/978-3-319-58808-7_5](https://doi.org/10.1007/978-3-319-58808-7_5).
- [DZZ14] Benjamin Draffin, Jiang Zhu, and Joy Zhang. “KeySens: Passive User Authentication through Micro-behavior Modeling of Soft Keyboard Interaction.” In: *Mobile Computing, Applications, and Services*. Ed. by Gérard Memmi and Ulf Blanke. Cham, Switzerland: Springer International Publishing, 2014, pp. 184–201. ISBN: 978-3-319-05452-0.
- [Eck14] Claudia Eckert. *IT-Sicherheit: Konzepte - Verfahren - Protokolle*. 9th ed. Munich, Germany: De Gruyter, 2014. ISBN: 978-3-486-77848-9.
- [FKH14] Tobias Fiebig, Jan Krissler, and Ronny Hänsch. “Security Impact of High Resolution Smartphone Cameras.” In: *8th USENIX Workshop on Offensive Technologies (WOOT 14)*. San Diego, CA, USA: USENIX Association, Aug. 2014.

- [Fri+17] Lex Fridman et al. “Active Authentication on Mobile Devices via Stylometry, Application Usage, Web Browsing, and GPS Location.” In: *IEEE Systems Journal* 11.2 (June 2017), pp. 513–521. ISSN: 1932-8184. DOI: [10.1109/JSYST.2015.2472579](https://doi.org/10.1109/JSYST.2015.2472579).
- [FSS18] Julian Fietkau, Starbug, and Jean-Pierre Seifert. “Swipe Your Fingerprints! How Biometric Authentication Simplifies Payment, Access and Identity Fraud.” In: *12th USENIX Workshop on Offensive Technologies (WOOT 18)*. Baltimore, MD, USA: USENIX Association, Aug. 2018.
- [Gri17] Roger A. Grimes. *Hacking the Hacker: Learn From the Experts Who Take Down Hackers*. Indianapolis, IN, USA: Wiley, 2017. ISBN: 978-1-119-39621-5.
- [Har05] Jan L. Harrington. *Network Security: A Practical Approach (The Morgan Kaufmann Series in Networking)*. San Francisco, CA, USA: Morgan Kaufmann, 2005. ISBN: 978-0-12-311633-8.
- [HO17] Silke Holtmanns and Ian Oliver. “SMS and One-Time-Password Interception in LTE Networks.” In: *2017 IEEE International Conference on Communications (ICC)*. May 2017, pp. 1–6. DOI: [10.1109/ICC.2017.7997246](https://doi.org/10.1109/ICC.2017.7997246).
- [Jak18] Markus Jakobsson. “Two-factor inauthentication – the rise in SMS phishing attacks.” In: *Computer Fraud & Security* 2018.6 (June 2018), pp. 6–8. ISSN: 1361-3723. DOI: [10.1016/S1361-3723\(18\)30052-6](https://doi.org/10.1016/S1361-3723(18)30052-6).
- [JRN11] Anil K. Jain, Arun A. Ross, and Karthik Nandakumar. *Introduction to Biometrics*. New York, NY, USA: Springer, 2011. ISBN: 978-0-387-77325-4. DOI: [10.1007/978-0-387-77326-1](https://doi.org/10.1007/978-0-387-77326-1).
- [KBC97] Hugo Krawczyk, Mihir Bellare, and Ran Canetti. *HMAC: Keyed-hashing for message authentication*. RFC 2104. RFC Editor, Feb. 1997. DOI: [10.17487/RFC2104](https://doi.org/10.17487/RFC2104).
- [Kei17] Konstantinos Markantonakis Keith Mayes. *Smart Cards, Tokens, Security and Applications*. 2nd ed. Cham, Switzerland: Springer International Publishing, 2017. ISBN: 978-3-319-50498-8.
- [KSM14] Gurudatt Kulkarni, Ramesh Sutar, and Sangita Mohite. ““RFID security issues challenges”.” In: *2014 International Conference on Electronics and Communication Systems (ICECS)*. Feb. 2014, pp. 1–4. DOI: [10.1109/ECS.2014.6892730](https://doi.org/10.1109/ECS.2014.6892730).
- [Mal+15] Aanchal Malhotra et al. *Attacking the Network Time Protocol*. Oct. 2015.
- [MRa+05] David M’Raihi et al. *HOTP: An HMAC-based one-time password algorithm*. RFC 4226. RFC Editor, Dec. 2005. DOI: [10.17487/RFC4226](https://doi.org/10.17487/RFC4226).
- [MRa+11] David M’Raihi et al. *TOTP: Time-Based One-Time Password Algorithm*. RFC 6238. RFC Editor, June 2011. DOI: [10.17487/RFC6238](https://doi.org/10.17487/RFC6238).

- [Mul+13] Collin Mulliner et al. “SMS-Based One-Time Passwords: Attacks and Defense.” In: *Detection of Intrusions and Malware, and Vulnerability Assessment*. Ed. by Konrad Rieck, Patrick Stewin, and Jean-Pierre Seifert. Berlin, Germany and Heidelberg, Germany: Springer Berlin Heidelberg, 2013, pp. 150–159. ISBN: 978-3-642-39235-1.
- [Oud16] Abdelkader Ouda. “A framework for next generation user authentication.” In: *2016 3rd MEC International Conference on Big Data and Smart City (ICBDSC)*. Mar. 2016, pp. 1–4. DOI: [10.1109/ICBDSC.2016.7460349](https://doi.org/10.1109/ICBDSC.2016.7460349).
- [Puz17] Sergey Puzankov. “Stealthy SS7 Attacks.” In: *Journal of ICT Standardization* 5.1 (Jan. 2017), pp. 39–52.
- [Shi+11] Elaine Shi et al. “Implicit Authentication through Learning User Behavior.” In: *Information Security*. Ed. by Mike Burmester et al. Berlin, Germany and Heidelberg, Germany: Springer Berlin Heidelberg, 2011, pp. 99–113. ISBN: 978-3-642-18178-8.
- [Sho14] Adam Shostack. *Threat Modeling: Designing for Security*. Indianapolis, IN, USA: Wiley, 2014. ISBN: 978-1-118-81005-7.
- [Sia+17] Hossein Siadati et al. “Mind your SMSes: Mitigating social engineering in second factor authentication.” In: *Computers & Security* 65 (2017), pp. 14–28. ISSN: 0167-4048. DOI: [10.1016/j.cose.2016.09.009](https://doi.org/10.1016/j.cose.2016.09.009).
- [Sic19] Bundesamt für Sicherheit in der Informationstechnik. “Kryptographische Verfahren: Empfehlungen und Schlüssellängen.” In: *Technische Richtlinie TR-02102-1, Bundesamt für Sicherheit in der Informationstechnik* 1 (2019).
- [Sta15] Mark Stanislav. *Two-Factor Authentication*. Ely, United Kingdom: IT Governance Publishing, Apr. 2015. ISBN: 978-1-84928-733-3.
- [Ste+17] Marc Stevens et al. “The First Collision for Full SHA-1.” In: *Advances in Cryptology – CRYPTO 2017*. Ed. by Jonathan Katz and Hovav Shacham. Cham, Switzerland: Springer International Publishing, Aug. 2017, pp. 570–596. ISBN: 978-3-319-63688-7. DOI: [10.1007/978-3-319-63688-7_19](https://doi.org/10.1007/978-3-319-63688-7_19).
- [Tod07] Dobromir Todorov. *Mechanics of User Identification and Authentication: Fundamentals of Identity Management*. Boca Raton, FL, USA: Auerbach Publications, 2007. ISBN: 978-1-4200-5219-0.
- [TW75] Rein Turn and W. H. Ware. “Privacy and Security in Computer Systems: The vulnerability of computerized information has prompted measures to protect both the rights of individual subjects and the confidentiality of research data bases.” In: *American Scientist* 63.2 (1975), pp. 196–203. ISSN: 0003-0996.

- [ULC19] Enis Ulqinaku, Daniele Lain, and Srdjan Capkun. “2FA-PP: 2Nd Factor Phishing Prevention.” In: *Proceedings of the 12th Conference on Security and Privacy in Wireless and Mobile Networks*. WiSec '19. Miami, Florida: ACM, 2019, pp. 60–70. ISBN: 978-1-4503-6726-4. DOI: [10.1145/3317549.3323404](https://doi.org/10.1145/3317549.3323404).
- [Vac17] John R Vacca. *Computer and Information Security Handbook*. 3rd ed. Cambridge, MA, USA: Morgan Kaufmann, 2017. ISBN: 978-0-12-803843-7.
- [Wel17] Bill Welch. “Exploiting the weaknesses of SS7.” In: *Network Security 2017.1* (2017), pp. 17–19. ISSN: 1353-4858. DOI: [10.1016/S1353-4858\(17\)30008-9](https://doi.org/10.1016/S1353-4858(17)30008-9).
- [XZL14] Hui Xu, Yangfan Zhou, and Michael R. Lyu. “Towards Continuous and Passive Authentication via Touch Biometrics: An Experimental Study on Smartphones.” In: *10th Symposium On Usable Privacy and Security (SOUPS 2014)*. Menlo Park, CA, USA: USENIX Association, July 2014, pp. 187–198. ISBN: 978-1-931971-13-3.
- [Yua05] Michael Juntao Yuan. *Nokia Smartphone Hacks*. Sebastopol, CA, USA: O'Reilly Media, 2005. ISBN: 978-0-596-00961-8.
- [ZKM12] Feng Zhang, Aron Kondoro, and Sead Muftic. “Location-Based Authentication and Authorization Using Smart Phones.” In: *2012 IEEE 11th International Conference on Trust, Security and Privacy in Computing and Communications*. June 2012, pp. 1285–1292. DOI: [10.1109/TrustCom.2012.198](https://doi.org/10.1109/TrustCom.2012.198).

Internet sources

- [BK18] Christiaan Brand and Eiji Kitamura. *Enabling Strong Authentication with WebAuthn*. May 29, 2018. URL: <https://developers.google.com/web/updates/2018/05/webauthn> (last accessed on 08/15/2019).
- [Bra19a] Brave. *Adding YubiKey Support to Brave for iOS*. June 24, 2019. URL: <https://brave.com/ios-yubikey-support/> (last accessed on 08/17/2019).
- [Bra19b] Brave. *With Yubico partnership and support for the new YubiKey 5Ci, Brave is the first web browser to offer secure phishing-resistant authentication via robust security keys on iPhones & iPads*. Aug. 20, 2019. URL: <https://brave.com/partnership-with-yubico/> (last accessed on 08/20/2019).
- [Bun18] Bundeskriminalamt. *Cybercrime, Bundeslagebild 2017*. Sept. 27, 2018. URL: <https://www.bka.de/SharedDocs/Downloads/DE/Publikationen/JahresberichteUndLagebilder/Cybercrime/cybercrimeBundeslagebild2017.html> (last accessed on 08/20/2019).
- [Col16] Katie Collins. *Facebook buys black market passwords to keep your account safe*. Nov. 9, 2016. URL: <https://www.cnet.com/news/facebook-chief-security-officer-alex-stamos-web-summit-lisbon-hackers/> (last accessed on 08/18/2019).
- [Dav18] Jon Davis. *Release Notes for Safari Technology Preview 71*. Dec. 5, 2018. URL: <https://webkit.org/blog/8517/release-notes-for-safari-technology-preview-71/> (last accessed on 08/15/2019).
- [dim19] infratest dimap. *ARD – DeutschlandTREND Januar 2019*. Jan. 2019. URL: https://www.infratest-dimap.de/fileadmin/user_upload/dt1901_bericht.pdf (last accessed on 08/20/2019).
- [Fri19] Christian Friemel. *Trotz „Collection #1-5“: Beim Passwortschutz lernen deutsche Internet-Nutzer nur langsam dazu*. Mar. 27, 2019. URL: <https://newsroom.web.de/2019/03/27/trotz-collection-1-5-beim-passwortschutz-lernen-deutsche-internet-nutzer-nur-langsam-dazu/> (last accessed on 08/20/2019).
- [Ger18] Chromium Gerrit. *Enable WebAuthN on Android by default (If95f7508) & Gerrit Code Review*. Aug. 16, 2018. URL: <https://chromium-review.googlesource.com/c/chromium/src/+1176736/> (last accessed on 08/15/2019).
- [Goo] Google. *Google 2-Step Verification*. URL: <https://www.google.com/landing/2step/> (last accessed on 08/01/2019).

- [Hom15] Egor Homakov. *How "../sms" could bypass Authy 2 Factor Authentication*. Mar. 15, 2015. URL: https://sakurity.com/blog/2015/03/15/authy_bypass.html (last accessed on 08/09/2019).
- [Jon19] J.C. Jones. *Web Authentication in Firefox for Android*. Aug. 5, 2019. URL: <https://blog.mozilla.org/security/2019/08/05/web-authentication-in-firefox-for-android/> (last accessed on 08/15/2019).
- [JT18] J.C. Jones and Tim Taubert. *Using Hardware Token-based 2FA with the WebAuthn API*. Jan. 16, 2018. URL: <https://hacks.mozilla.org/2018/01/using-hardware-token-based-2fa-with-the-webauthn-api/> (last accessed on 08/15/2019).
- [Kes18] Limor Kessem. *IBM Security: Future of Identity Study*. Jan. 2018. URL: <https://www.ibm.com/downloads/cas/QRBY08N0> (last accessed on 08/20/2019).
- [Kre14] Stefan Krempel. *31C3: CCC-Tüftler hackt Merckels Iris und von der Leyens Fingerabdruck*. Dec. 28, 2014. URL: <https://heise.de/-2506929> (last accessed on 08/09/2019).
- [Mic19] Microsoft. *How to use two-step verification with your Microsoft account*. July 25, 2019. URL: <https://support.microsoft.com/en-us/help/12408/microsoft-account-how-to-use-two-step-verification> (last accessed on 08/01/2019).
- [Pla] PlayStation. *2-Step Verification*. URL: <https://www.playstation.com/en-us/account-security/2-step-verification/> (last accessed on 08/01/2019).
- [Sta18] P.I.E. Staff. *Security Concerns Surrounding WebAuthn: Don't Implement ECDA (Yet)*. Aug. 23, 2018. URL: <https://paragonie.com/b/ya9unbDYhvmp2EUy> (last accessed on 08/09/2019).
- [Ste19] Lukas Stefanko. *Malware sidesteps Google permissions policy with new 2FA bypass technique*. June 17, 2019. URL: <https://www.welivesecurity.com/2019/06/17/malware-google-permissions-2fa-bypass/> (last accessed on 08/09/2019).
- [Sup19a] Apple Support. *Two-factor authentication for Apple ID*. July 30, 2019. URL: <https://support.apple.com/en-us/HT204915> (last accessed on 08/01/2019).
- [Sup19b] Apple Support. *Two-step verification for Apple ID*. May 29, 2019. URL: <https://support.apple.com/en-us/HT204152> (last accessed on 08/01/2019).
- [Sup19c] Microsoft Support. *Lifecycle FAQ—Internet Explorer and Edge*. June 12, 2019. URL: <https://support.microsoft.com/en-us/help/17454/lifecycle-faq-internet-explorer> (last accessed on 08/15/2019).

List of Figures

2.1	Exemplary, but simplified, authentication by knowledge flow	6
2.2	Exemplary, but simplified, authentication by possession flow	7
2.3	Exemplary, but simplified, authentication by biometrics flow	8
4.1	Exemplary MFA authentication flow	17
5.1	Exemplary MFA phishing of an OTP	18
5.2	Social engineering used to phish an OTP in MFA	21
5.3	SS7 exploit to phish an OTP used in MFA	22
6.1	Failed try to use the Web Authentication API with the Brave Browser on an iPhone 6	26

Listings

List of Tables

1	Web browser support of the Web Authentication API	24
---	---	----

Glossary

S

SS7 A telephony signaling protocol.

T

TPM A secure chip designed to provide security functions such a secure random number generator, sealing, protection of cryptographic keys or remote attestation to an operating system.

W

W3C The international standards organization for the World Wide Web.

Acronyms

Symbols

2FA Two-factor Authentication

A

API Application Programming Interface

B

BLE Bluetooth Low Energy

BSI Federal Office For Information Security

C

CSO Chief Security Officer

E

ECC Elliptic-curve Cryptography

F

FAR False Acceptance Rate

FIDO Fast IDentity Online

FRR False Rejection Rate

H

HMAC Keyed-Hashing For Message Authentication

HTOP HMAC-based One-time Password Algorithm

I

IT Information Technology

M

MAC Message Authentication Code

MFA Multi-factor Authentication

MITM Man-in-the-Middle

N

NFC Near-field Communication

NIST National Institute Of Standards And Technology

NTP Network Time Protocol

O

OATH Initiative For Open Authentication

OTP One-time Password

P

PIN Personal Identification Number

R

RFC Request For Comments

RFID Radio-frequency Identification

S

SHA Secure Hash Algorithm

SS7 Signalling System No. 7, *Glossary*: SS7

SSO Single Sign-on

T

TOTP Time-based One-Time Password Algorithm

TPM Trusted Platform Module, *Glossary*: TPM

U

U2F Universal Second Factor

UAF Universal Authentication Framework

W

W3C World Wide Web Consortium, *Glossary*: W3C

A Appendix

A.1 Test

B Annex

B.1 Table of Content of the CD-Rom

```
/Volumes/CWniwQ7mThQP_0/Masterthesis/LaTeX/cd_rom
├── Web Authentication API Support Test Android
│   ├── 360
│   │   ├── Screenshot_20190816-154301_360.png
│   │   ├── Screenshot_20190816-154306_360.png
│   │   └── Screenshot_20190816-154438_Settings.png
│   ├── Brave
│   │   ├── Screenshot_20190816-153730_Brave.png
│   │   ├── Screenshot_20190816-153901_Brave.png
│   │   ├── Screenshot_20190816-153910_Brave.png
│   │   └── Screenshot_20190816-153936_Brave.png
│   ├── Chrome
│   │   ├── Screenshot_20190816-121238_Google_Play_services.png
│   │   ├── Screenshot_20190816-121245_Google_Play_services.png
│   │   └── Screenshot_20190816-121304_Chrome.png
│   ├── Edge
│   │   ├── Screenshot_20190816-135319_Edge.png
│   │   ├── Screenshot_20190816-135334_Edge.png
│   │   └── Screenshot_20190816-135347_Edge.png
│   ├── Firefox
│   │   ├── Screenshot_20190816-121429_Firefox.png
│   │   └── Screenshot_20190816-122820_Firefox.png
│   ├── Mint
│   ├── Opera
│   │   ├── Screenshot_20190816-155037_Opera.png
│   │   ├── Screenshot_20190816-155044_Opera.png
│   │   └── Screenshot_20190816-155108_Opera.png
│   ├── Opera mini
│   │   ├── Screenshot_20190816-155738_Opera_Mini.png
│   │   ├── Screenshot_20190816-155750_Opera_Mini.png
│   │   └── Screenshot_20190816-155815_Opera_Mini.png
│   └── QQ
│       ├── Screenshot_20190816-121712_QQ.png
│       ├── Screenshot_20190816-121734_QQ.png
│       └── Screenshot_20190816-122522_Settings.png
```


└─ Samsung Internet

└─ Screenshot_20190816-123031_Samsung_Internet.png

└─ Screenshot_20190816-123054_Samsung_Internet.png

└─ Stock Browser (Jelly)

└─ Screenshot_20190816-152110_Settings.png

└─ Screenshot_20190816-152309_Browser.png

└─ Screenshot_20190816-152349_Browser.png

└─ Screenshot_20190816-152417_Browser.png

└─ UC

└─ Screenshot_20190816-154548_UC_Browser.png

└─ Screenshot_20190816-154620_UC_Browser.png

Declaration of academic integrity

Hereby, I declare that I have composed the presented paper independently on my own and without any other resources than the ones indicated. All thoughts taken directly or indirectly from external sources are adequately denoted as such.

Hamburg, August 25, 2019

Tim Brust

Theses

1. The status quo of password usage is bad, often chosen passwords are re-used and weak.
2. Humans are the weakest link.
3. 2FA is not phishing resistant, both the secret when setting it up and the second factor can be phished or stolen. Software solutions are more probable to be phished.
4. The biggest threat to 2FA is the transportation especially when using SMS or unencrypted e-mail traffic.
5. MFA can made be phishing resistant but it requires more effort to do so.
6. Web Authentication API is not yet usable enough nor widely adopted, this is especially true because iOS lacks support for it and the Internet Explorer is still widely used.
7. The user needs to be educated about passwords, the risk of password re-use, phishing and how to protect themselves against common (internet) threats.