

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: September 4, 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.

Acknowledgements

Foremost I would like to thank my supervisor Prof. Dr.-Ing. habil. Andreas Ahrens for the continued support throughout this thesis, the fast and valuable feedback and

Moreover I thank SinnerSchrader for backing me financially in such a way as that I was able to focus my work on this thesis without worries.

In addition I want thank my fellow students, Jasmina, Jens and Gregor for always answering my questions about the regularities en route to writing this thesis, as well as the our study group.

Finally, I would like to express my sincere gratitude to Caro for the countless hours of proofreading, providing value feedback and of course the continuous encouragement and understanding during this challenging time.

This accomplishment would not have been possible without you all.
Thank you.

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	Knowledge	12
3.1.2	Possession	15
3.1.3	Biometrics	16
3.1.4	Further methods	17
3.1.5	General threats	17
4	Multi-factor authentication	19
4.1	Motivation for the usage of multi-factor authentication	19
4.2	Transmission of information	20
4.3	One-time password	20
4.3.1	Message authentication code	20
4.3.2	HMAC	22
4.3.3	Counter-based	24
4.3.4	Time-based	25
4.3.5	Yubico OTP	27
4.4	Smartcards	28
4.5	Security Tokens	29
4.5.1	RSA SecurID	29

4.5.2	YubiKey	29
4.5.3	Software tokens	30
5	Security of multi-factor authentication	31
5.1	Introduction	31
5.2	HOTP and TOTP	32
5.2.1	Algorithm	32
5.2.2	Transportation	33
6	Introduction to the Web Authentication API	39
6.1	History and evolution	39
6.1.1	FIDO Alliance	39
6.1.2	UAF	39
6.1.3	U2F	39
6.1.4	FIDO 2	39
6.2	Technical implementation and details	39
6.2.1	CTAP	39
6.2.2	Browser support	40
6.2.3	Usability	43
6.3	Security aspects	43
6.3.1	Problems	43
7	Comparison	44
8	Conclusion and Outlook	45
	Bibliography	VII
	Internet sources	XIV
	List of Figures	XVII
	Listings	XVIII
	List of Tables	XIX
	Glossary	XX
	Acronyms	XXI
A	Appendix	XXV
A.1	Test	XXV
B	Annex	XXVI
B.1	Table of Content of the CD-Rom	XXVI
	Declaration of academic integrity	XXVIII

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, as 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 with the risk of ruining a whole company if confidential data is leaked or obtained by a competitor.

To make things worse, very few people are using multi-factor authentication (MFA) and even fewer 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 constant threat. While MFA can protect against threats such as brute force attacks or stolen credentials, it is still affected and vulnerable to phishing attacks. Besides that, short message service (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

¹See Col16.

²See Kes18; See Fri19.

³See dim19; See Bun18, pp. 6–7.

supported in major browsers such as Chrome, Firefox, or Edge. The Web Authentication API allows a secure registration, login, and two-factor authentication (2FA) – all without the generation, storage, and remembering of passwords by utilizing asymmetric cryptography. The private keys are stored, e.g., on external devices such as USB sticks, but can be stored on built-in hardware, too. These are, for example, protected by a fingerprint sensor or dedicated chip designed for secure operations.

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., Diffie–Hellman 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 of 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 is described, followed by an analysis 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, it is explained against which attacks the Web Authentication API can offer protection. But it is 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 is 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 summing-up and 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 (subscriber identity module (SIM)). 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.

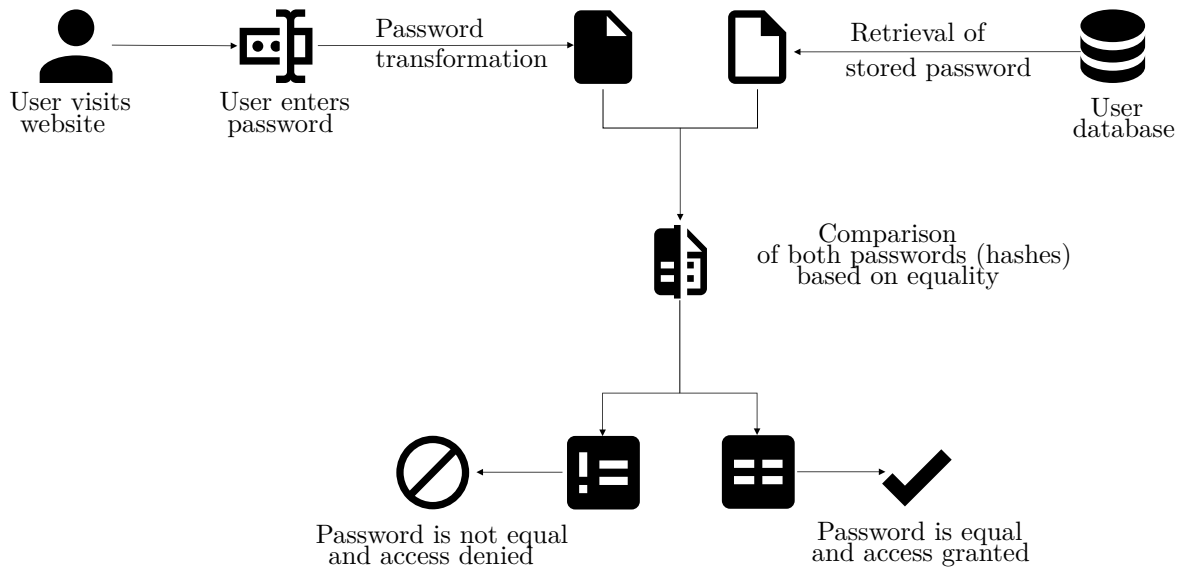


Figure 2.1: Exemplary, but simplified, authentication by knowledge flow⁷

Figure 2.1 shows a simplified authentication by knowledge flow. First, the user visits a website in this example 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, 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 such as 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 smartcard) or software (e.g., a smartphone application) token. They can either be disconnected, connected (e.g., via USB or as a smartcard) 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

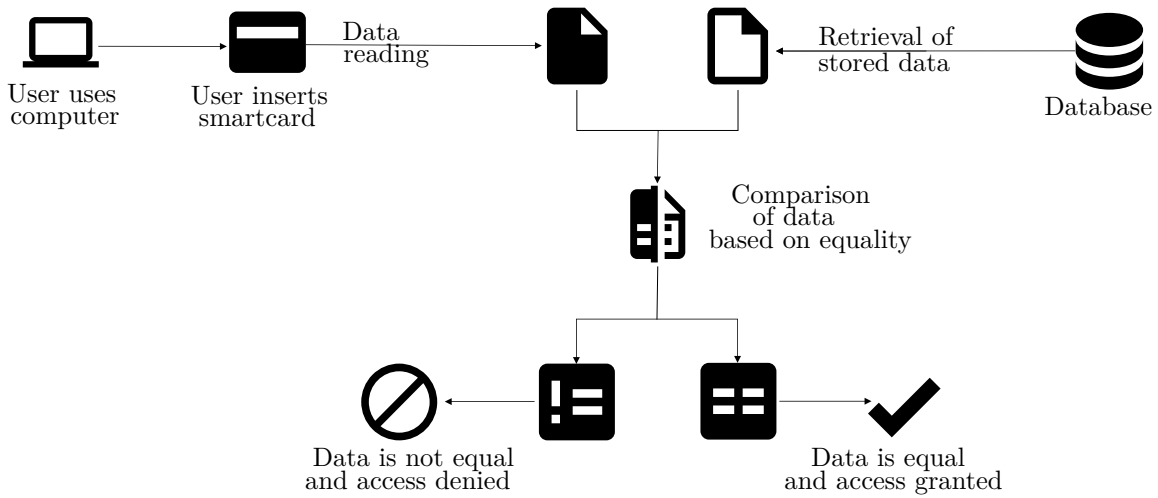


Figure 2.2: Exemplary, but simplified, authentication by possession flow⁹

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, e.g., the gait, the ear, DNA, or even the human odor can be a biometric factor.¹⁰

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

While it seems natural to authenticate a person with a biometric factor, it also comes with a couple of challenges. Both, the false rejection rate (FRR), i.e., the system rejects a user even though it is a legitimate user, and false acceptance rate (FAR), i.e., an imposter is granted access, needs to be accounted for the usage.

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

⁹Source: diagram by author

¹⁰See JRN11, pp. 30–34.

¹¹See DRN17, p. 186.

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 it is 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.

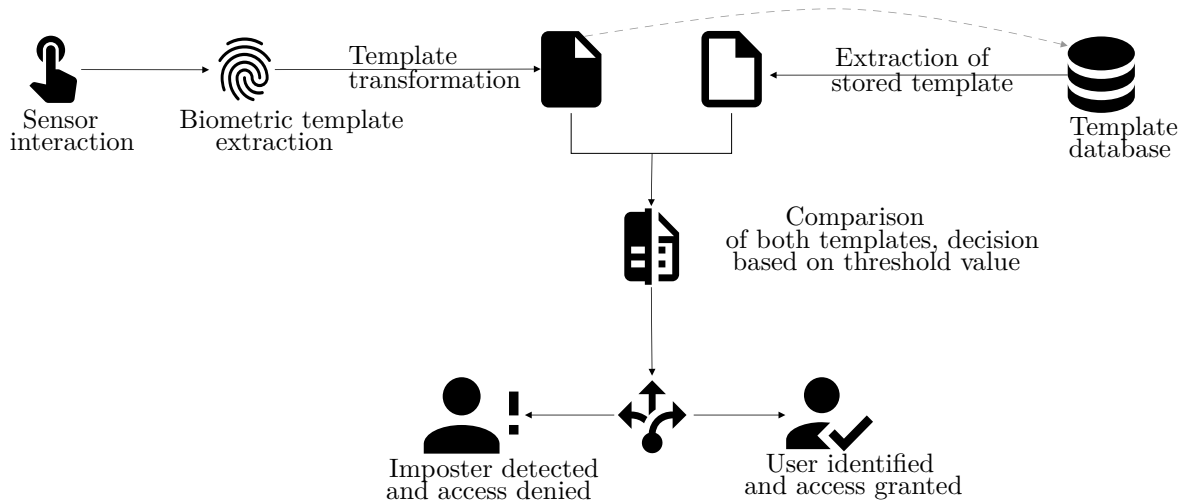


Figure 2.3: Exemplary, but simplified, authentication by biometrics flow¹³

Figure 2.3 shows an exemplary authentication flow using biometrics, in this 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 of difference is tolerable finally decides 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 Global Positioning System (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.

A combination of active and passive authentication is also possible. For example, the biometric passport («ePassport») contains both active authentication and passive authentication with the help of an integrated RFID chip.¹⁸

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.¹⁹ The biometric passport authenticates against a reading device with an asymmetric challenge-response protocol. This security measure helps to identify cloned passports.²⁰

2.2.2 Passive authentication

In contrast to the active authentication process, in the passive authentication process the user is authenticated without action on their part. Use cases of passive authentication are, for example, 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.²¹ The biometric passport provides a way to calculate the integrity and authenticity from a reading device to improve the protection against forgery.²²

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.²³

¹⁸See Eck14, p. 545.

¹⁹See DZZ14, pp. 185–186.

²⁰See Eck14, p. 545.

²¹See DZZ14, p. 186; See XZL14.

²²See Eck14, p. 545.

²³See DRN17, pp. 236–238; See Fri+17.

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.

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,²⁴ to two-step-verification, sometimes written as 2-Step Verification, too.²⁵

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.²⁶

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.

²⁴Sup19a.

²⁵Sup19b; Pla; Goo; Mic19.

²⁶See Gri17, p. 117.

3 Single-factor authentication

3.1 Threats

3.1.1 Knowledge

»Passwords are both the bane and the foundation of [...] security«,²⁷ yet the most used authentication method remains knowledge, in IT, especially passwords.²⁸ While it seems the simplest method to use, it also comes with many downsides, too. The service providers expect the user to remember the knowledge. Nevertheless, the human brain has difficulty remembering a unique and secure password, PIN, or secret questions for every different account the user has registered. The average amount of different internet accounts a user has is ten or more, not including, e.g., credit card PINs.²⁹

Because of this fact, the user often does a couple of insecure things:

- (a) using the same secret knowledge for multiple accounts or variations of the same knowledge³⁰
- (b) using something easy to guess or knowledge that is tied to a personal object, such as birthdays or names³¹
- (c) writing down the username and passwords, e.g., on a piece of paper that is accessible easily for others, storing PINs, e.g., in the briefcase or saving an unencrypted file on their computer or smartphone³²

This enables an attacker to steal the login credentials of a user easily. Written down post-it notes enable any physical attacker to steal the credentials. It might be captured by a camera, too. Leaving an unencrypted file on the computer enables computer viruses and trojans to send the file to an attacker. Mobile devices are

²⁷Har05, p. 206.

²⁸See Bid06, p. 424.

²⁹See Las18, pp. 7, 9.

³⁰See You18, p. 8; See Löw16, p. 14; See Las18, p. 7.

³¹See Fri19; See And08, p. 34.

³²See Fri19; See You19, p. 6.

affected, too, since, e.g., mobile trojans exist, too.

When using a weak password, an attacker might be to guess the chosen password. Writing down the banking PIN and storing it in the same briefcase as the credit card even annuls the 2FA example of possession and knowledge.

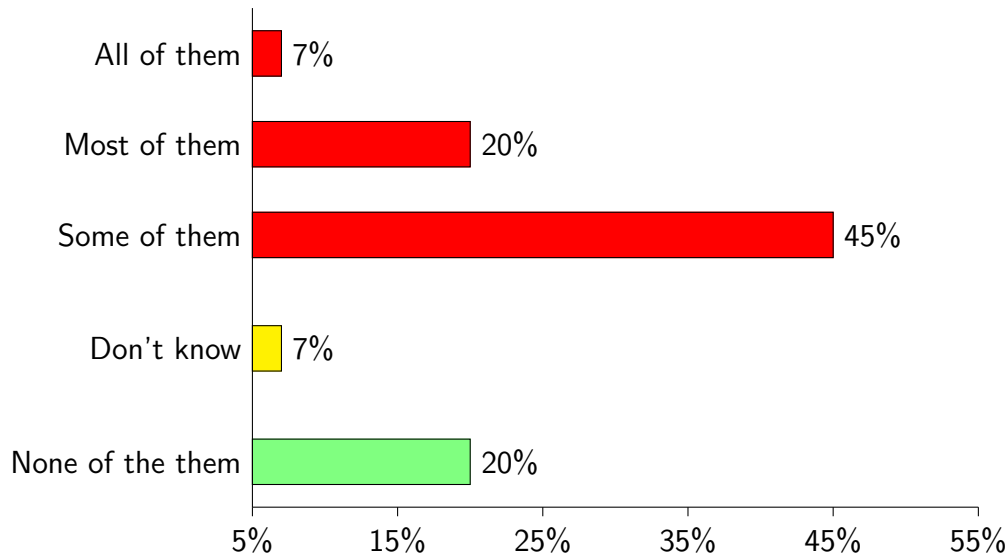


Figure 3.1: Percentage of online accounts sharing the same password in the United States in 2018³³

Figure 3.1 shows a representative study of password re-usage in the United States in 2018 conducted by YouGov. In the survey, over 70% of all participants answered that they at least re-use some of their passwords for different accounts. Only 20% of the participants use a unique password for every service. The survey is further classified into age and gender. While there is only a marginal difference between the genders, the survey is showing that the password re-usage rate in the age group 18 to 34 is 79% in total, which is weakening the potential argument that younger people tend to be more aware of the risks of stolen credentials and therefore use more complex and more different passwords. Other surveys strengthen the observation that millennials are re-using passwords more often.³⁴

Regarding the security of recovery and secret questions, it must be noted that these might even decrease security. Relatives and friends can answer common examples of questions such as »the first pet name, first car model, middle name of a parent, or the city where your parents met«, enabling a malicious insider attack. Some

³³Source: You18, p. 8.

³⁴See Kes18, p. 10; See You18, p. 8; See Las18, p. 11; See Tho+17, p. 1429.

questions might be answerable by employing a social engineering attack, too. Besides that, data can even be gathered by using, e.g., data mining of publicly available data sources and reports. Ironically, it is more secure to answer the security questions wrong than honest and correct or to provide custom ones, when allowed by the service. Additionally, it is not uncommon to be able to guess the partner's password.³⁵

Unfortunately, in the history it was thought that a forced change of password increases the security and a lot of enterprises, policies, and standards still contain sections regarding the enforced password rotation.³⁶ However, studies show that the security is not increased by forcing the user to change their password on a regular basis. Of course this does not mean that the user should not change their password in case of a potential data breach.³⁷

Further, especially true for passwords, it is not known to the user what the service provider does in order to protect the security of the passwords. As security breaches happen nearly daily, it is crucial to protect the password of the user. For instance, if the passwords are stored in a database, they can be:

- (a) unencrypted (worst case)
- (b) hashed, but not salted
- (c) hashed and salted (best case)
- (d) encrypted

It is pretty evident that unencrypted passwords in a database render the most significant threat, especially when re-used. Along with the e-mail or username an attacker can probably use the stolen credentials for other accounts, too, or in case of an e-mail provider breach, re-issue a new password with the »forgotten password« mechanism.³⁸

Even if the password is hashed, but not salted, it renders the credentials at risk. Weaker hashing algorithms such as MD5 or SHA1 might be broken in the future, but besides that, if it is a weak password, too, the hash might already be reversed. Having the hashed password list enables the attacker to execute a brute force attack in order to reverse as many hashes as possible. A rainbow table attack, a dictionary

³⁵See Las18, p. 11; See Bra+06, p. 169; See Bon+15; See Rab08, pp. 5–6; See SBE09, p. 386.

³⁶See Sic16, p. 1520.

³⁷See Gra+17, p. 14; See Sch16; See And08, p. 34.

³⁸See Sho14, p. 277.

attack, or just searching it in databases that contain a billion of reversed hash values is another attack vector.³⁹

The best protection is a unique salt for each password, which decreases the risk of a successful rainbow or brute force attack dramatically. In this scenario, each password is not only hashed but salted, too. A salt is a fixed-length cryptographically strong random value or a number used once (nonce) that is concatenated with the actual password in order to avoid having the same hashes even when two users have chosen the same password.⁴⁰

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 must 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. A different 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.⁴¹

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.⁴²

Compared with knowledge, a replacement is more costly, complicated, and time-consuming (e.g., when a passport is lost or stolen). If for example a whole algorithm is broken, such as the first generation of RSA SecurID or some YubiKey models happened to be vulnerable, it can cause severe problems depending on the number of keys that need to be replaced.⁴³

³⁹See Tho+17, p. 1425; See Bid06, pp. 427–430; See And08, pp. 56–57.

⁴⁰See LM16, pp. 32–34; See BB17, pp. 130–131.

⁴¹See Sho14, pp. 263–264.

⁴²See KSM14.

⁴³See DRN17, p. 18; See BLP05; See Wes19.

3.1.3 Biometrics

In contrast to possession and knowledge, the biometric trait cannot easily be stolen, but it can be copied, e.g., the fingerprint from high-resolution photographs or face models to circumvent face recognition systems.⁴⁴ 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 elected President of the European Commission, from high-resolution photographs.⁴⁵ It must 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.⁴⁶

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.⁴⁷

Traits such as facial recognition must also be usable with, e.g., different amounts of facial hair, hairstyles, or with and without glasses.⁴⁸

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.⁴⁹ It is crucial that the stored biometric probe is not accessible by third parties nor shared with them. For example, a theft of a smartphone should not mean theft of the biometrics, e.g., fingerprint or facial scan, too.

However, the primary threat remains the difficulty of replacing a compromised biometric template. A password or a security key can be changed or replaced, but for instance, a fingerprint cannot be altered, changed, or replaced since it remains the

⁴⁴FKH14; FSS18.

⁴⁵Kre14.

⁴⁶See Vac17, p. 299.

⁴⁷See JRN11, pp. 13–17, 52.

⁴⁸See JRN11, p. 98.

⁴⁹See Kes18, p. 8.

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.⁵⁰

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.⁵¹

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 GPS spoofing, where an attacker modifies the actual GPS by broadcasting false information. Further, the Caller ID spoofing technique can be used with Voice over Internet Protocol (VoIP) to disguise the location. Besides these techniques, the most common variant remains the usage of a virtual private network (VPN) or Domain Name System (DNS) proxy to hide the genuine location.⁵²

For time-based authentication, an attacker could use attacks against the Network Time Protocol (NTP) in order to either gain access to the verification system or to modify the synchronized time in order to allow the login attempt to succeed.⁵³

3.1.5 General threats

Besides the specific risk and threats that affect each of the authentication methods, there are some general threats and independent risks, such as the enrollment or the transmission of the authentication data. The following sections take these risks into account, too.

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 malware compromises a user's computer and installs a

⁵⁰See Sho14, p. 266.

⁵¹See Tod07, p. 37.

⁵²See Har05, pp. 138–145; See Yua05, Chapter 4.5.3; See Eck14, pp. 115–116, 133.

⁵³See Mal+15.

keylogger, then an entered password is no longer a secret and therefor compromised. 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. Mobile phones are subjects to trojans, too, enabling the risk that, for instance, the camera is intercepted and a scanned Quick Response (QR) code that contains enrollment data for a time-based one-time password (TOTP) is sent to an attacker. With the recent rise of the Internet of Things (IoT) devices, e.g., the mentioned security cameras might be compromised by an attacker.⁵⁴

Transmission

Further, the chosen transmission channel is an important fact to take into account. Entering a password on an unencrypted website (HTTP) enables network sniffing because the password is transmitted in cleartext and therefore accessible for everyone on the same network. For example, public Wi-Fi hotspots are a lucrative target, especially when the user is accepting custom SSL certificates which enable the attacker to perform an MITM attack and even steal the passwords that are sent via an encrypted channel. The risk also applies to other authentication methods, too. A manipulated USB or smartcard port could copy the data on a security key or smartcard, or a tampered sensor can capture the fingerprint of a user. SMS traffic is at high risk of being intercepted or eavesdropped (e.g., the transmission of PINs or transaction authentication numbers (TANs)) as well as unencrypted e-mail traffic containing, e.g., temporary passwords or TOTP.

⁵⁴See Mul+13, pp. 152–153; See ULC19, p. 61; See Dmi+14, pp. 371–375.

4 Multi-factor authentication

In this Chapter a variety of different MFA solutions is described in detail. MFA is a more general term for 2FA. It describes the process of using two (2FA) or more (MFA) distinct authentication methods for an authentication of a user. The MFA can combine, e.g., the password (knowledge) with another method, e.g. the possession of a security token or a biometric factor, such as fingerprints or facial recognition.

Since this thesis is focusing on the internet and web technologies, the first factor is always assumed as knowledge, i.e., in the majority of the use cases a password. Therefore further knowledge based authentication methods are not taken into account in this Chapter.

While not officially and often different defined, MFA is also referred as Strong Authentication by, e.g., the Federal Office for Information Security (BSI) or the European Union (EU) or the National Information Assurance Glossary.⁵⁵⁵⁶

4.1 Motivation for the usage of multi-factor authentication

The motivation for the usage of MFA is derived from the previous chapter. It has been shown that various security issues and risks exist, independent from the chosen authentication method. These make user accounts vulnerable.

In order to decrease or even eliminate these risks and threats the user needs to deploy additional security measures that explained in this chapter.

Further, new formalities such as the new version of the Payment Services Directive (PSD), EU Directive 2015/2366, coming into full effect in September 2019, even require the usage of MFA.⁵⁷

⁵⁵See Nat18, p. 47.

⁵⁶See Sic19, p. 11.

⁵⁷See Noc18, p. 10.

4.2 Transmission of information

A key aspect to take into account is the chosen transmission channel for the second or different (multi) factor. Out-of-band (OOB) transmission helps to reduce the risks of eavesdropping drastically. This technique describes the transmission of information on another channel or network than the current transmission of information is happening. While, e.g., the *normal* transmission of information on websites happens via the internet, an example for OOB transmission is a phone call or SMS to transmit the second factor.

4.3 One-time password

A widely used method of authentication in order to achieve MFA are OTPs which belong to the category of possession of a shared secret between the client and the server.

To fully understand how the OTP works, the basics and origins, especially the underlying message authentication code (MAC), have to be introduced first. In the following subsections are the required algorithms shortly described and in subsection 4.3.3 and subsection 4.3.4 the variants of OTPs, both the HMAC-based one-time password (HOTP) and the TOTP which are based on keyed-hash message authentication code (HMAC).

4.3.1 Message authentication code

The message authentication code (MAC) is a *code*, i.e., some sort of information to protect and ensure the integrity of a *message*. Integrity, besides confidentiality and availability, is one of the key concepts of IT security. The MAC is built using two parameters, a secret key that both parties know and the message itself. The algorithm generates a checksum that the sender can send alongside with the message. The recipient calculates the checksum (MAC) itself from the retrieved message. If it differs then the message has been manipulated or there might have been a faulty transmission. Technically the MAC can be generated with, e.g., cryptographic-hash functions, such as HMAC, or using block ciphers such as cipher block chaining message authentication code (CBC-MAC) or Data Encryption Standard (DES).⁵⁸

⁵⁸See Bid06, p. 565; See And08, pp. 163–168; See Eck14, pp. 391–393.

The MAC is standardized in different norms from various institutions, for example National Institute of Standards and Technology (NIST) Federal Information Processing Standard Publication (FIPS) 198-1, the BSI technical guideline TR-02102-1 («Cryptographic Mechanisms: Recommendations and Key Length») or the International Organization for Standardization (ISO) norm ISO/IEC 9797-1 and ISO/IEC 9797-2.⁵⁹

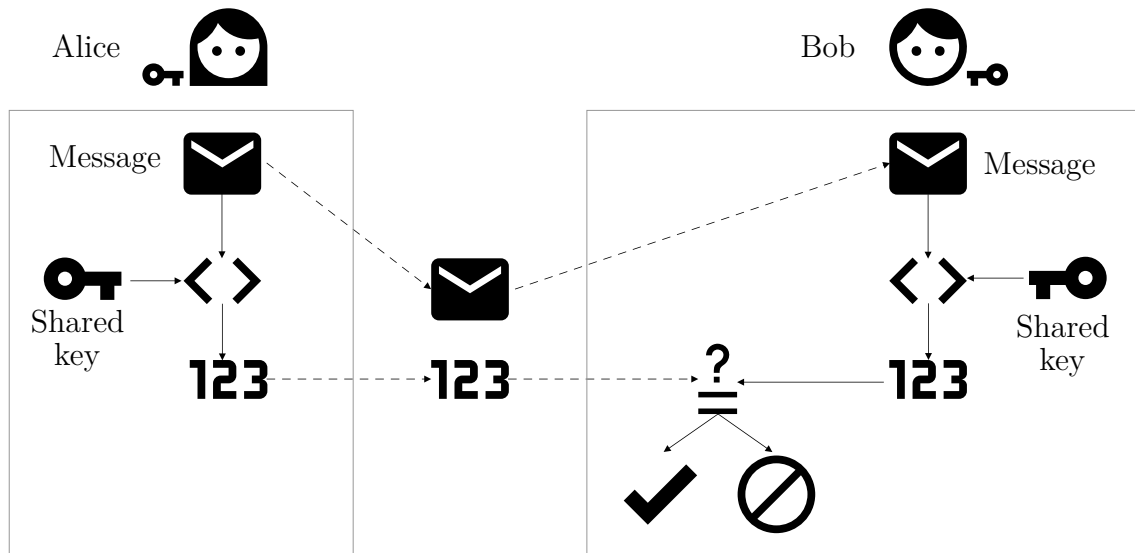


Figure 4.1: Message authentication code used to protect a sent message⁶⁰

Figure 4.1 shows the MAC in use between Alice and Bob. Both Alice and Bob exchange a secret key only they know via a secure channel. Alice now wants to send a message to Bob. In order to secure the message integrity, she uses an algorithm that takes both message and the secret key as inputs and computes the cryptographic hash of the message, the MAC. She transmits both the message and the MAC to Bob. If the message is not confidential, it's also possible to choose an insecure transmission channel. Bob is now able to calculate the MAC himself by using the same algorithm, key, and the received message from Alice.

If his computation of the MAC matches the one sent by Alice then the integrity and authenticity of the message is present, otherwise the message might have been tampered with.

Mathematically the MAC is defined as

$$mac = MAC(M, K)$$

⁵⁹See ST08; See Inf19; See ISO11a; See ISO11b.

⁶⁰Source: diagram by author

Where M is the input message, MAC the used MAC function, K the shared secret key and mac the resulting message authentication code.

Sometimes the MAC is also called Message Integrity Code (MIC) in order to avoid confusion with the media access control (MAC) address used in network protocols. Additionally, the MIC does not prove authenticity since an attacker can just modify the message and re-generate the MIC of the modified message.⁶¹

Further, while the MAC provides authenticity regarding the origin of the data and the data integrity, it does not provide any authenticity regarding the content of the data. For example, mobile code is not be detected by the MAC, as long as the MAC belongs to the sent message. This implication has to be taken into account when using the MAC to authenticate and evaluate the trustworthiness of received messages.

4.3.2 HMAC

The keyed-hash message authentication code (HMAC) is an extension of the MAC and standardized in Request For Comments (RFC) 2104 and NIST's standard FIPS 198-1 that allows the usage of any cryptographic hash function, such as Secure Hash Algorithm (SHA) family, Message Digests (MDs) algorithms, bcrypt, or whirlpool. Due to the black-box design of the HMAC, the easy replacement of the used cryptographic hash function is possible.⁶² Besides authentication the HMAC is, e.g., used in Transport Layer Security (TLS) and JSON Web Token (JWT) to ensure data authenticity and integrity.⁶³

Mathematically the HMAC is defined as follows:

$$HMAC(K, m) = H((K' \oplus opad), H((K' \oplus ipad), m))$$

Where K is the shared secret key, K' is the result by appending zeroes to the key K until it reaches a full block size (B) defined by the hash function. The inner padding $ipad$ is constructed by repeating the byte $0x36$ B -times, and $opad$ is the outer padding constructed by repeating the byte $0x5C$ B -times.

⁶¹See Tod07, pp. 60–62.

⁶²See KBC97; See ST08.

⁶³See DR08, p. 14; See JBS15, p. 8; See TC11, pp. 3–4.

Naively one could think that the HMAC is constructed by just hashing the secret key with the message. In order to increase the security and to protect against probable collusion of the hash functions the algorithm design is slightly different and shown in the next figure.

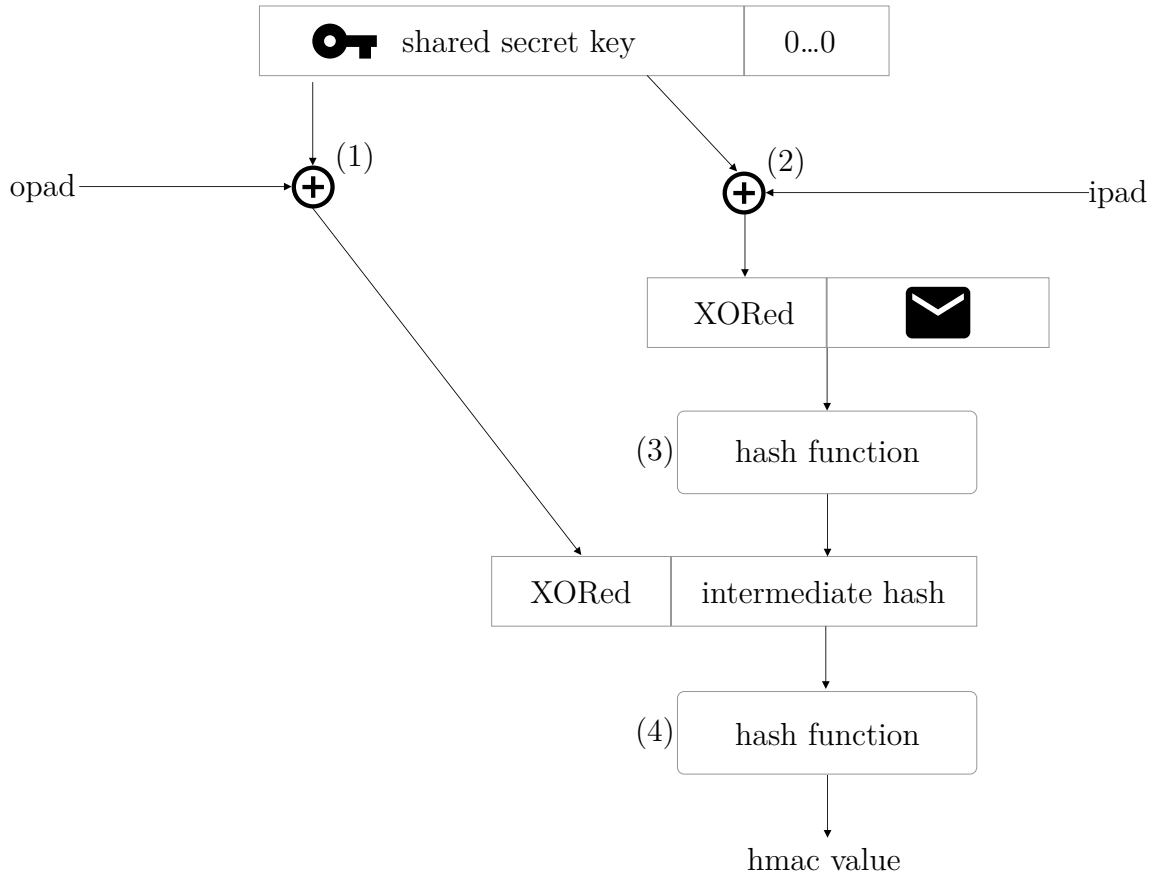


Figure 4.2: Visualization of the HMAC algorithm⁶⁴

The exclusive or (XOR) operation is performed on the key and *opad* (1) and *ipad* (2), respectively, instead. Besides that, the hash function is invoked twice, first on the result of the XOR operation on K' and the *ipad* (3) with the message and then again on the final result of the concatenation of (1), (2) and (3). Figure 4.2 shows the intermediate steps in order to generate the HMAC.

One of the key aspects of the HMAC is that the efficiency of original hash function is maintained and not altered by wrapping it in the HMAC algorithm. The security of the MAC relies on the used cryptographic hash function and on the strength, for example length and chosen alphabet, of the secret key. The best known attack

⁶⁴Source: diagram by author, based on Eck14, p. 395.

against HMAC remains the brute force and birthday attack and due to the stated algorithm the collisions of, e.g., MD5 or SHA-1 do not expose a threat towards using the HMAC with these cryptographic hash functions.⁶⁵

4.3.3 Counter-based

The HMAC-based one-time password (HOTP) is an extension and truncation of the HMAC which is standardized in the RFC 4226 and joint effort between the Internet Engineering Task Force (IETF) and the Initiative for Open Authentication (OATH). It is an algorithm for the generation of OTPs, in contrast to before not an algorithm for message authentication and integrity. The security relies on the fact that a «moving factor», i.e., in this case a counter is used to generate passwords that are only valid once. Alternatively the HOTP is also referred as event-based and the secret key is called the seed. The length of the numeric OTP is configurable and the defined minimum are six digits. The standard only defines HMAC-SHA-1 as the cryptographic hash function to use, but it's also possible to replace the cryptographic hash function, although the implementation won't comply with the RFC anymore.⁶⁶

The HOTP is mathematically defined as:

$$HOTP(K, C) = truncate(HMAC(K, C)) \bmod 10^d$$

Where K is the secret key, C is a counter value and *truncate* the function to dynamically truncate the result of the HMAC. The result is then transformed via the modulo operation into decimal numbers ($\bmod 10^d$, where d is the number of digits to generate). The *truncate* function is the core of the HOTP and explained below:

1. At first the dynamic truncation extracts the least four significant bits as an offset from the 20 byte long HMAC-SHA-1 result, i.e., from the byte 20.
2. Extracting the next 31 bits from the offset position in order to generate 4-byte long string. The most significant bit is skipped in order to avoid issues such as modulo operations on negative numbers, caused by varying computation results based on implementation differences.

⁶⁵See Bis18, Chapter 10.4.1; See Sta17, p. 398; See BCK96, pp. 3, 10–13; See PO95.

⁶⁶See MRa+05; See Sta15, Chapter 3.

Due to its design there are couple of limitations to the HOTP. The counter used between the parties can become out of synchronization requiring further efforts to resynchronize. Due to the fact that the server only increases the counter on successful authentication, the out of sync scenario can occur. The server and client can become synchronized again by generating the next OTP by increasing the counter (look-ahead window) in order to verify if this OTP matches.

Another method for resynchronization is the sending of multiple future values.⁶⁷ It is important to limit the look-ahead window to decrease the attack surface. Further, the server should throttle the authentication attempts in order to counterfeit brute-force attacks. Further analysis is done in section 5.2.

Additionally, the HOTP allows bidirectional authentication, i.e., the user can authenticate the server if it sends the next OTP value that the client then can validate. HOTPs are commonly used in physical security keys, such as YubiKeys, but are also present in software solutions, e.g., in the Google Authenticator.⁶⁸

4.3.4 Time-based

The HMAC-based one-time password (HOTP) is again an extension of the HOTP that is time-based instead of counter-based. It's a joint effort of the IETF and the OATH, too, resulting in a standardization in RFC 6238.⁶⁹

Mathematically the TOTP is defined equal as the HOTP:

$$TOTP(K, T) = \text{truncate}(HMAC(K, T)) \bmod 10^d$$

The only difference is that the counter is substituted by a T , a computed time value derived a reference date ($T0$), the default is the Unix epoch time (1st January 1970) and a time-step value (X) after which time counter is increased by one. The default of the RFC is 30 seconds.

More formally correct, T can be described as:

$$T = \frac{(Current\ Unix\ time - T0)}{X}$$

⁶⁷See SM18, p. 236; See Bis18, Chapter 13.5.1.

⁶⁸See Vac17, p. 716; See MRa+05, p. 14.

⁶⁹See MRa+11.

In contrast to the HOTP definition the RFC 6238 explicitly defines the use of other cryptographic hash algorithms such as SHA-256 or SHA-512. Besides the introduced security considerations and usability implications introduced in subsection 4.3.3, such as throttling and synchronization, an important aspect of the TOTP to take into account is the configured time-step. While an increased time-step size increases the usability of the user, it also expands the attack window. In addition, the user has to wait a longer time until a new OTP is generated in case a fresh one is required. If a user or attacker sends the same OTP in the same time-step window, the server must not accept the same value after a successful authentication but instead wait until the next time-step window.

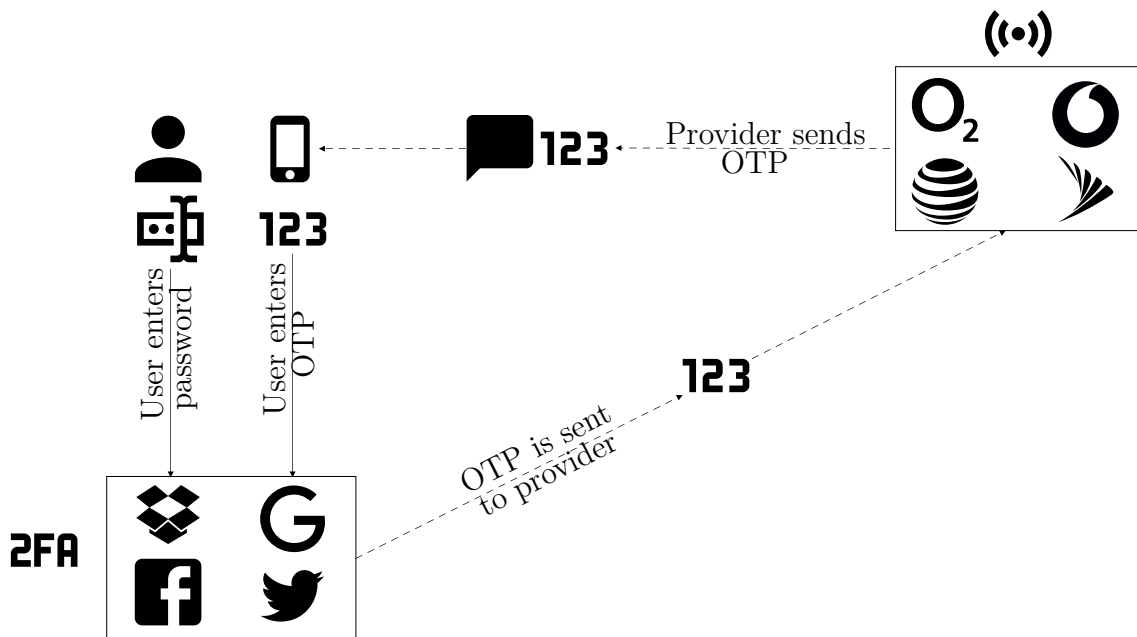


Figure 4.3: Exemplary MFA flow⁷⁰

Figure 4.3 shows an example authentication flow using TOTPs. In this scenario the user tries to login to a service that uses 2FA. After entering their password (knowledge; first factor), they either

- (a) use, e.g., a smartphone app, or hardware token to generate the TOTP.
- (b) receive the TOTP from the service, e.g., via a text message, e-mail or phone call (the figure shows a SMS).

Once the user has obtained the OTP (possession; second factor), they can enter it at the login screen and send it to the server, the relying party. The service can now

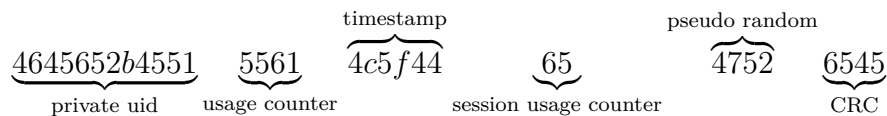
⁷⁰Source: diagram by author

validate the OTP again, while respecting the look-ahead window, and allow the user authentication.

4.3.5 Yubico OTP

In contrast to the open standards TOTP and HOTP the Swedish company Yubico developed a proprietary OTP protocol, too. It is available for all their produced and sold YubiKeys. The produced OTP is a 44-characters long string which is constructed by using Advanced Encryption Standard (AES) with 128-bit encoded into 32 hexadecimal characters using a modified hexadecimal (»modhex«) encoding, yielding a 22-byte value. Each YubiKey contains a unique public ID of 6-bytes that is optionally prepended to the OTP. The OTP is 16-bytes long which is exactly the block size of the AES 128-bit algorithm.⁷¹

The constructed OTP consists of:



Where the 48-bit *private unique or secret ID* is stored in the YubiKey configuration and can be changes (write-only), the 16-bit *usage counter* is a non-volatile usage counter, the 24-bit *timestamp* value, set to a random value after startup and increased by an 8-Hz clock, the *session usage counter*, a 8-bit volatile counter that's initialized with zero after power-up and then increased by one each OTP generation, the *pseudo random number* of 16-bits and a cyclic redundancy check (CRC) *checksum* of 16-bits for the fields. Finally the generated OTP is encrypted with the per device unique AES-128 key.⁷²

The authentication server can either be used as a service from Yubico, as only they know the pre-configured AES key of each YubiKey. This renders their central key server a lucrative target for criminals though, since it is a centralized place of all AES keys. Alternatively the validation server software is available as a self-hosted solution in different programming languages. This requires changing the AES key of the YubiKeys in order to save the shared key on the server, too, since Yubico will not give access to the pre-configured AES key.⁷³

⁷¹KS12; See Jac16.

⁷²See Yub15, pp. 8–9, 33–34.

⁷³See Yub12, pp. 8–9.

4.4 Smartcards

Smartcards, sometimes called chip cards or integrated circuit cards (ICCs), too, are physical plastic cards, often the size of a credit card and contain an internal chip for user authentication. The chip is either exposed or can be accessed contactless. Common examples are SIM cards, credit cards, Common Access Cards (CACs) used by the United States Department of Defense, or identity cards issued by authorities. In IT smartcard can also store certificates and are used for computer log on. The smartcard differs from a regular storage card by having a microprocessor and an erasable programmable read-only memory (EPROM) or electrically erasable programmable read-only memory (EEPROM). It is defined in the ISO standard 7816, which also defines different sizes of smartcards. The NIST standard defines in FIPS 201-2 the usage of smartcards for Personal Identity Verification (PIV) of federal employees.⁷⁴

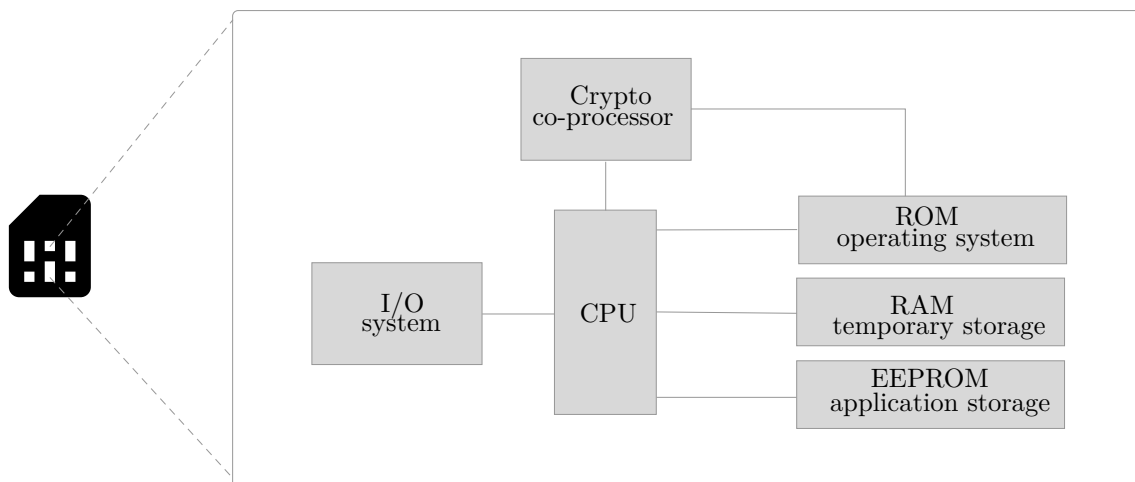


Figure 4.4: Typical smartcard architecture⁷⁵

Figure 4.4 shows the typical architecture of a smartcard chip (ICC). The read-only memory (ROM) contains the operating system (OS) of the smartcard while the random-access memory (RAM) is used for temporary storage. The application storage uses the EEPROM. Some smartcard also contain a second processor for cryptographic operations.

Security wise a key requirement is that an attacker cannot access the private data on the internal chip, i.e., that the smartcard is tamper-resistant. This is, e.g., achieved

⁷⁴See Eck14, pp. 525–527; See ISO11c; See Kei17, pp. 6–9; See ST13.

⁷⁵Source: diagram by author, based on Fer15, p. 33; Kei17, p. 228.

by physically covering the central processing unit (CPU), RAM and EEPROM with a shield. The data stored on the smartcard can itself protected by using a PIN or biometrics, such as a fingerprint, to access the data.⁷⁶

In the aspect of usability, the smartcard always requires a dedicated hardware, either external or built-in, a smartcard reader in order to use the smartcard as an authentication method. While especially enterprise notebooks contain a smartcard slot, e.g., mobile phones do not. With the chip card interface device (CCID) protocol which defines a USB protocol it is at least possible to use a USB card reader.

4.5 Security Tokens

Besides smartcards, further MFA solutions with possession as the second factor involve the usage of security tokens.

Hardware and software are possible. The minimum security specification are, e.g., defined in NIST FIPS 140-3.⁷⁷

4.5.1 RSA SecurID

The RSA SecurID exists in several variants, both hardware and software token. First hardware revisions used a 64-bit proprietary protocol called «SecurID has function», hardware keys newer than 2003 use the standardized 128-bit RSA algorithm in order to generate OTPs. Newer revisions also feature a USB port which allows the device to store custom certificates, too, i.e., making it a smartcard device, too. Each token contains a burned in seed, a random key that was generated while manufacturing the device. Since this seed needs to be known to validate the OTP, the RSA SecurID server needs to be used.

Mobile application exists, too, offering support for a soft-token based solution.

4.5.2 YubiKey

Variety of tokens available, all support Yubico's OTP algorithm, HOTP and TOTP. Many support Universal Second Factor (U2F), too. Some static passwords and PKI. Some are PIV conform and FIPS 140 certified.

⁷⁶See Tod07, p. 34; See Kei17, p. 228.

⁷⁷See ST19.

4.5.3 Software 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.

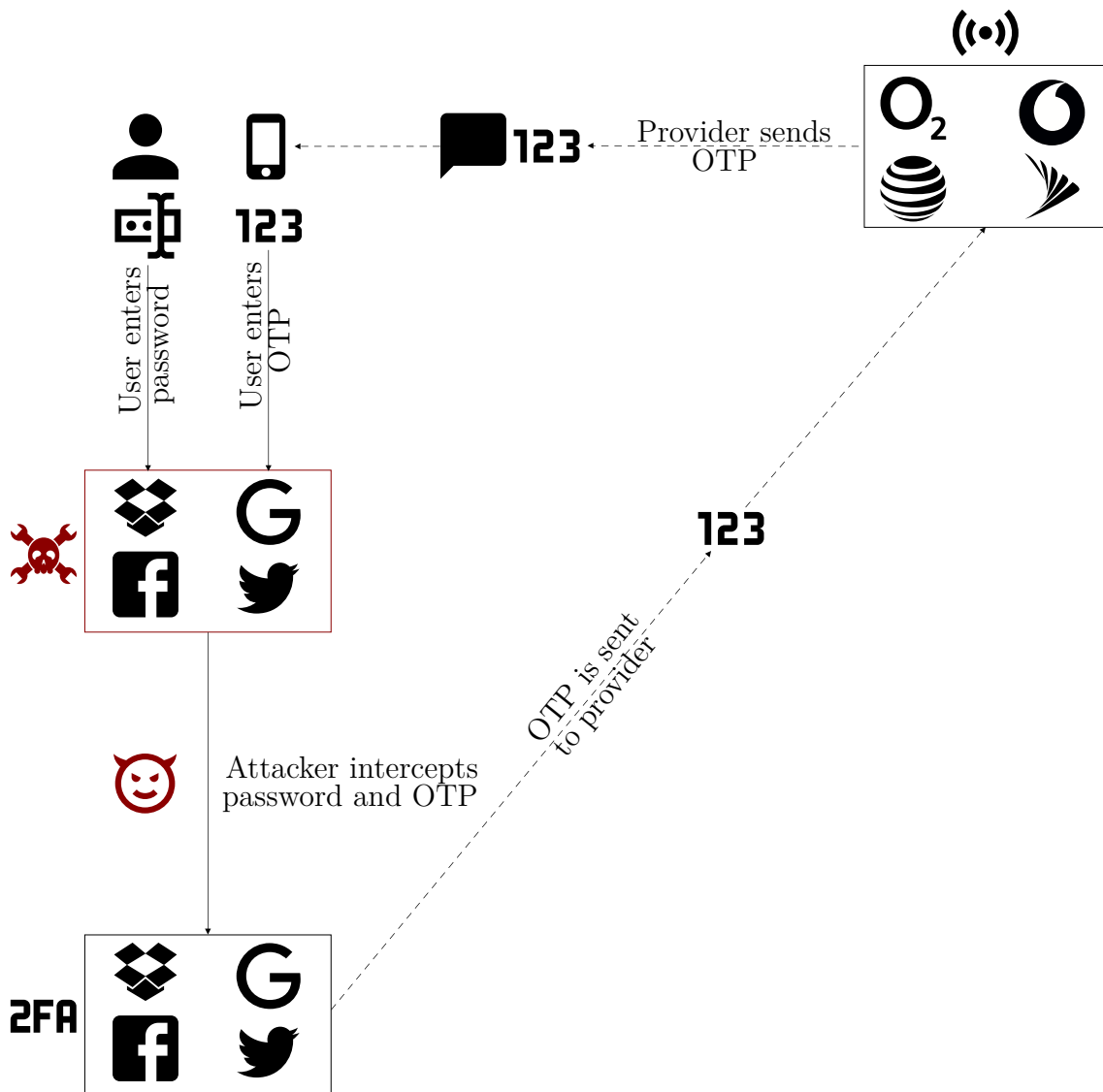


Figure 5.1: Exemplary 2FA phishing of an OTP⁷⁸

Figure 5.1 shows the already in Figure 4.3 explained MFA flow using a TOTP. In this figure the scenario is expanded with a phishing attack. The user visits a phishing copy of the website they want to use and do not recognize this. Because he knows that this site is using MFA they provide the TOTP to the phishing site, too. This allows the interceptor to steal both the password (knowledge; first factor) and TOTP (possession; second factor) to successfully login to the victims account and effectively bypassing the MFA solution.

5.2 HOTP and TOTP

In this section the security of both HOTP and TOTP is being analyzed.

5.2.1 Algorithm

pros

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

cons

”Just an algorithm”

1. synchronization
2. invalidation
3. nobody knows how the algorithm is implemented
4. Differences (e.g. Steam - only 5 digits, limited Alphabet)
5. Brute Force if server does not limit
6. Not phishing resistant

⁷⁸Source: diagram by author

As both the HOTP 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 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 BSI lists these algorithms as secure for HMAC⁷⁹

Citations:⁸⁰

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 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.

⁷⁹Inf19.

⁸⁰Ste+17.

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.⁸¹

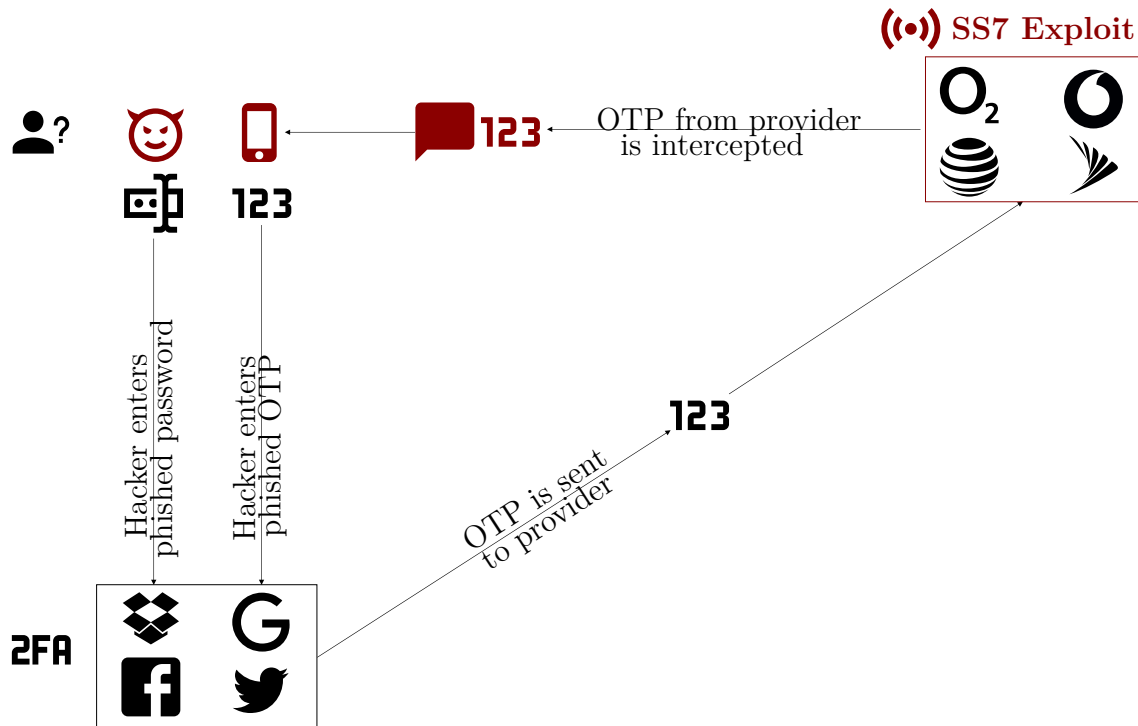


Figure 5.2: SS7 exploit to phish an OTP used in MFA⁸²

Figure 5.2 again shows the described MFA flow using TOTP. In this scenario the attacker is still able to phish the TOTP designated for the user. The figure shows that the attacker uses an exploit in the SS7 network. This allows them to intercept all incoming SMSs.

⁸¹Wel17; HO17; Puz17.

⁸²Source: diagram by author

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 are 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.

In contrast to the web and e-mail 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.⁸³

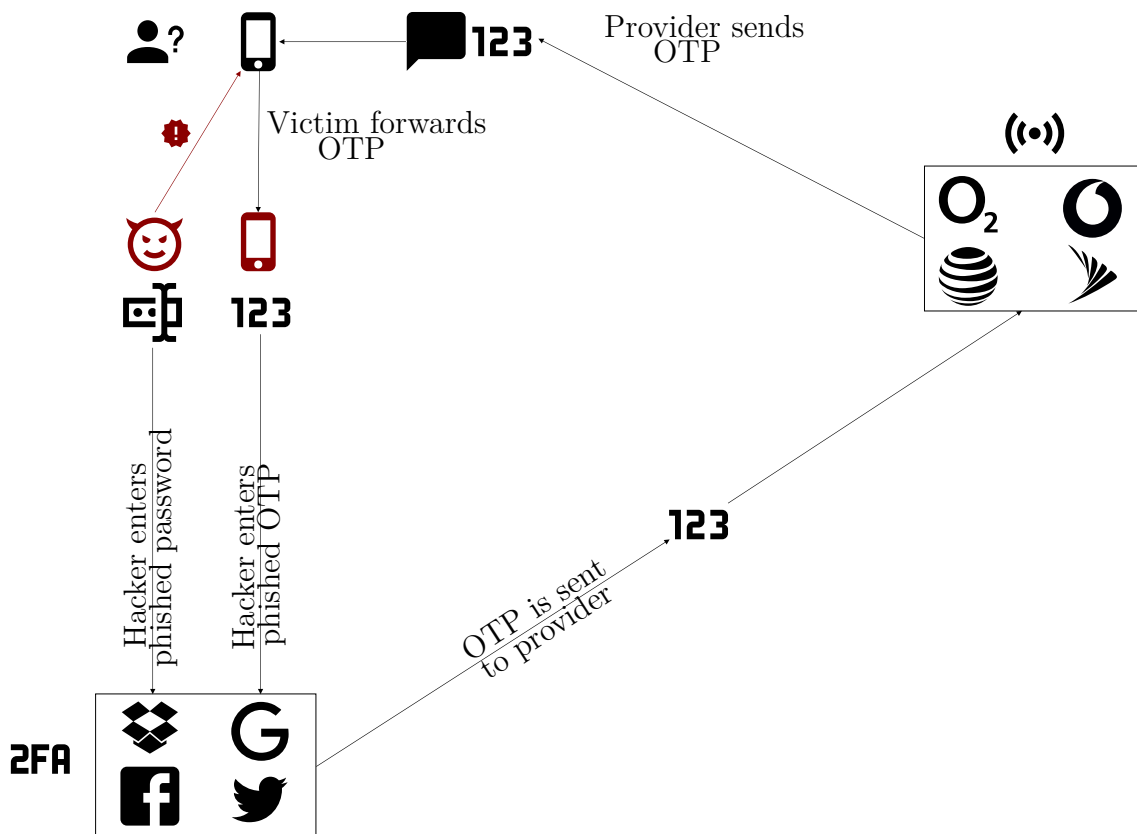


Figure 5.3: VCFA to phish an OTP used in MFA⁸⁴

Figure 5.3 shows an example of a VCFA. An attack logs in to the user's account with, e.g., hacked or phished credentials. Because the account is protected by MFA, the user receives a verification code via SMS or smartphone. The attacker send now

⁸³Jak18; Sia+17.

⁸⁴Source: diagram by author

a fake SMS to the victim, stating that the service has detected unusual activity and that the user should reply with the just received verification code in order to stop this activity and proof they are the account owner. Of course the attack now has access to the OTP, too, since they tricked the user into forwarding their code.

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

Further, it cannot be guaranteed that the user has a working mobile network, that the registered mobile phone number is still active or that the user receives the SMS on time. These non-influencable, external factors strengthen the fact that SMS are not a wise choice as the transportation medium.

Additional weaknesses of SIM are the attack risks of

- (a) SIM cloning
- (b) SIM swapping scam

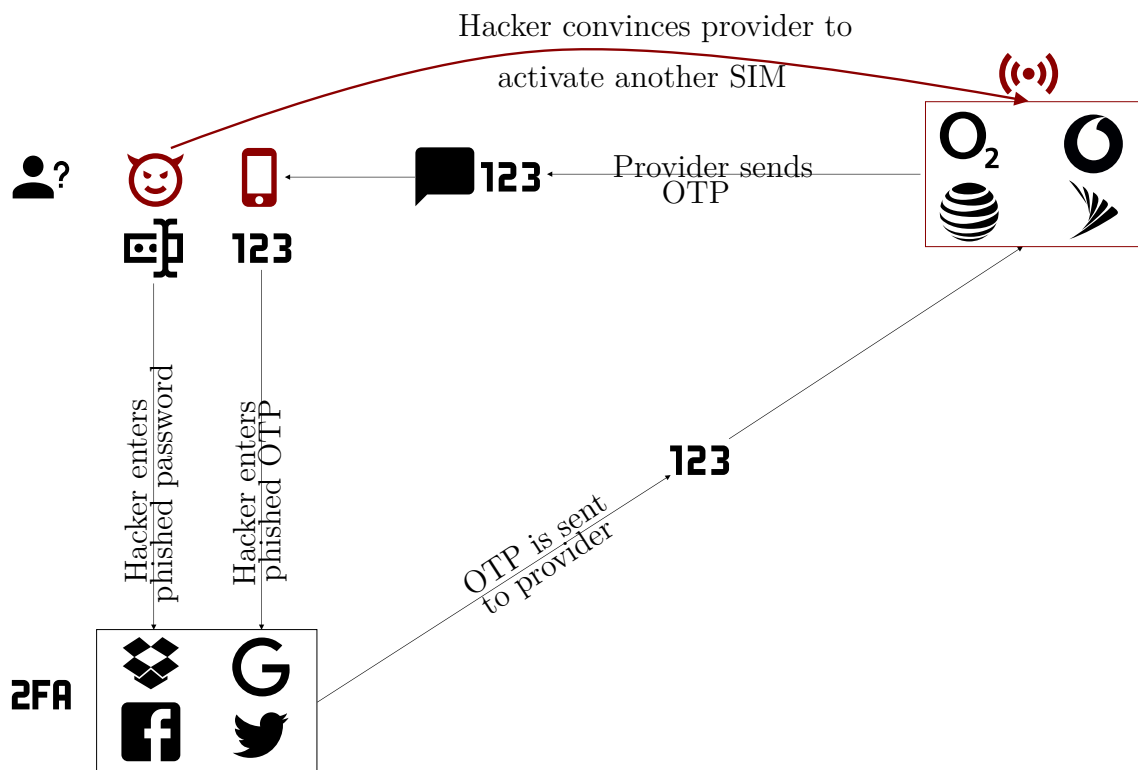


Figure 5.4: Social engineering used to phish an OTP in MFA⁸⁵

Figure 5.4 shows presented MFA flow using TOTP again, but in this case another phishing scenario. An attacker has again access to the user's password, e.g., from a

⁸⁵Source: diagram by author

previous, successful phishing attack. In order to obtain or phish, respectively, they target the human weakness in the cell phone provider of the user. They successfully convince them to activate another SIM card for the victims phone number and receive the SMS with the TOTP, too, which enables the attacker to successfully complete the MFA flow. Yet another variant which is technically more complex, but feasible, is the SIM card cloning. This allows the attacker to intercept the TOTP, too, by registering the phone number twice.

[ST08] [Gra+17] (Twitter CEO hack) [Con19]

Given all these facts SMS transportation should be avoided at all costs,⁸⁶ since there are multiple flaws in the SS7 network itself and the process how the SMS reaches the user. It's also not resistant against phishing or mobile phone trojans.

App

pros

1. Works offline
2. cheaper

cons

1. Secret can be phished while setup (either on phone or computer)
2. Trusted apps? OSS?⁸⁷
3. Vulnerabilities -> e.g. Authy⁸⁸

E-Mail

pros

1. widely used
2. cheap and easy

⁸⁶Jak18.

⁸⁷Ste19.

⁸⁸Hom15.

cons

1. unencrypted
2. malware
3. MITM

6 Introduction to the Web Authentication API

6.1 History and evolution

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

6.1.1 FIDO Alliance

6.1.2 UAF

1.0

1.1

6.1.3 U2F

1.0

1.2

6.1.4 FIDO 2

6.2 Technical implementation and details

6.2.1 CTAP

6.2.2 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 API⁸⁹

⁸⁹Sources: 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 such as 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 10.⁹⁰ 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.⁹¹

⁹⁰See Sup19c.

⁹¹See Bio16.

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.⁹²



Figure 6.1: Failed try to use the Web Authentication API with the Brave Browser on an iPhone 6⁹³

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.

⁹²See Bra19a; See Bra19b.

⁹³Source: 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 OSs for example Windows Phone 8, BlackBerry OS, BlackBerry 10 or KaiOS do not support the Web Authentication API.

6.2.3 Usability

6.3 Security aspects

Problems:⁹⁴

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.

⁹⁴Sta18.

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.
- [BCK96] Mihir Bellare, Ran Canetti, and Hugo Krawczyk. “Keying Hash Functions for Message Authentication.” In: *Advances in Cryptology — CRYPTO '96*. Ed. by Neal Koblitz. Berlin, Germany and Heidelberg, Germany: Springer Berlin Heidelberg, Aug. 1996, pp. 1–15. ISBN: 978-3-540-68697-2. DOI: [10.1007/3-540-68697-5_1](https://doi.org/10.1007/3-540-68697-5_1).
- [Bid06] Hossein Bidgoli. *Handbook of Information Security Threats, Vulnerabilities, Prevention, Detection, and Management*. Vol. 3. Handbook of Information Security. Hoboken, NJ, USA: Wiley, 2006. ISBN: 978-0-471-64832-1.
- [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.
- [BLP05] Alex Biryukov, Joseph Lano, and Bart Preneel. “Recent attacks on alleged SecurID and their practical implications.” In: *Computers & Security* 24.5 (Aug. 2005), pp. 364–370. ISSN: 0167-4048. DOI: [10.1016/j.cose.2005.04.006](https://doi.org/10.1016/j.cose.2005.04.006).
- [Bon+15] Joseph Bonneau et al. “Secrets, Lies, and Account Recovery: Lessons from the Use of Personal Knowledge Questions at Google.” In: *Proceedings of the 24th International Conference on World Wide Web*. WWW '15. Florence, Italy: International World Wide Web Conferences Steering Committee, May 2015, pp. 141–150. ISBN: 978-1-4503-3469-3. DOI: [10.1145/2736277.2741691](https://doi.org/10.1145/2736277.2741691).
- [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).
- [Dmi+14] Alexandra Dmitrienko et al. “On the (In)Security of Mobile Two-Factor Authentication.” In: *Financial Cryptography and Data Security*. Ed. by Nicolas Christin and Reihaneh Safavi-Naini. Berlin, Germany and Heidelberg, Germany: Springer Berlin Heidelberg, Mar. 2014, pp. 365–383. ISBN: 978-3-662-45472-5. DOI: [10.1007/978-3-662-45472-5_24](https://doi.org/10.1007/978-3-662-45472-5_24).
- [DR08] Tim Dierks and Eric Rescorla. *The Transport Layer Security (TLS) Protocol Version 1.2*. RFC 5246. RFC Editor, Aug. 2008. DOI: [10.17487/RFC5246](https://doi.org/10.17487/RFC5246).
- [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, Nov. 2014, pp. 184–201. ISBN: 978-3-319-05452-0. DOI: [10.1007/978-3-319-05452-0_14](https://doi.org/10.1007/978-3-319-05452-0_14).
- [Eck14] Claudia Eckert. *IT-Sicherheit: Konzepte - Verfahren - Protokolle*. 9th ed. Munich, Germany: De Gruyter, 2014. ISBN: 978-3-486-77848-9.
- [Fer15] Nuno Alvarez Fernandes. “Reliable electronic certification on mobile devices.” MA thesis. Instituto Superior Técnico, Nov. 2015. DOI: [10.13140/RG.2.1.2397.8323](https://doi.org/10.13140/RG.2.1.2397.8323).
- [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.
- [Gra+17] Paul A. Grassi et al. *Digital Identity Guidelines: Authentication and Lifecycle*. Special Publication 800-63b. National Institute of Standards and Technology, June 2017. DOI: [10.6028/NIST.SP.800-63b](https://doi.org/10.6028/NIST.SP.800-63b).

- [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)*. Paris, France, May 2017, pp. 1–6. ISBN: 978-1-4673-8999-0. DOI: [10.1109/ICC.2017.7997246](https://doi.org/10.1109/ICC.2017.7997246).
- [Inf19] Federal Office for Information Security. “Cryptographic Mechanisms: Recommendations and Key Lengths.” In: *Technical Guideline TR-02102-1, Federal Office for Information Security* 1 (Feb. 2019).
- [ISO11a] ISO/IEC 9797-1:2011. *Information technology – Security techniques – Message Authentication Codes (MACs) – Part 1: Mechanisms using a block cipher*. Standard 9797-1. Geneva, Switzerland: International Organization for Standardization, Mar. 2011.
- [ISO11b] ISO/IEC 9797-2:2011. *Information technology – Security techniques – Message Authentication Codes (MACs) – Part 2: Mechanisms using a dedicated hash-function*. Standard 9797-2. Geneva, Switzerland: International Organization for Standardization, May 2011.
- [ISO11c] ISO/IEC 7816-1:2011. *Identification cards – Integrated circuit cards – Part 1: Cards with contacts – Physical characteristics*. Standard 7816-1. Geneva, Switzerland: International Organization for Standardization, Feb. 2011.
- [Jac16] Todd A. Jacobs. “Secure Token-based Authentication with YubiKey 4.” In: *Linux Journal* 2016.265 (May 2016). ISSN: 1075-3583.
- [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).
- [JBS15] Michael B. Jones, John Bradley, and Nat Sakimura. *JSON Web Token (JWT)*. RFC 7519. RFC Editor, May 2015. DOI: [10.17487/RFC7519](https://doi.org/10.17487/RFC7519).
- [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. DOI: [10.1007/978-3-319-50500-8](https://doi.org/10.1007/978-3-319-50500-8).

-
- [KS12] Robert Künnemann and Graham Steel. “YubiSecure? Formal Security Analysis Results for the Yubikey and YubiHSM.” In: *Security and Trust Management*. Ed. by Audun Jøsang, Pierangela Samarati, and Marinella Petrocchi. Pisa, Italy: Springer Berlin Heidelberg, Sept. 2012, pp. 257–272. ISBN: 978-3-642-38004-4. DOI: [10.1007/978-3-642-38004-4_17](https://doi.org/10.1007/978-3-642-38004-4_17).
 - [KSM14] Gurudatt Kulkarni, Ramesh Sutar, and Sangita Mohite. ““RFID security issues challenges”” In: *2014 International Conference on Electronics and Communication Systems (ICECS)*. Coimbatore, India, Feb. 2014, pp. 1–4. ISBN: 978-1-4799-2320-5. DOI: [10.1109/ECS.2014.6892730](https://doi.org/10.1109/ECS.2014.6892730).
 - [LM16] Jonathan LeBlanc and Tim Messerschmidt. *Identity and Data Security for Web Development: Best Practices*. Sebastopol, CA, USA: O’Reilly Media, 2016. ISBN: 978-1-4919-3701-3.
 - [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, July 2013, pp. 150–159. ISBN: 978-3-642-39235-1. DOI: [10.1007/978-3-642-39235-1_9](https://doi.org/10.1007/978-3-642-39235-1_9).
 - [Nat18] Committee on National Security Systems. *National Information Assurance (IA) Glossary*. Tech. rep. 4009. Committee on National Security Systems, Apr. 2018.
 - [Noc18] Mark Noctor. “PSD2: Is the banking industry prepared?” In: *Computer Fraud & Security* 2018.6 (June 2018), pp. 9–11. ISSN: 1361-3723. DOI: [10.1016/S1361-3723\(18\)30053-8](https://doi.org/10.1016/S1361-3723(18)30053-8).
 - [Oud16] Abdelkader Ouda. “A framework for next generation user authentication.” In: *2016 3rd MEC International Conference on Big Data and Smart City (ICBDSC)*. Muscat, Oman, Mar. 2016, pp. 1–4. ISBN: 978-1-4673-9584-7. DOI: [10.1109/ICBDSC.2016.7460349](https://doi.org/10.1109/ICBDSC.2016.7460349).
 - [PO95] Bart Preneel and Paul C. van Oorschot. “MDx-MAC and Building Fast MACs from Hash Functions.” In: *Advances in Cryptology — CRYPTO’95*. Ed. by Don Coppersmith. Santa Barbara, CA, USA: Springer Berlin Heidelberg, Aug. 1995, pp. 1–14. ISBN: 978-3-540-44750-4. DOI: [10.1007/3-540-44750-4_1](https://doi.org/10.1007/3-540-44750-4_1).
 - [Puz17] Sergey Puzankov. “Stealthy SS7 Attacks.” In: *Journal of ICT Standardization* 5.1 (Jan. 2017), pp. 39–52. ISSN: 2246-0853.

- [Rab08] Ariel Rabkin. “Personal Knowledge Questions for Fallback Authentication: Security Questions in the Era of Facebook.” In: *Proceedings of the 4th Symposium on Usable Privacy and Security*. SOUPS ’08. Pittsburgh, Pennsylvania, USA: ACM, July 2008, pp. 13–23. ISBN: 978-1-60558-276-4. DOI: [10.1145/1408664.1408667](https://doi.org/10.1145/1408664.1408667).
- [SBE09] Stuart Schechter, A. J. Bernheim Brush, and Serge Egelman. “It’s No Secret. Measuring the Security and Reliability of Authentication via “Secret” Questions.” In: *2009 30th IEEE Symposium on Security and Privacy*. Berkeley, CA, USA: IEEE, May 2009, pp. 375–390. DOI: [10.1109/SP.2009.11](https://doi.org/10.1109/SP.2009.11).
- [Sch16] Bruce Schneier. “Stop Trying to Fix the User.” In: *IEEE Security Privacy* 14.5 (Sept. 2016), pp. 96–96. ISSN: 1540-7993. DOI: [10.1109/MSP.2016.101](https://doi.org/10.1109/MSP.2016.101).
- [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, Oct. 2011, pp. 99–113. ISBN: 978-3-642-18178-8. DOI: [10.1007/978-3-642-18178-8_9](https://doi.org/10.1007/978-3-642-18178-8_9).
- [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 (Mar. 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).
- [Sic16] Bundesamt für Sicherheit in der Informationstechnik. *IT-Grundschutz-Kataloge*. 15th ed. Cologne, Germany: Bundesanzeiger Verlag, 2016. ISBN: 978-3-88784-915-3.
- [Sic19] Bundesamt für Sicherheit in der Informationstechnik. *IT-Grundschutz-Kompendium*. 2nd ed. Cologne, Germany: Bundesanzeiger Verlag, 2019. ISBN: 978-3-8462-0906-6.
- [SM18] Michael Schwartz and Maciej Machulak. *Securing the Perimeter*. New York, NY, USA: Apress, 2018. ISBN: 978-1-4842-2601-8. DOI: [10.1007/978-1-4842-2601-8](https://doi.org/10.1007/978-1-4842-2601-8).
- [ST08] National Institute of Standards and Technology. *The Keyed-Hash Message Authentication Code (HMAC)*. Federal Information Processing Standards Publication Series 198-1. National Institute of Standards and Technology, July 2008. DOI: [10.6028/NIST.FIPS.198-1](https://doi.org/10.6028/NIST.FIPS.198-1).
- [ST13] National Institute of Standards and Technology. *Personal Identity Verification (PIV) of Federal Employees and Contractors*. Federal Information Processing Standards Publication Series 201-2. National Institute of Standards and Technology, Aug. 2013. DOI: [10.6028/NIST.FIPS.201-2](https://doi.org/10.6028/NIST.FIPS.201-2).

- [ST19] National Institute of Standards and Technology. *Security Requirements for Cryptographic Modules*. Federal Information Processing Standards Publication Series 140-3. National Institute of Standards and Technology, Mar. 2019. DOI: [10.6028/NIST.FIPS.140-3](https://doi.org/10.6028/NIST.FIPS.140-3).
- [Sta15] Mark Stanislav. *Two-Factor Authentication*. Ely, United Kingdom: IT Governance Publishing, Apr. 2015. ISBN: 978-1-84928-733-3.
- [Sta17] William Stallings. *Cryptography and Network Security: Principles and Practice, Global Edition*. 7th ed. London, United Kingdom: Pearson, 2017. ISBN: 978-1-292-15858-7.
- [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).
- [TC11] Sean Turner and Lily Chen. *Updated Security Considerations for the MD5 Message-Digest and the HMAC-MD5 Algorithms*. RFC 6151. RFC Editor, Mar. 2011. DOI: [10.17487/RFC6151](https://doi.org/10.17487/RFC6151).
- [Tho+17] Kurt Thomas et al. “Data Breaches, Phishing, or Malware?: Understanding the Risks of Stolen Credentials.” In: *Proceedings of the 2017 ACM SIGSAC Conference on Computer and Communications Security*. CCS ’17. Dallas, TX, USA: ACM, 2017, pp. 1421–1434. ISBN: 978-1-4503-4946-8. DOI: [10.1145/3133956.3134067](https://doi.org/10.1145/3133956.3134067).
- [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, May 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* (Jan. 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*. Liverpool, United Kingdom, 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/Publikation/en/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).
- [Con19] Kate Conger. *Twitter C.E.O. Jack Dorsey's Account Hacked*. Aug. 30, 2019. URL: <https://www.nytimes.com/2019/08/30/technology/jack-dorsey-twitter-account-hacked.html> (last accessed on 08/31/2019).
- [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).
- [Las18] LastPass. *Psychology of Passwords: Neglect is Helping Hackers Win*. May 2018. URL: <https://lp-cdn.lastpass.com/lporcamedia/document-library/lastpass/pdf/en/logmein-lastpass-survey-ebook-v8.pdf> (last accessed on 08/30/2019).
- [Löw16] Anne-Marie Eklund Löwinder. *Lösenord för alla*. Sept. 1, 2016. URL: https://internetstiftelsen.se/docs/Rapport_Losenord_for_alla.pdf (last accessed on 08/30/2019).
- [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).
- [Wes19] Olivia von Westernhagen. *YubiKey: Yubico ruft Security-Keys der FIPS-Serie zurück*. June 19, 2019. URL: <https://heise.de/-4448794> (last accessed on 08/30/2019).
- [You18] YouGov. *YouGov Online Passwords*. Oct. 2018. URL: https://d25d2506sfb94s.cloudfront.net/cumulus_uploads/document/81iu1qr2x/Passwords%20results,%20Sept.%202017%20%E2%80%93%20Oct.%202018.pdf (last accessed on 08/30/2019).
- [You19] YouGov. *YouGov Computer Protection 2019*. Jan. 2019. URL: https://d25d2506sfb94s.cloudfront.net/cumulus_uploads/document/ubt2ymvq7p/Computer%20protection,%20Jan.%2015%202019.pdf (last accessed on 08/30/2019).
- [Yub12] Yubico. *YubiKey Authentication Module DesignGuideline*. May 7, 2012. URL: <https://www.yubico.com/wp-content/uploads/2012/10/YubiKey-Authentication-Module-Design-Guideline-v1.0.pdf> (last accessed on 09/01/2019).
- [Yub15] Yubico. *The YubiKey Manual*. Mar. 27, 2015. URL: https://www.yubico.com/wp-content/uploads/2015/03/YubiKeyManual_v3.4.pdf (last accessed on 09/01/2019).

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
3.1	Percentage of online accounts sharing the same password in the United States in 2018	13
4.1	Message authentication code used to protect a sent message	21
4.2	Visualization of the HMAC algorithm	23
4.3	Exemplary MFA flow	26
4.4	Typical smartcard architecture	28
5.1	Exemplary MFA phishing of an OTP	31
5.2	SS7 exploit to phish an OTP used in MFA	34
5.3	VCFA to phish an OTP used in MFA	35
5.4	Social engineering used to phish an OTP in MFA	36
6.1	Failed try to use the Web Authentication API with the Brave Browser on an iPhone 6	42

Listings

List of Tables

1	Web browser support of the Web Authentication API	40
---	---	----

Glossary

N

Nonce A number that can only be used once in a cryptographic operation or communication.

O

OATH ...

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

AES Advanced Encryption Standard

API Application Programming Interface

B

BLE Bluetooth Low Energy

BSI Federal Office For Information Security

C

CAC Common Access Card

CBC-MAC Cipher Block Chaining Message Authentication Code

CCID Chip Card Interface Device

CPU Central Processing Unit

CRC Cyclic Redundancy Check

CSO Chief Security Officer

D

DES Data Encryption Standard

DNS Domain Name System

E

ECC Elliptic-Curve Cryptography

EEPROM Electrically Erasable Programmable Read-Only Memory

EPROM Erasable Programmable Read-Only Memory

EU European Union

F

FAR False Acceptance Rate

FIDO Fast IDentity Online

FIPS Federal Information Processing Standard Publication

FRR False Rejection Rate

G

GPS Global Positioning System

H

HMAC Keyed-Hash Message Authentication Code

HOTP HMAC-Based One-Time Password

I

ICC Integrated Circuit Card

IETF Internet Engineering Task Force

IoT Internet Of Things

ISO International Organization For Standardization

IT Information Technology

J

JWT JSON Web Token

M

MAC Media Access Control

MAC Message Authentication Code

MD Message Digest

MFA Multi-Factor Authentication

MIC Message Integrity Code

MITM Man-In-The-Middle

N

NFC Near-Field Communication

NIST National Institute Of Standards And Technology

nonce Number Used Once, *Glossary*: Nonce

NTP Network Time Protocol

O

OATH Initiative For Open Authentication, *Glossary*: OATH

OOB Out-Of-Band

OS Operating System

OTP One-Time Password

P

PIN Personal Identification Number

PIV Personal Identity Verification

PSD Payment Services Directive

Q

QR Quick Response

R

RAM Random-Access Memory

RFC Request For Comments

RFID Radio-Frequency Identification

ROM Read-Only Memory

S

SHA Secure Hash Algorithm

SIM Subscriber Identity Module

SMS Short Message Service

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

SSO Single Sign-On

T

TAN Transaction Authentication Number

TLS Transport Layer Security

TOTP Time-Based One-Time Password

TPM Trusted Platform Module, *Glossary*: TPM

U

U2F Universal Second Factor

UAF Universal Authentication Framework

V

VCFA Verification Code Forwarding Attack

VoIP Voice Over Internet Protocol

VPN Virtual Private Network

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, September 4, 2019

Tim Brust

Theses

1. The status quo of password usage is terrible; often chosen passwords are re-used and weak.
2. Humans are the weakest link.
3. Multi-factor authentication 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 multi-factor authentication is transportation, especially when using SMS or unencrypted e-mail traffic.
5. Multi-factor authentication can be made 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 the common (internet) threats.