FIDO2 With Two Displays—Or How to Protect Security-Critical Web Transactions Against Malware Attacks

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Abstract—With the rise of attacks on online accounts in the past years, more and more services offer two-factor authentication for their users. Having factors out of two of the three categories something you know, something you have and something you are should ensure that an attacker cannot compromise two of them at once. Thus, an adversary should not be able to maliciously interact with one’s account. However, this is only true if one considers a weak adversary. In particular, since most current solutions only authenticate a session and not individual transactions, they are noneffective if one’s device is infected with malware. For online banking, the banking industry has long since identified the need for authenticating transactions. However, specifications of such authentication schemes are not public and implementation details vary wildly from bank to bank with most still being unable to protect against malware. In this work, we present a generic approach to tackle the problem of malicious account takeovers, even in the presence of malware. To this end, we define a new paradigm to improve two-factor authentication that involves the concepts of one-out-of-two security and transaction authentication. Web authentication schemes following this paradigm can protect security-critical transactions against manipulation, even if one of the factors is completely compromised. Analyzing existing authentication schemes, we find that they do not realize one-out-of-two security. We give a blueprint of how to design secure web authentication schemes in general. Based on this blueprint we propose FIDO2 With Two Displays (FIDO2D), a new web authentication scheme based on the FIDO2 standard and prove its security using Tamarin. We hope that our work inspires a new wave of two-factor authentication that involves the concepts of one-out-of-two security, transaction authentication, and authentication, transaction authentication, one-out-of-two security, Tamarin, 2DA, FIDO2D

I. INTRODUCTION

In recent years, the World Wide Web and the multitude of different services offered within changed almost everyone’s life. Whether we want to send an email, do online banking, buy a product, or update our social media profile, we use the Web. In general, each of these activities requires a separate account with which we authenticate ourselves. According to a study by Google in partnership with The Harris Poll in 2019, the average American has 27 different online accounts [1].

Passwords always were and still are the main means of authentication on the Internet. However, since one cannot possibly remember that many different passwords (and the adoption of password managers is still very low) re-using passwords on a multitude of different sites is a common practice [2]. This means that one stolen password from an account on an unimportant website might also give an adversary access to more important ones, like an online banking account.

As more and more of our private and professional life started to happen on the Internet, compromising accounts through simple and cheap attacks like credential stuffing and phishing became increasingly more attractive and lucrative for attackers.

To mitigate these risks, security experts started to advertise the use of two-factor authentication instead of only a single password [3]. A mandatory second authenticating factor (like a one-time password (OTP)) severely restricts the utility of stolen passwords for an attacker. Users and account providers alike took a very long time to adopt this recommendation, but nowadays many web applications offer at least one form of two-factor authentication. Most implementations require the user to present a second factor together with a password during login. If successful, the user then receives an authenticated session token (stored within a cookie), which she can use to interact with the site and her account without having to authenticate herself again for a while.

When using two-factor authentication, it is recommended to use two of the three following factors: something you know, something you have and something you are. Behind this categorization lies the assumption that it is improbable for the same adversary to compromise factors from different categories (e.g., an adversary that gets a password from a password leak cannot also steal a copy of the user’s fingerprint). However, this is only true in a very specific adversarial model. An attacker who has compromised a victim’s computer does not need to steal a copy of the fingerprint; he can simply manipulate all interactions with a website by using the authenticated session token stored in the browser after the victim performed a legitimate login.

Indeed, two-factor authentication as it is used today does not help against a number of attack techniques used by real-life adversaries [4]–[6]. Most schemes are susceptible to malware attacks and some popular forms, like OTP, are also vulnerable to real-time phishing, in which an adversary
relays authentication details from a fake website to a legitimate one [7], [8].

Bruce Schneier adequately summarized the applicability of two-factor authentication in as early as 2005: “Two-factor authentication isn’t our savior. It won’t defend against phishing. It’s not going to prevent identity theft. It’s not going to secure online accounts from fraudulent transactions. It solves the security problems we had 10 years ago, not the security problems we have today” [9].

In recent years, online banking has been moving into the right direction security-wise by introducing transaction authentication, which is the verification of transaction details (often on an additional device, but not necessarily). Authenticating transactions individually mitigates the risk of session hijacking by stealing a cookie. Furthermore, manipulation of transaction details can be detected if one is using an additional device to check them.

The chip authentication program (CAP) protocol used in online banking thus provides a high level of security. It relies on a dedicated card reader with a display. The device offers a very small attack surface for infection by malware as it has limited functionality and is specifically built for this use case. Carrying an additional device has been identified as unpleasant for many users [10], [11]. In consequence, many banks abandoned dedicated hardware tokens and transitioned to app-based authentication schemes such as photoTAN. However, similar to regular computers, smartphones have large attack surfaces, are susceptible to, and have been attacked by malware [12]. By compromising the smartphone, attackers can bypass confirmation of transactions on the device [13]. Therefore, if an attacker gets access to the user’s password, he can access the online banking system and execute arbitrary transactions (see Section III). Some banks even allow initiating transactions from the same device [13]. Thus, most current online banking schemes, which are required by law to offer strong security [14], do not adequately protect against malware attacks, since the smartphone needs to be fully trusted. Besides online banking, many other use cases such as administration panels and electronic health records handle security-critical transactions (see Section VII). However, most of them do not implement transaction authentication and thus do not protect against malware attacks.

The recent FIDO2 standard provides a widely implemented browser API called WebAuthn that simplifies integration of secure web authentication mechanisms relying on public-key cryptography and supporting authentication of individual transactions. However, authentication with FIDO2 is primarily used for login today and thus suffers from susceptibility to malware attacks as described before. The support for transaction authentication has even been removed from the latest version of the WebAuthn standard [15].

We show how to design web authentication schemes using two devices (one of which could be a smartphone) which protect security-critical transactions, even if one device is fully compromised. While this might seem like an impossible task, it can be done. In the following, we show how.

In this work, we analyze the security of web authentication schemes in the presence of malware and real-time phishing attacks. We find that even strong authentication schemes for online banking that rely on transaction authentication as required by the revised Payment Services Directive (PSD2) do not protect against these attacks.

As a remedy, we propose that web authentication schemes handling security-critical transactions should fulfill one-out-of-two security, a security notion that neither requires a primary device nor an additional device trusted. We show how this security notion introduced for electronic payment can be adapted to web authentication. Furthermore, we provide a blueprint to design web authentication schemes that fulfill this notion and thus protect security-critical transactions even if one device is fully compromised.

Based on our blueprint, we design and implement FIDO2 With Two Displays (FIDO2D), a web authentication scheme based on the FIDO2 standard. We identify shortcomings of FIDO2 for implementing malware-resistant web authentication and show how they can be treated. Integration into the FIDO2 standard would pave the way for broad adoption of our approach. We examine multiple use cases that benefit from the security guarantees of FIDO2D.

Finally, we provide a formal model of FIDO2D and prove that it fulfills one-out-of-two security using Tamarin.

III. ATTACKS ON WEB AUTHENTICATION

In this section, we analyze attacks on current web authentication schemes and introduce our attack model that serves as the basis for all of the following.

A. Password Attacks

Password authentication is by far the most prominent authentication scheme in the web. The main problems of password authentication are that users choose weak passwords and reuse them across multiple sites [16]. Brute-force and password spraying attacks exploit weak passwords while credential-stuffing attacks focus on reused passwords. For example, the video conferencing solution Zoom was hit by a credential-stuffing attack and a large number of accounts were compromised [17]. The success of these attacks is not surprising considering the amount of publicly available credentials [18].

Risk-based authentication (RBA) aims to strengthen password authentication by monitoring features such as the IP address and the user agent of the browser and triggering additional authentication during login if they differ from those recorded before [19]. While this limits the impact of a stolen password, most features are easy to detect and spoof during a phishing or malware attack. Criminal platforms evolved that sell access to user profiles containing credentials and features that allow bypassing RBA [20].
We assume malware to be executed with the highest user privileges available such as root or administrator and thus malware might manipulate the operating system. This assumption is supported by prior work that documents the use of privilege escalation attacks in the wild [12]. Furthermore, a similar model for malware has been used in prior work [8], [13].

Because of the high prevalence of password and phishing attacks [16], we assume all attackers to be able to carry them out by malware to issue a malicious transaction.

1) Transaction Manipulation: In the following, we assume that an authentication scheme is used that does not display transaction details on an additional device. Malware on the primary device can then carry out a transaction manipulation attack as depicted in Figure 1. Suppose that a user wants to make a security critical transaction on a website. After logging in (potentially with two factors), she enters the desired transaction details t (1), however, the compromised device initiates a manipulated transaction t’ (2). If the service relies on session authentication only, the manipulated transaction t’ is authenticated by the cookie sent by the browser and thus confirmed immediately. However, the service might require confirmation by a second factor for transaction t’ such as an OTP (3). In this case, the malware prompts the user to confirm the original transaction t (4). As the user cannot detect the manipulation, she supplies the required OTP (5). The attacker can use the OTP to confirm the manipulated transaction t’ (6). This attack applies to other authentication schemes such as FIDO2 as well. Transaction manipulation has been used extensively in the wild by online banking malware such as ZeuS and SpyEye [4]. Note that RBA does not prevent this attack, as the transaction is initiated in a valid session of the user.

2) Transaction Initiation: Authentication schemes that incorporate an additional device for transaction verification are often susceptible to a transaction initiation attack as depicted in Figure 2. We assume that the attacker compromised the additional device and installed malware. In a next step, the attacker needs to determine the user’s password using one of the methods from Sections III-A and III-B. Potentially, the password is even stored on the additional device and thus accessible to the attacker. With the password, the attacker logs in to the service from his own device using the victim’s account (1). The service might require confirmation of the login attempt on the additional device, e.g., because the service implements RBA and detected a change in the user profile. Usually, confirmation of the login attempt relies on text messages, email or an app [26]. However, since the attacker remotely controls the additional device, he can confirm the login request (3) [13]. After logging in successfully, the attacker can initiate an arbitrary transaction t (4). The service might require confirmation of the transaction (5), however, again the attacker controlling the additional device can confirm the request (6).

D. Our Attack Model
We identify the following three main means of attack on web authentication schemes:

- Password attacks
- Real-time Phishing
- Malware

Malware attacks are more powerful than real-time phishing and password attacks. Password attacks give access to passwords only. In addition, real-time phishing grants access to other credentials entered by the user such as an OTP. The strongest type of attack is compromising a device and infecting it with malware. This grants full access to input and output interfaces of a device such as the keyboard and display, as well as credentials stored on the device. Thus, malware on a device might eavesdrop on credentials entered by the user, as well as manipulate information displayed on the screen.

We assume malware to be executed with the highest user privileges available such as root or administrator and thus malware might manipulate the operating system. This assumption is supported by prior work that documents the use of privilege escalation attacks in the wild [12]. Furthermore, a similar model for malware has been used in prior work [8], [13].

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B. Real-Time Phishing
In 2018, Amnesty International reported targeted phishing attacks on Google and Yahoo accounts that bypassed one-time password (OTP)-based two-factor authentication [5]. By automating the process of using the stolen password and OTP, the attackers were able to work around the short validity of the token. Despite being more complex than classic phishing attacks that only harvest passwords for later use, real-time phishing attacks are not sophisticated. Several tools are publicly available to automate this attack [21], [22]. In addition, real-time phishing attacks can be used to identify features of the user necessary to bypass RBA [20].

C. Malware
As described in prior work, multiple ways exist to remotely infect devices with malware ranging from drive-by downloads and email attachments to social engineering attacks that convince a user to install malware herself [23], [24]. Google’s Threat Analysis Group even detected the use of a zero-day exploit to install malware stealing cookies for popular websites such as Google, Microsoft and LinkedIn [25]. Of course, smartphones are affected by malware too [12]. In the following, we discuss two types of attacks that can be carried out by malware to issue a malicious transaction.

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out. However, we differentiate attackers by their ability to infect involved devices with malware (see Section VIII). Furthermore, we consider that an attacker can carry out multiple attacks targeting the same user. For example, an attacker that infects a smartphone with malware can also mount a password or phishing attack targeting the account of the user.

IV. MALWARE-RESISTANT WEB AUTHENTICATION

As discussed in the last section, a secure web authentication scheme should protect against real-time phishing and malware attacks. In the following, we argue that the concept of transaction authentication is inevitable to protect against malware attacks and that two-factor authentication, as it is currently defined, does not provide security benefits in this attack model.

A. Transaction Authentication

Usually, users sign in into a web service before using it. During this process, the web service authenticates the user and establishes a session. Session authentication means that that once the session is created, the user is allowed to perform an arbitrary number of actions by sending requests to the service. It can be described as authenticating the session and then assuming every action performed as part of the session has been authorized by the user.

On the other hand, using transaction authentication transactions are initiated in an authenticated session, but confirmation of each individual transaction is required (e.g., verification of transaction details by the user on a separate device). Nonetheless, transaction authentication is usually used for security-critical transactions only. For example in online banking, transferring money between a checking and a savings account of the same user could rely on session authentication. Security-critical transactions such as bank transfers to an external account should require transaction authentication. These transactions must be identified for each use case on its own. We provide examples for such transactions in Section VII.

Relying on session authentication only is fundamentally flawed in the presence of malware. Taking control of the session lets an attacker interact with the service on behalf of the user, independently of the used authentication procedure. Thus, strong security guarantees can only be stated for transactions protected by transaction authentication. However, transaction authentication is not sufficient to protect against malware attacks on its own [13]. Combined with other measures proposed below, individual transactions can be protected to make it impossible for an attacker to perform an unsolicited transaction without the user explicitly authenticating it.

B. Flaws in Two-Factor Authentication

The notion of two-factor authentication is too weak in a realistic attack model and does not imply any security guarantees in the presence of a malware or phishing attacker, even for individually authenticated transactions. Intuitively, we expect a two-factor authentication scheme to be secure as long as one of the two factors is not compromised. However, this is satisfied neither by the notion nor by currently deployed schemes in the presence of malware. As described in Section III, malware and real-time phishing attacks are not prevented thoroughly by current two-factor authentication schemes.

Two-factor authentication schemes used in online banking such as the chip authentication program (CAP) protocol and photoTAN provide resistance against malware on the device running the browser. However, the reason for this does not lie in the fact that they fulfill the two-factor authentication definition, but that they require the user to verify transaction details on a separate device. Thus, we need a new way of defining two-factor authentication that fulfills the intuitive promise of the notion: ensuring the security of a scheme even if one of two factors is fully compromised. This redefinition of two-factor authentication makes malware and real-time phishing attacks infeasible and thus solves the weaknesses of current web authentication schemes.

C. One-out-of-two Security for the Web

In their work on secure electronic payment, Achenbach et al. [27] formalize exactly this requirement. The authors model an electronic payment protocol using two separate devices that is still secure (with regards to specific security properties) even if one of the devices is fully compromised. They call this property one-out-of-two security and show that it can be fulfilled by requiring the user to verify the transaction details on both devices. We adapt this idea of one-out-of-two security to web authentication by letting the user verify details of individual transactions on two separate devices.

The authors rely on a so-called confirmation channel to build a scheme that fulfills one-out-of-two security. The transaction details are displayed to the user (e.g., on an additional device) and explicit confirmation is required before performing the transaction. We reuse the idea of a confirmation channel in the design of our web authentication scheme. However, whereas Achenbach et al. explicitly allow an attacker to break their protocol by guessing the Personal Identification Number (PIN) correctly, we use a slightly stronger version of one-out-of-two security. Our notion also prevents attacks that circumvent compromising a device by breaking an underlying authentication scheme such as passwords. According to our definition, a protocol that uses two separate devices exhibits one-out-of-two security, if an attacker who has the capabilities defined in our attack model in Section III is not able to issue a fraudulent transaction without compromising both devices.

Note that the goal of the security property is authenticity of transactions and not confidentiality of the transaction details. To be able to confirm the authenticity of a transaction on two devices, the user must either see or enter the details on each device separately. In either case, both devices will need to handle the transaction details in plain text. Thus, compromising one device is enough to violate the confidentiality of transaction details. As described in Section VII, by limiting access to actions that return or change data on the service, the authenticity guarantee of transactions can be used to achieve integrity and confidentiality of data stored on the server.
D. Blueprint for Secure Web Authentication

Constructing a web authentication scheme that fulfills one-out-of-two security and is thus only vulnerable to attackers that are able to compromise both devices is not an easy task. As we will show in Section VIII, commonly used schemes do not have this property.

We propose Two Display Authentication (2DA), a blueprint for secure web authentication. Following the blueprint simplifies constructing schemes that fulfill one-out-of-two security. We identify the following requirements for 2DA.

(2DA.1) Authenticate each security-critical transaction individually.

(2DA.2) Require verification of transaction details by the user on both devices.

(2DA.3) Use mechanisms for client and server authentication that protect against non-malware attacks.

(2DA.4) Use local authentication mechanisms to limit access to the devices.

The first requirement addresses that the security guarantees can only be stated for transactions that are authenticated individually. The second requirement is necessary to thwart attacks that involve one of the two devices being compromised. Entering the transaction details on a device instead of reading them from the display is also possible. Furthermore, the third requirement relates to the communication between the devices and the server. It ensures that an attacker is not able to authenticate to the service without compromising a device. For example, using a password for login, compromise of the primary device is not necessary to attack the scheme. Password and phishing attacks are sufficient to bypass authentication of the primary device. Thus, one-out-of-two security cannot be fulfilled by relying on password authentication for one of the devices. Finally, the fourth requirement protects devices in case they are stolen. Even though this is not strictly necessary to fulfill one-out-of-two security, we consider it important as it prevents physical attackers from compromising or abusing stolen devices.

Note that a secure transaction authentication scheme does not protect a user from authenticating an unintended transaction if the original transaction data was manipulated in the first place. Thus, it is of utmost importance that the transaction data is either self-explanatory or the user has the ability to compare the transaction data with a known safe value. For example, attacks on online banking have been described that are based on manipulating digital invoices [28]. If the original transaction details are only available on one device, then no scheme can offer protection when the device is compromised.

The goal of 2DA is to simplify creating web authentication schemes that protect security-critical transactions by relying on one-out-of-two security. In the following section, we show that building on existing web authentication mechanisms such as FIDO2, we can use this new paradigm to design an authentication scheme that is secure, even in the presence of malware and real-time phishing attacks.

V. Two Display Authentication Using FIDO2

We use our blueprint 2DA from the last section to design FIDO2 With Two Displays (FIDO2D), a new scheme for web authentication that fulfills one-out-of-two security, i.e., the scheme is secure as long as one of the two devices is not compromised. We refer to Section VI for a detailed security proof. On a high level, a user U aims to initiate a transaction at a server S using a computer B running a browser. The user also holds an additional device A, such as a smartphone.

We assume that (2DA.4) is already satisfied by existing mechanisms that restrict the access to B and A. Following (2DA.3), we build on top of an existing authentication mechanism with appropriate security, and following (2DA.2) we use two instances of this mechanism. That is, one instance is executed between B and S, and one instance is executed between A and S. Again, following (2DA.2) we let the user verify the transaction details during both instances. To be more precise, we organize both instances in a way that the user enters the transaction details in the browser on B and require verification of the transaction data by the user on A using a confirmation channel. In the following, we introduce the underlying authentication scheme FIDO2, and then describe the protocol for registration and authentication in its entirety.

A. FIDO2

We use FIDO2 as the underlying authentication mechanism. That is, our protocol consists of two instances of FIDO2. FIDO2 is an interactive public-key challenge-response authentication protocol published by the Fast IDentity Online (FIDO) Alliance. It is used on top of TLS. Both registration and authentication consist of a three-message flow between client and server. The first message from client to server initiates the interaction. The second message is sent from server to client and contains a randomly sampled challenge. Finally, the client sends a signature of this challenge and some additional data to the server.

More precisely, the client does not do all the computation itself, but rather forwards messages to a so-called authenticator, which contains all key material and performs cryptographic operations. FIDO2 differentiates platform authenticators that are integrated into devices and roaming authenticators that can be connected via transports such as USB. For our further description, we focus on the FIDO client, because most authenticators do not contain a display to show transaction data themselves that is crucial for verification by U.

There are mainly two reasons for our choice of FIDO2. First, it is supported as an API by all modern browsers on the client side and libraries for various programming languages on the server side. This makes our protocol easy to implement and integrate. Second, it offers the security we need for (2DA.3) as well as the user verification we need for (2DA.4). Intuitively, FIDO2 is resilient to replay and phishing attacks because both a random challenge as well as the identifier of S, typically a domain name, is signed. Next, we describe our protocol FIDO2D in its entirety to show how the two instances of FIDO2 work together.
B. Registration

First, the user registers B using the standard FIDO2 registration ceremony. During registration, S stores the public key pubB from B. Then, S provides a nonce to B to link the second device A to the account. The nonce is transferred from B to A using a QR code. Again, we use the FIDO2 registration ceremony to store the public key pubA from A on S.

In more detail, the registration process is depicted in Figure 3. The server responds to a user registration request with a set of options opt, containing a random challenge, the identifier of the server and the new user, as well as further parameters for the creation of credentials. First, the authenticator of B creates a new credential and sends the public key pubB back to S. During this process, the user is asked to confirm registration. Next, the server S randomly generates a nonce n, links it to the username, and sends it to B. Then, n is transferred from B to A (e.g., using a QR code). Again, the user is asked to confirm the registration on the device A. Then, A can initiate a similar FIDO2 registration ceremony, allowing S to link both ceremonies using n.

As a result of the registration, S is aware of public keys pubA, pubB linked to user U. The devices A and B know the secret keys sA, sB for the public keys pubA, pubB, respectively.

C. Transactions

The message flow during a transaction is shown in Figure 4. Recall that a user U wants to issue a transaction with data d at a server S. First, U uses B to transfer the intended transaction data d in combination with the username to S. S sends a set of options opt, containing a random challenge ch, and expecting a signature of ch for the public key pubB as a result. Again, the user has to confirm before the challenge is signed by B and the signature is sent to S. To be more precise, the signature is computed over the challenge, an identifier of S, extension data, and the authenticator’s signature counter, which is used for clone detection. This follows the FIDO2 standard. In Figure 4 this is simply presented as Sig(sB, authch) while authch contains the aforementioned data. After receiving the signed challenge from B, the transaction is not yet fully authenticated. The server S requires a signature from A too. After transmitting d to A, the same FIDO2 protocol is performed between A and S. Note that for this protocol a fresh challenge ch′ and the public key pubA is used. S links both challenges ch and ch′ to the transaction data d. We use the Simple Transaction Authorization Extension (txAuthSimple) of FIDO2 with data d for A. This extension ensures that A receives the transaction data d in combination with the challenge ch′ as part of options opt′, and presents it to the user. After U’s confirmation, A not only signs ch′, but also d. This allows to bind the challenge ch′ to the transaction data d, which is important when the data is transmitted over an insecure channel. As we propose to use TLS, transferring d separately and not signing it would suffice in our attack model. However, using txAuthSimple allows adapting the protocol to devices that are not connected to the Internet directly and thus require another device to relay the messages to them. Again, there is additional data that is signed as in authch, and we denote this as authch′,d in our diagram. S only accepts the transaction with data d when both authentication ceremonies are successful and A signed the correct transaction data d.

D. Prototypical Implementation

To verify the feasibility of our approach, we implemented a prototype of FIDO2D consisting of a server component for S and an Android app running on A. On the server, we use a Go library for FIDO2 by Duo-Labs. We had to add support for the txAuthSimple extension. More specifically, the server

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1https://github.com/duo-labs/webauthn
has to check that the authenticator signed the extension data containing the transaction details and that they have not been tampered with. For our app, we use an Android library by Duo-Labs\(^2\) to create credentials and sign supplied challenges. Again, we added support for the txAuthSimple extension, which mainly required signing the extension data. On device B, we use the Web Authentication (WebAuthn) browser API which is part of the FIDO2 standard and is supported by all modern browsers.

Following the principle (2DA.4) we limit access to the devices by a local authentication mechanism such as a lock screen. On A we force the use of a lock screen by enabling the option setUnlockedDeviceRequired of the Android Keystore\(^3\). This ensures that the private key can only be used if the device is unlocked. Access to the private key can be further restricted by requiring to push a physical button or displaying transaction data on a protected screen [29]. However, these mechanisms might affect usability negatively and are not necessary to fulfill one-out-of-two security. We assume that device B has a lock screen set up too. Furthermore, we enable the requireUserVerification parameter in the WebAuthn API and require the User Verified flag to be set in the signed authenticator data. This ensures that roaming authenticators that are prone to theft cannot be used without authentication e.g., using a PIN.

Figure 5 shows the user interface of the registration process. On B the browser shows a pop-up asking the user to confirm registration with FIDO2. Afterwards, the user links the app on A to the account by scanning a QR code from the browser. In the background, the app establishes a connection to the server and initiates a FIDO2 registration ceremony as well. Figure 6 shows the transaction confirmation screen of our app. In this example, the user initiated a new post on a fictitious micro-blogging service. The app displays all relevant information including the username and identifier of the service.

Even though the Client to Authenticator Protocol (CTAP) protocol is designed to relay data to an authenticator, we decided against using it for our App. CTAP requires the user to connect the smartphone to the computer during authentication [30]. However, Bluetooth and NFC are not available on all platforms and USB requires a wired connection. Furthermore, current browsers do not forward unsupported extensions and thus txAuthSimple could not be used [31]. Thus, we suggest using push messages and TLS for the communication of A and S. In our implementation, we use the push service Firebase Cloud Messaging\(^4\). However, we do not transmit any data in the push message, but request the app to establish a TLS connection to the server and retrieve data from there. Integration of a push-based transport into CTAP would be desirable, as it would allow FIDO2D to rely on standard FIDO2 only. Recently, attempts to integrate such a mechanism into CTAP [32] have been made, however, they are not yet included in the standardized protocol. We hope that our work strengthens these developments. Furthermore, our prototypical app could be superseded by integrated support for FIDO2 in mobile operating systems. This requires that the smartphone can be used as a roaming authenticator on another device and that it supports the txAuthSimple extension such that transaction data can be verified. Sadly, the extension txAuthSimple has been removed in the second level of the WebAuthn API [15].

Although we do not consider recovery in our implementation, promising methods for recovery of FIDO2 authenticators have been proposed that do not sacrifice security by incorporating a backup authenticator [33].

**VI. Security Proof**

We formally prove the security property one-out-of-two-security (see Section IV-C) of our protocol FIDO2D with the help of Tamarin Prover (Tamarin) [34]. Our lemma definitions, which from Tamarin’s point of view constitute the protocol’s security properties, are inspired by [8]. We also analyze the

\(^2\)https://github.com/duo-labs/android-webauthn-authenticator

\(^3\)https://developer.android.com/reference/android/security/keystore/KeyGen ParameterSpec.Builder

\(^4\)https://firebase.google.com
effect of users not verifying transaction data on the security of FIDO2D. While our scheme does not fulfill one-out-of-two-security in this scenario, we prove that it still protects against most types of attacks including phishing and malware on the additional device.

In the following, we give a brief introduction to Tamarin and then describe how we modeled our protocol as well as the security property.

A. A Short Introduction to Tamarin

By modeling a protocol in its custom modeling language, Tamarin performs unbounded verification of given security properties (called lemmas) for the protocol in the symbolic model. Within the custom modeling language, individual protocol steps are expressed as multi-set rewrite rules. These rules describe world state changes during execution flow of a protocol. This world state is tracked by Tamarin in the form of a set of facts. A fact is an atom, optionally associated with data such as key material, nonces, identities or constants. A rule can query facts as well as add new facts to the state.

Application of a rule can be subject to the existence of a fact within the state. Such a fact is called an in-fact. Similarly, facts that a rule adds to the global state, as a result of its application, are called out-facts. Chaining of two rules first, and second is achieved by matching first’s out-facts with the in-facts of second (see Figure 7). Additionally, facts may contain data, such as cryptographic key material, constants and nonces.

Within Tamarin’s input language, interaction with the attacker is modeled by special in- and out-facts, which we briefly explain in the following:

• Fr(~var) is an in-fact that instantiates a variable binding that represents a perfect randomly chosen value. These values can (among others) be used to model generation of nonces and cryptographic key material.
• In(var) is an in-fact that reads a value from the network.
• Out(var) is an out-fact that writes the contents of its argument to the network.

These facts can be employed arbitrarily by the protocol’s rules, are not captured in the global state and as such do not need to have a corresponding counterpart embodied in the global state already.

Facts within the global state as well as facts that are written on the trace, including their respective data captures, are not known to the attacker. Instead, the attacker’s knowledge is specifically extended by writing data to the attacker-controlled network. This mechanism can be used to leak any kind of data such as key material, identities, nonces as well as a protocol’s message flow.

A protocol declaration in Tamarin usually contains at least one rule with an empty set of in-facts. This rule can be instantiated on the state that only contains facts that are populated by Tamarin at the start of a program verification session.

B. Our Tamarin Model for FIDO2D

Our model consists of 13 rules and two lemma definitions. We refer to Appendix A for a complete definition of each rule, including an enumeration of facts that are produced and consumed by it. Each rule’s purpose is briefly explained below:

• new_server: registers a new honest server as a global fact. Honest servers cannot be used in phishing attacks.
• register_first_device: Registers a new account at a server and connects a user’s first device with it. The device is identified by a public key generated for the particular account. Account and device identities are then leaked to the attacker.
• register_second_device: Finishes registration of a user’s account by connecting a second device with it. This step also leaks the public key registered by the second device to the attacker.
• init_transaction: A user commences a transaction at a server for which there already exists a personal account with two registered devices. After sending the transaction with its accompanying data to the network, it waits for a nonce from the server.
• receive_transaction: An honest server receives a transaction from a previously registered user. It generates a nonce and sends this back to the user.
• phish_transaction: A user initiates a transaction on a phishing server.
• receive_transaction_phisher: A phishing server receives a transaction of a previously phished user.
• sign_nonce: A user signs a nonce on her first device for a transaction that has also been started by her.
• verify_signature: A server verifies the signature of a previously issued nonce of a user’s first device. It then generates a second nonce, which is sent to the user’s second device.
• sign_second_nonce: A user’s second device receives a transaction request. After the user verified that the displayed transaction data corresponds to the transaction she previously initiated, her second device signs the second nonce. The signed nonce is sent back to the server.
• verify_second_signature: A user’s second signature is verified on the server. If verification succeeds the transaction is completed, i.e., the server executes the user requested transaction internally.
• compromise_first_device: A user’s primary device is compromised. We model this by leaking the device’s private key to the adversary.

\[ \text{rule \ first:} \]
\[
\begin{align*}
\text{[ ]} \\
\rightarrow\text{[ ]} \rightarrow \\
\text{[ NowSecond ( )]}
\end{align*}
\]

\[ \text{rule \ second:} \]
\[
\begin{align*}
\text{[ NowSecond ( )]} \\
\rightarrow\text{[ ]} \rightarrow \\
\text{[ NowThird ( )]}
\end{align*}
\]

Fig. 7. Example of chaining two Tamarin rules.
• compromise_second_device: A user’s additional device is compromised. We model this by leaking the device’s private key to the adversary.

An example trace containing a transaction accepted by a server can be obtained by instantiating the rules in the order given in Figure 8, excluding rules that model phishing or compromise of devices. In our model, there are two rules that do not require custom facts to be present within the global state, namely new_server and register_first_device. Consequently, these two rules can be instantiated regardless of the current world state within Tamarin. In this example, protocol instantiation starts with registration of an honest server (omitted for clarity in Figure 8), registration of a user’s devices at this server, initialization of a transaction and verification of a transaction by the server. These rules correspond to three distinct categories: registration, transaction initialization and transaction verification. In order to model phishing attacks, which is a transaction that is started on a malicious server, transaction initialization contains two more rules, init_transaction_phisher and receive_transaction_phisher.

C. How Our Model Captures Reality

Tamarin builds on the Dolev-Yao [35] attack model. In this model, the attacker obtains knowledge of every message sent over the network. He is also able to modify message contents, suppress and inject messages as well as re-send known messages at any time in protocol execution. However, the model assumes that the attacker is not able to break cryptographic schemes without knowing the key.

Although we expect typical implementations of FIDO2D to be embedded within already bootstrapped Transport Layer Security (TLS) sessions, our Tamarin model relies on unilateral authentic channels only. Specifically, we require the communication channels from the server to the user’s devices to be authentic. We use the rules suggested in the Tamarin manual to model the authentic channel [36]. As a result, the actual payload of a transaction is always assumed to be transmitted in the clear over an attacker-controlled network. These simplifications allow us to present a more concise model in contrast to a model in which FIDO2 and TLS have also been realized. Furthermore, this highlights again that we assume a strong attack model. In a real-world implementation of FIDO2D, confidentiality is guaranteed by performing transactions within the context of a TLS session.

FIDO2D relies on FIDO2 and thus we also model a simplified version of the FIDO2 protocol. We use the built-in signing model of Tamarin that provides the necessary functions of a signature scheme. To model drawing a fresh nonce as challenge, we use the built-in fact Fr(~nonce). We simplified the signed authenticator data to include the server identity and nonce only. Thus in our model, the signature generation can be described as sign(<S, nonce>, privkey). In our implementation, the second device signs the transaction details by usage of the FIDO2 txAuthSimple extension. Therefore, our model assumes that the authenticator data also contains the transaction data for the second device. This is expressed by the term sign(<S, d, nonce>, privkey).

During registration, the registered public keys are written to the attacker-controlled network. We thereby model that authentication information stored on a server can be leaked by
Fig. 9. A FIDO2D security property which states that only honest (i.e., user initiated) transactions are accepted by a server, captured as a Tamarin lemma. In conjunction with replay_attack_impossible, this lemma constitutes one-out-of-two-security.

D. Proving One-out-of-two Security

This model is verified by Tamarin against two lemmas, only-user-initiated-transactions-accepted and replay-attacks-impossible. Together they form our protocol’s notion of one-out-of-two-security. The lemmas are inspired by the Tamarin proof of SecurePay [8]. We give the definition of the first lemma in Figure 9. For brevity, we omit the second lemma and refer to Appendix A for the complete definition. Informally the first lemma states that every transaction that is accepted by a server has been initiated by an honest user and has not been tampered with. Additionally, the second lemma is necessary to prevent replay attacks. It ensures that each accepted transaction corresponds to exactly one transaction initiated by an honest user. Furthermore, both lemmas contain an additional clause. The additional clause ensures that the lemma is also satisfied if both of the user’s devices have been compromised. In this case, the protocol cannot provide any security guarantees.

For simplicity, the lemmas do not impose any temporal order on the sequence of actions on the trace. Thereby, the lemmas are more general but consider traces with specific temporal order as well. For example, the point of time at which the start of a transaction is recorded should be before the corresponding completion of said transaction.

By using the Tamarin theorem prover, we verified that our protocol satisfies both lemmas only-user-initiated-transactions-accepted and replay-attacks-impossible and thus exhibits one-out-of-two security. We sketch why the scheme intuitively fulfills one-out-of-two security and adheres to these lemmas. Assume a user’s first device is compromised and her second device is benign. Then, the attacker is able to issue fraudulent transactions or manipulate benign transactions. During protocol execution the user is asked to confirm the transaction data $d$ on her second device although she did not initiate a transaction at all or initiated a transaction with data $d \neq d$. Clearly, the user will not confirm this transaction and thus the server will not execute the transaction. On the other hand, assume her second device is compromised and her first device is benign. In this case, the attacker cannot initiate a transaction himself. If the user initiates a transaction, the attacker is not able to manipulate the transaction data because the server links the challenge sent to the user’s second device to the transaction data entered on the corresponding first device beforehand. Thus, the attacker can only complete a fraudulent transaction by compromising both devices.

E. Comparing Transaction Data

Our model expects the user to verify transaction data properly. User studies suggest that this is not always the case [37]. Similar to prior work, we extend our model to consider users that do not verify transaction data at all [38]. In our model, it is sufficient to remove parameters from the fact UserWaitForConfirmation. Thereby, the user only confirms a transaction after she initiated one but does not compare the transaction data. Under this assumption, our protocol does not satisfy one-out-of-two-security. An attacker can break the scheme by compromising the first device to manipulate a transaction initiated by the user. Then, the user confirms the manipulated transaction on the second device because she does not verify the transaction data. However, by removing the rule compromise_first_device we can prove that our protocol resists an attacker that compromises the additional device and carries out password and phishing attacks even if the user does not verify the transaction details at all. Thus, FIDO2D provides strong security guarantees and even provides one-out-of-two-security if the user verifies transaction data.
VII. ON WHEN TO USE FIDO2D

FIDO2D can improve security in several scenarios. Before we describe possible use cases, we present general guidelines and requirements.

A. Guidelines and Requirements

To adopt FIDO2D, the first step is to identify security-critical actions that should be protected from malware attacks. Our scheme can be used to achieve two separate security goals. First, the confidentiality of data stored on the server can be protected by requiring the user to confirm requests for said data. However, once the user approves a request, the data is shown on the primary device and might be eavesdropped by malware. Nonetheless, malware on a single device cannot get access to data protected by transactions without the user requesting or confirming it. Furthermore, transactions can protect the integrity of data stored on the server or activities triggered by the server. For example, money transfers are often protected by transactions as they change the account balance stored on the server. Actions have to be chosen carefully, as requiring transaction authentication for many actions can easily cause authentication fatigue, drastically reducing security benefits.

For the security of FIDO2D, it is important that transaction details contain all necessary information about the transaction, so that the user can verify them. As FIDO2D might be used for multiple accounts and services, the transaction details should always include the domain name of the service and the account name. Furthermore, the length of the transaction details should also be considered when identifying suitable actions.

Services can still provide a login mechanism and offer to initiate a transaction from the authenticated session. However, security-critical actions chosen by the provider must be verified by the user on the additional device. Of course, not all users want to confirm messages individually. Thus, the use of FIDO2D should be configurable. However, disabling FIDO2D for an account must also require verification with FIDO2D. Otherwise, FIDO2D can be bypassed trivially.

To be able to use FIDO2D, users need a smartphone and a computer that supports FIDO2D either with an integrated platform authenticator or with a roaming authenticator. Windows 10 provides a FIDO2 platform authenticator out-of-the-box. Hence, many users only need to install an app on their smartphone. Our app can be used for multiple web applications that implement our protocol. While platform authenticators are bound to a specific device, a roaming authenticator might also be used to access an account from multiple devices.

B. Use Cases

FIDO2D is suited best for scenarios with security-conscious users as it unfolds its full potential when users verify transaction data properly. We introduce four use cases where FIDO2D can protect users against malware attacks.

1) Online Banking: Of course, FIDO2D can be used in online banking scenarios. For example, transactions can be used to protect the integrity of money transfers and settings such as transfer limits. For money transfers, the transaction details should include the recipient and the amount. Changing limits, should include the new value of the limit. These types of transactions can be verified on a smartphone properly.

Even though transaction authentication is already used in online banking, applying FIDO2D yields the following advantages. First, it encourages the user to initiate and confirm transactions on separate devices. And second, it replaces the use of passwords to access the online banking system.

2) Electronic health record: In electronic health records, FIDO2D can be used to protect the confidentiality of stored health information. Sensitive information would only be accessible for a patient after confirmation on the smartphone. The transaction data should indicate which data was requested. Such requests can be verified on a smartphone properly.

3) Microblogging: In a microblogging service, the integrity of posted messages can be protected using FIDO2D. In this scenario, publishing a message might have a huge impact depending on the author. Messages of influential people such as the former president of the United States have been associated with stock market activity but might also influence international affairs. As messages in a microblogging service are short (e.g., 280 characters on Twitter), they are suitable for verification on a second device. The transaction details should include the name of the account as well as the full message content.

4) Administration Panels: Management panels such as Plesk allow users to carry out administrative tasks on remote servers. For example, DNS settings for registered domains can be configured. Manipulating the DNS settings of a domain allows to eavesdrop and manipulate all traffic destined to the domain. Thus, protecting integrity of the DNS settings using FIDO2D is beneficial. The transaction details should include the domain name, the record type and the value. Since this information is short, it is suitable for verification on a smartphone.

VIII. RELATED WORK

We consider three types of related work: formal frameworks to prove security properties of cryptographic protocols, security models and work that introduces web authentication schemes. Finally, we compare the security of existing web authentication schemes with FIDO2D.

A. Proof Frameworks

Defining and proving the security of a protocol within a formal model is an important step during the development of new security protocols. To this end, various frameworks and models have been proposed in the past. The Universal Composability (UC) Framework [41] for example is widely used by the cryptographic community and is considered to be

3https://fidoalliance.org/microsoft-achieves-fido2-certification-for-windo
4https://www.plesk.com/
the most popular and most expressive framework. It is best suited for modeling basic cryptographic primitives and simple protocols; however, modeling protocols is a manual task and there is no support for automated proof checking. Lots of technical artifacts (like its reliance on Turing Machines for modeling protocol participants) therefore make modeling complex protocols error-prone and lead to complex security proofs which even humans sometimes cannot verify completely.

In contrast, the Tamarin modeling framework allows verification of models in an automated fashion [34]. Tamarin-models consist of multi-set rewrite rules as well as lemmas, defining protocols and security properties respectively. These constructs are expressed in a domain specific language. Protocols and their security properties are verified in the symbolic model. A proof of correctness can then be obtained by executing the Tamarin theorem prover. A curated list of Tamarin-proofs for various protocols can be found on the Tamarin website\(^1\). For instance, Tamarin has been used to verify all claimed security properties of a draft specification of TLS 1.3 [42].

### B. Security Models

To remedy the issue of a single point of failure within a trusted device, Achenbach et al. [27] put forth the notion of “one-out-of-two security”. They provide a model for the security of electronic payment protocols based on the UC framework. Furthermore, they introduce a protocol for cash withdrawal at an ATM with an additional device such as a smartphone, and prove that it fulfills one-out-of-two security. Thus, the protocol is secure as long as one device is not compromised. While their protocol and model are specifically tailored to electronic payments and cannot be directly applied to web authentication, our work is inspired by theirs.

Jacomme et al. introduce a formal model for multi-factor authentication in the applied pi calculus [7]. They analyze the Universal Second Factor (U2F) protocol, a predecessor of FIDO2 and Google 2-step authentication. Their threat model includes phishing and malware attacks, as well as fingerprint spoofing to bypass RBA. Using ProVerif they identify several weaknesses of the analyzed protocols. Google 2-step is susceptible to phishing attacks that include fingerprint spoofing and U2F to malware controlling an attached authenticator. They propose that these protocols should incorporate verification of transaction data, which is exactly what FIDO2D provides.

Bonneau et al. [43] compare schemes proposed to replace passwords for web authentication regarding usability, deployability, and security. They consider a wide range of schemes such as password managers, federated schemes, OTPs, and hardware tokens. The security of a scheme is assessed based on the resilience to different kinds of attacks. However, phishing and malware attacks are not considered to their full extent. For example, malware is only assumed to steal credentials passively but not to manipulate the browser. Furthermore, real-time phishing attacks are excluded explicitly.

### C. Web Authentication

FIDO2 is a standard for web authentication published by the FIDO Alliance. It consists of a widely implemented browser API called WebAuthn [15]. This API simplifies integration of strong authentication mechanisms in web applications. The underlying challenge-response protocol relies on public-key cryptography. Even though the protocol is resistant to real-time phishing, it does not prevent malware attacks [7].

This also applies to Google’s Advanced Protection program [47]. It restricts login attempts to FIDO tokens; however, they can still be abused by malware. Other proprietary solutions such as Duo Push and Akamai MFA confirm login attempts using push messages [48], [49]. However, they do not authenticate transactions individually and are thus susceptible to malware using session hijacking or transaction manipulation (see Section III).

The CAP protocol is a transaction authentication scheme used in online banking [44]. A dedicated card reader is used to allow the user to verify transaction details. Even though the CAP protocol is resilient to malware on the primary device, it does not exhibit one-out-of-two security. In the unlikely event that the card reader is compromised, the scheme can be attacked by using phishing to initiate a malicious transaction (see Section III). Nonetheless, it provides a high level of security as compromise of the card reader is less likely than of a smartphone. However, the protocol is of proprietary nature and requires the user to carry an additional device, which has been shown to hinder adoption significantly [10].

Recent attempts to improve authentication schemes focus on banning weak schemes but do not reason about security properties and requirements systematically, e.g., the European Commission issued the revised Payment Services Directive (PSD2), a regulation requiring strong customer authentication for online banking [14]. PSD2 suggests that users have to be made aware of the transaction details, but does not prevent malware attacks, as it allows operating both factors on one device [13]. NIST introduced security levels for authentication called Authenticator Assurance Level (AAL) [50], but does not systematically consider what needs to be authenticated. Thus, these regulations do not solve the problems of two-factor authentication schemes.

Mannan and van Oorschot [45] introduce Mobile Password Authentication (MP-Auth). The scheme is based on a trusted smartphone that stores cryptographic keys. By incorporating public-key cryptography, the protocol achieves phishing-resistance. The authors use transaction authentication to thwart malware attacks, yet MP-Auth is only secure if the smartphone is not compromised. Because smartphones are multi-purpose devices that are connected to the Internet, they are susceptible to malware as well. Similarly, Chow et al. introduce a scheme that relies on a trusted smartphone [46]. The smartphone is used as a OTP generator that displays the transaction data and requires confirmation by the user.

Konoth et al. propose a solution to secure two-factor authentication when both factors are operated on a single

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\(^1\)https://tamarin-prover.github.io/
To protect security-critical web transactions against attacks with malware, current web authentication schemes do not offer this protection. Consequently, we showed how to protect security-critical web transactions against attacks with malware. Current web authentication schemes do not offer this protection.

We identified requirements for such authentication schemes, namely one-out-of-two security and transaction authentication. Web authentication schemes that fulfill these requirements protect security-critical transactions against malware attacks as long as one device is not compromised.

We introduced 2DA, a generic blueprint for designing web authentication schemes that fulfill one-out-of-two security. Based on this blueprint, we designed and implemented a new web authentication scheme called FIDO2D, which is applicable to a wide range of use-cases. We proved the security of FIDO2D using Tamarin.

By relying on protocols and APIs of the FIDO2 standard, FIDO2D can be integrated into web applications easily. We demonstrated this by creating a prototypical implementation.

Lastly, we urge the FIDO Alliance to fully embrace one-out-of-two security and transaction authentication as a design paradigm for secure web authentication in future versions of their standard.
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APPENDIX
TAMARIN MODEL FOR FIDO2D

Our Tamarin model including the security lemmas can be found below. For brevity, we omitted sanity lemmas, as well as the variations of the model for users that do not compare transaction data. However, the full Tamarin model is available online.

theory fido2d
begin

  builtins : signing

  rule new_server:
  [ ]
  --> [ HonestServer(SS) ] ->
  [ !Honest(SS) ]

  rule register_first_device:
  [ Fr(~privkey) ]
  --> [ ] ->
  [ !Ltk_Dev1(SI, SS, ~privkey),
    !Pk_Dev1(SI, SS, pk(~privkey)),
    RegisteredPartially(SI, SS),
    Out(<SI, pk(~privkey)>)
  ]

  rule register_second_device:
  [ Fr(~privkey),
    RegisteredPartially(I, S)
  ]
  --> [ AccountRegistered(I, S) ] ->
  [ !Ltk_Dev2(I, S, ~privkey),
    !Pk_Dev2(I, S, pk(~privkey)),
    !Registered(I, S),
    Out(<I, pk(~privkey)>)
  ]

  rule init_transaction:
  [ !Registered(I, S),
    !Honest(S)
  ]
  --> [ TransactionBegin(I, S, $d) ] ->
  [ UserWaitForConfirmation(I, S, $d),
    Dev1WaitForNonce(I, S, $d),
    Out(<I, S, $d>)
  ]

  rule receive_transaction:
  [ !Registered(I, S),
    !Honest(S),
    In(<I, S, d>),
    Fr(~nonce)
  ]
  --> [ TransactionReceived(I, S, d) ] ->
  [ ServerWaitForSignature(I, S, d, ~nonce),
    Out_A(S, I, <I, d, ~nonce>)
  ]

  rule phish_transaction:

https://tinyurl.com/2022-fido2d-tamarin
[Registro(I, S),
In(P)]
−−[TransactionBegin(I, S, P), Phisher(P)]
[UserWaitForConfirmation(I, S, P),
Dev1WaitForNonce(I, P, P),
Phished(I, S, P)]

rule receive_transaction_phisher:
[In(<d, nonce>),
Phished(I, S, P)]
−−[ ]
[Out_A(P, I, <I, d, nonce>)]

rule sign_nonce:
[Dev1WaitForNonce(I, S, d),
In_A(S, I, <I, d, nonce>),
\!Ltk_Dev1(I, S, privkey)]
−−[NonceSigned(I, S, nonce)]
[Out(sign(<S, nonce>, privkey))]

rule verify_signature:
[In(signature),
ServerWaitForSignature(I, S, d, nonce),
\!Pk_Dev1(I, S, pubkey),
Fr(~nonce2)]
−−[Eq(verify(signature, <S, nonce>, pubkey), true), SignatureVerifiedDev1(I, S, d)]
[ServerWaitForSecondSignature(I, S, d, nonce2),
Out_A(S, I, <S, I, d, nonce2>)]

rule sign_second_nonce:
[UserWaitForConfirmation(I, S, d),
In_A(S, I, <S, I, d, nonce>),
\!Ltk_Dev2(I, S, privkey)]
−−[DisplayData(I, S, d), NonceSigned(I, S, nonce)]
[Out(sign(<S, d, nonce>, privkey))]

rule verify_second_signature:
[In(signature),
ServerWaitForSecondSignature(I, S, d, nonce),
\!Pk_Dev2(I, S, pubkey)]
−−[Eq(verify(signature, <S, d, nonce>, pubkey), true), TransactionComplete(I, S, d)]
[ ]

rule compromise_first_device:
rule compromise_second_device:
[ !Ltk_Dev2(I, S, privkey) ]
  --> [ CompromiseDev2(I, S) ] =>
[ Out(privkey) ]

// Authentic Channel Rules from Tamarin Manual

rule ChanOut_A:
[ Out_A(A, B, x) ]
  --> [ ChanOut_A(A, B, x) ] =>
[ !Auth(A, x),
  Out(<A, B, x>) ]

rule ChanIn_A:
[ !Auth(A, x),
  In(B) ]
  --> [ ChanIn_A(A, B, x) ] =>
[ In_A(A, B, x) ]

restriction Equality:
"All x y #i. Eq(x,y) @i => x = y"

restriction HonestServersDontPhish:
"All server #i #j. HonestServer(server) @i & Phisher(server) @j => F"

// This restriction is not required for security but simplifies proofs and counterexamples

restriction UniqueAccounts:
"All acc server #i #j. AccountRegistered(acc, server) @i & AccountRegistered(acc, server) @j => #i = #j"

lemma only_user_initiated_transactions_accepted:
"All initiator transaction server #i. TransactionComplete(initiator, server, transaction) @i => ((Ex #j. TransactionBegin(initiator, server, transaction) @j) | (Ex #k #1. CompromiseDev1(initiator, server) @k & CompromiseDev2(initiator, server) @j))"

lemma replay_attack_impossible:
"All initiator1 transaction1 initiator2 transaction2 server #i #j. TransactionComplete(initiator1, server, transaction1) @i & TransactionComplete(initiator2, server, transaction2) @j & not #i = #j => ((Ex #k #1. TransactionBegin(initiator1, server, transaction1) @k & TransactionBegin(initiator2, server, transaction2) @l & not #k = #1) | (Ex #m #n. CompromiseDev1(initiator1, server) @m & CompromiseDev2(initiator1, server) @n) | (Ex #m #n. CompromiseDev1(initiator2, server) @m & CompromiseDev2(initiator2, server) @n))"