True2F: Backdoor-resistant authentication tokens

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U2F: Effective hardware 2FA
23  Google: Security Keys Neutralized Employee Phishing

Google has not had any of its 85,000+ employees successfully phished on their work-related accounts since early 2017, when it began requiring all employees to use physical Security Keys in place of passwords and one-time codes, the company told KrebsOnSecurity.
U2F protocol steps

1. Registration (associating a token with an account)
2. Authentication (logging into an account)
U2F Step #1: Registration

Associate a token with an account.
U2F Step #2: Authentication

Log into an account.

- From the U2F device:
  - Challenge to "github.com"
  - Signature

- From the browser:
  - Challenge to "github.com"
  - Signature

- To the server:
  - "github.com"
U2F defends against phishing and browser compromise

Even if malware takes over your browser, it can’t authenticate without the token.
… but what about vulnerabilities in the token itself?
... but what about vulnerabilities in the token itself?

1. Implementation bugs
2. Supply-chain tampering
Security threat #1: Implementation bugs in token

[NSS+17]
Security threat #1: Implementation bugs in token

[NSS+17]
Security threat #1: Implementation bugs in token

There is a bug in certain Infineon TPM firmware versions which results in RSA keys generated by the TPM being vulnerable to an attack that allows to recover the private half of the RSA key from just the public key. The researchers who found the vulnerability have published high-level information here:

[NSS+17]
Security threat #1: Implementation bugs in token

Infineon RSA Key Generation Issue

Infineon Technologies, one of Yubico’s secure element vendors, has informed us of a security issue in their cryptographic firmware library. The issue affects TPMs in millions of computers, and multiple smart card and security token vendors.

[NSS+17]
Security threat #1: Implementation bugs in token

[NSS+17]
Security threat #2: Supply-chain tampering

Experts Call for Transparency Around Google’s Chinese-Made Security Keys

Google’s Titan Security Keys, used to lock down accounts, are produced in China. Several experts want more answers on that supply chain process, for fears of tampering or security issues.
True2F: U2F protections + faulty-token protection
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U2F protection

Browser learns no secrets.
True2F: U2F protections + faulty-token protection

- **U2F protection**: Browser learns no secrets.
- **True2F addition: Faulty-token protection**: Browser enforces correct behavior to prevent token leaking secrets.
True2F: U2F protections + faulty-token protection

Goals:

- Augment U2F to protect against **faulty tokens**
  - Same protections as U2F even if token is buggy or backdoored
- **Backwards-compatible** with U2F server
  - Only requires changes to token and browser, not server
- **Practical** on commodity hardware tokens
  - Evaluated on Google hardware
True2F: U2F protections + faulty-token protection

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Design principles:

- Both browser and token **contribute randomness** to the protocol.
- **Browser can verify** all deterministic token operations.
True2F implementation

Google development board running True2F.

Google production USB token with same hardware specs.

ARM SC-300 processor clocked at 24 MHz
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1. Registration (associating a token with an account)

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True2F protocol steps

0. Initialization (after purchasing a token) [New]

1. Registration (associating a token with an account) [Modified]

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True2F protocol steps

0. Initialization (after purchasing a token) [New]
   ➔ Ensure token master secret incorporates good randomness.

1. Registration (associating a token with an account) [Modified]

2. Authentication (logging into an account) [Modified]

Principle: Both browser and token contribute randomness to the protocol.
Step #0: Initialization
Step #0: Initialization

collaborative key generation

msk

mpk
Initialization: Security properties

The token cannot bias mpk.

[GJKR99], [CMBF13]
Initialization: Security properties

- The token cannot bias mpk.
- The browser learns nothing about msk.

[GJKR99], [CMBF13]
Initialization properties

The token cannot bias mpk.

The browser learns nothing about msk.

Our protocol reduces the number of group operations by 3x compared to [CMBF13] (see paper).
True2F protocol steps

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1. Registration (associating a token with an account) [Modified]
   ➔ Ensure per-site keys generated correctly.

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Principle: Browser can verify all deterministic token operations.
Step #1: U2F Registration

Associate a token with an account.
Security threat #1: Implementation bugs in token

Generate \((sk_{\text{github.com}}, pk_{\text{github.com}})\) using weak randomness

Bad randomness in embedded devices:
[EZJ+14], [LHA+14], [NDWH14], [YRS+09]
Security threat #2: Supply-chain tampering
Verifiable Identity Families (VIFs)

Derive server-specific keypairs in a deterministic and verifiable way from a master keypair.
Verifiable Identity Families (VIFs)

Formally, we prove that VIFs are unique, verifiable, unlinkable, and unforgeable.
Contribution: Simple (weak) VIF construction

$G = \langle g \rangle$ is a group of prime order $q$. 
Contribution: Simple (weak) VIF construction

\[ G = \langle g \rangle \text{ is a group of prime order } q. \]

\[ \text{msk} = x \in \mathbb{Z}_q \]

\[ \text{mpk} = X = g^x \in G \]
Contribution: Simple (weak) VIF construction

\( G = \langle g \rangle \) is a group of prime order \( q \).

\[
\begin{align*}
\text{msk} & = x \in \mathbb{Z}_q \\
k & = H(X)
\end{align*}
\]

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github.com
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\alpha &\leftarrow \text{PRF}(k, \text{github.com}) \\
(\text{sk}, \text{pk}) &\leftarrow (\alpha x, g^{\alpha x})
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\text{Check if } \text{pk} &= X^\alpha
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\[ (sk, pk) \leftarrow (\alpha x, g^{\alpha x}) \]

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\[ k = H(X) \]

\[ \alpha \leftarrow \text{PRF}(k, \text{github.com}) \]

\[ \text{Check if } pk = X^\alpha \]

\[ \square \text{ Unique: The token can produce the unique keypair for github.com.} \]
Contribution: Simple (weak) VIF construction

$G = \langle g \rangle$ is a group of prime order $q$.

$\text{msk} = x \in \mathbb{Z}_q$

$k = H(X)$

$\alpha \leftarrow \text{PRF}(k, \text{github.com})$

$(\text{sk, pk}) \leftarrow (\alpha x, g^{\alpha x})$

$\text{mpk} = X = g^x \in G$

$k = H(X)$

$\alpha \leftarrow \text{PRF}(k, \text{github.com})$

Check if $\text{pk} = X^\alpha$

**Verifiable:** The token can prove to the browser that $\text{pk}$ is really the unique public key for $\text{github.com}$. 
Contribution: Simple (weak) VIF construction

\[ G = \langle g \rangle \text{ is a group of prime order } q. \]

\[ \text{msk} = x \in \mathbb{Z}_q \]

\[ k = H(X) \]

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\[ \text{mpk} = X = g^x \in G \]

\[ k = H(X) \]

\[ \alpha \leftarrow \text{PRF}(k, \text{github.com}) \]

Check if \( \text{pk} = X^\alpha \)

✓ Unforgeable: The browser cannot forge a signature under \( \text{pk} \text{github.com}. \)
Contribution: Simple (weak) VIF construction

$G = \langle g \rangle$ is a group of prime order $q$.

$\text{msk} = x \in \mathbb{Z}_q$

$k = H(X)$

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$(\text{sk}, \text{pk}) \leftarrow (\alpha x, g^{\alpha x})$

$\text{mpk} = X = g^x \in G$

$\text{pk} \leftarrow \text{PRF}(k, \text{github.com})$

Check if $\text{pk} = X^\alpha$

**Weak unlinkability:** github.com cannot distinguish $\text{pk}$ from a random ECDSA public key.
Contribution: Simple (weak) VIF construction

$G = \langle g \rangle$ is a group of prime order $q$.

$\text{msk} = x \in \mathbb{Z}_q$

$k = H(X)$

$\alpha \leftarrow \text{PRF}(k, \text{github.com})$

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$\text{mpk} = X = g^x \in G$

$k = H(X)$

$\alpha \leftarrow \text{PRF}(k, \text{github.com})$

Check if $\text{pk} = X^\alpha$

**Full unlinkability:** Informally, browser cannot generate public keys without the token (see paper).
True2F protocol steps

0. Initialization (after purchasing a token)  [New]
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   ➔ Ensure per-site keys generated correctly.

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2. Authentication (logging into an account) [Modified]
   ➔ Ensure authentication leaks no data.

Principle: Both browser and token contribute randomness to the protocol.
Step #2: U2F Authentication

Log into an account.

- From the security key, send a challenge to the browser.
- The browser signs the challenge and sends it to the server.
- The server sends a challenge and a signature back to the browser.
- The browser verifies the signature and sends the challenge back to the server.
- The server sends a signature back to the browser.
- The browser verifies the signature and completes the authentication.
Security threat #1: Implementation bugs in token

Choose signing nonce with weak randomness

Bad randomness in embedded devices:
[EZJ+14], [LHA+14], [NDWH14], [YRS+09]
Security threat #2: Supply-chain tampering

Subliminal channels: [Sim84], [Des88]
Unique signatures: [BLS01]
Firewalled ECDSA Signatures

Two ideas:

1. The token and browser use **collaborative key generation** to generate a signing nonce.
2. Because of ECDSA malleability, signatures are **re-randomized** by the browser.

... see paper for details.

[AMV15], [MS15], [DMS16]
True2F protocol steps

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   ➔ Ensure token master secret incorporates good randomness.  

1. Registration (associating a token with an account)  
   ➔ Ensure per-site keys generated correctly.  

2. Authentication (logging into an account)  
   ➔ Ensure authentication leaks no data.
Other contributions (see paper)

- Cryptographic optimizations tailored to token hardware
  - Offload hash-to-point to the browser
  - Cache Verifiable Random Function outputs at the browser

- Flash-optimized data structure for storing U2F authentication counters
  - Provides stronger unlinkability than many existing U2F tokens
  - “Tear-resistant” and respects constraints of token flash
Multiple Browsers

1. Token gives mpk to browser (protect against bugs)
2. Sync mpk across browser instances
True2F evaluation

Google development board running True2F.

Google production USB token with same hardware specs.

ARM SC-300 processor clocked at 24 MHz
True2F imposes minimal authentication overhead

![Graph showing time vs. token processing]

- Collaborative Keygen
- VIF.Eval
- ECDSA.Sign
- Browser

No optimizations: 446 ms

U2F: 23 ms
True2F imposes minimal authentication overhead
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True2F imposes minimal authentication overhead

- No optimizations: 446ms
- Fast keygen only: 361ms
- Hash-to-point assist only: 217ms
- VRF caching only: 142ms
- True2F (+ all): 57ms
- U2F: 23ms
True2F imposes minimal authentication overhead

- True2F only ~2.5x slower than U2F
Comparatively small end-to-end slowdown
Comparatively small end-to-end slowdown

True2F only 12-16% slower than U2F
True2F: Don’t settle for untrustworthy hardware

True2F
- Augments U2F to protect against backdoored tokens
- Backwards-compatible with existing U2F servers

Practical to deploy: performant on commodity hardware tokens

Next steps: help with FIDO adoption

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https://arxiv.org/abs/1810.04660
https://github.com/edauterman/true2f
https://github.com/edauterman/u2f-ref-code
References