# True2F: Backdoor-resistant authentication tokens

**Emma Dauterman**, Henry Corrigan-Gibbs, David Mazières, Dan Boneh, Dominic Rizzo

Stanford and Google

*IEEE Security & Privacy 2019*

# U2F: Effective hardware 2FA

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**KrebsonSecurity**

In-depth security news and investigation

23 JUL 18

## Google: Security Keys Neutralized Employee Phishing

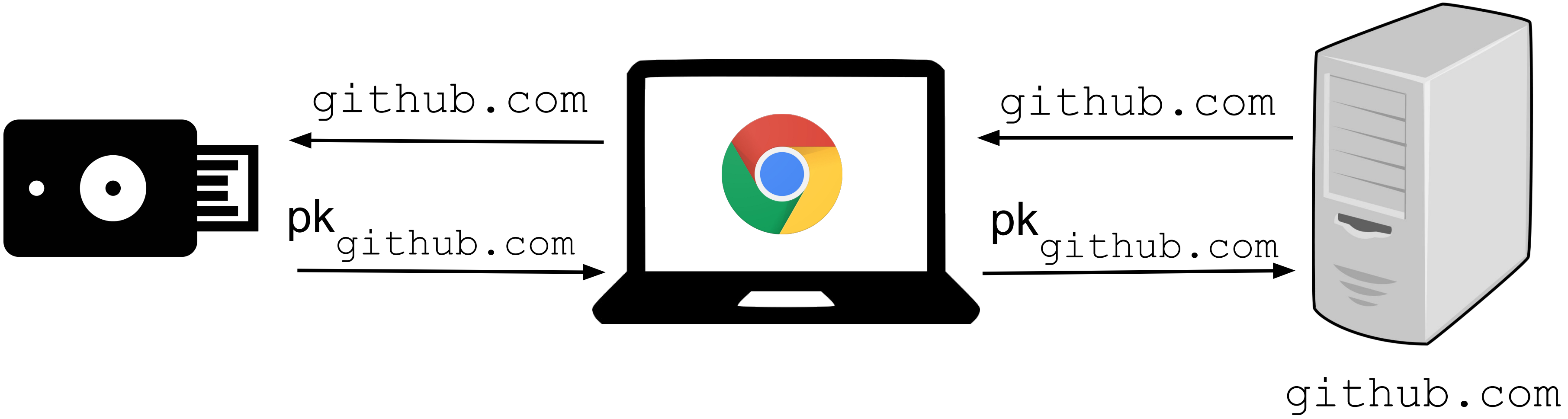
**Google** has not had any of its 85,000+ employees successfully phished on their work-related accounts since early 2017, when it began requiring all employees to use physical Security Keys in place of passwords and one-time codes, the company told KrebsOnSecurity.

# U2F protocol steps

1. Registration (associating a token with an account)
2. Authentication (logging into an account)

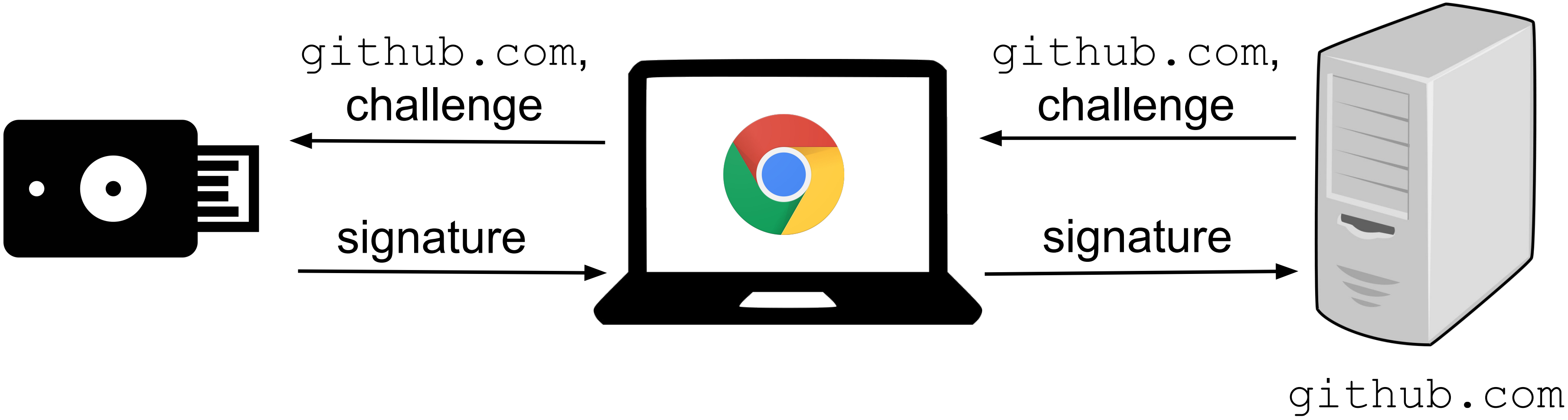
# U2F Step #1: Registration

Associate a token with an account.



# U2F Step #2: Authentication

Log into an account.



# 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?

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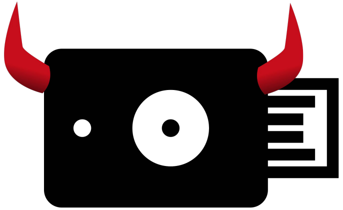
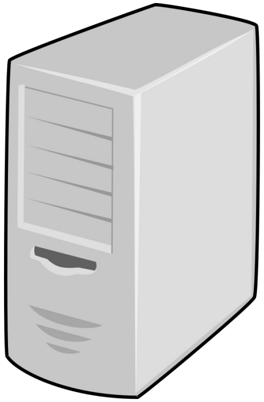
1. Implementation bugs
2. Supply-chain tampering



$sk_{\texttt{github.com}}$



github.com

# Security threat #1: Implementation bugs in token

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*COMPLETELY BROKEN —*

## Millions of high-security crypto keys crippled by newly discovered flaw

Factorization weakness lets attackers impersonate key holders and decrypt their data.

DAN GOODIN - 10/16/2017, 4:00 AM

[NSS+17]

# Security threat #1: Implementation bugs in token


[NSS+17]

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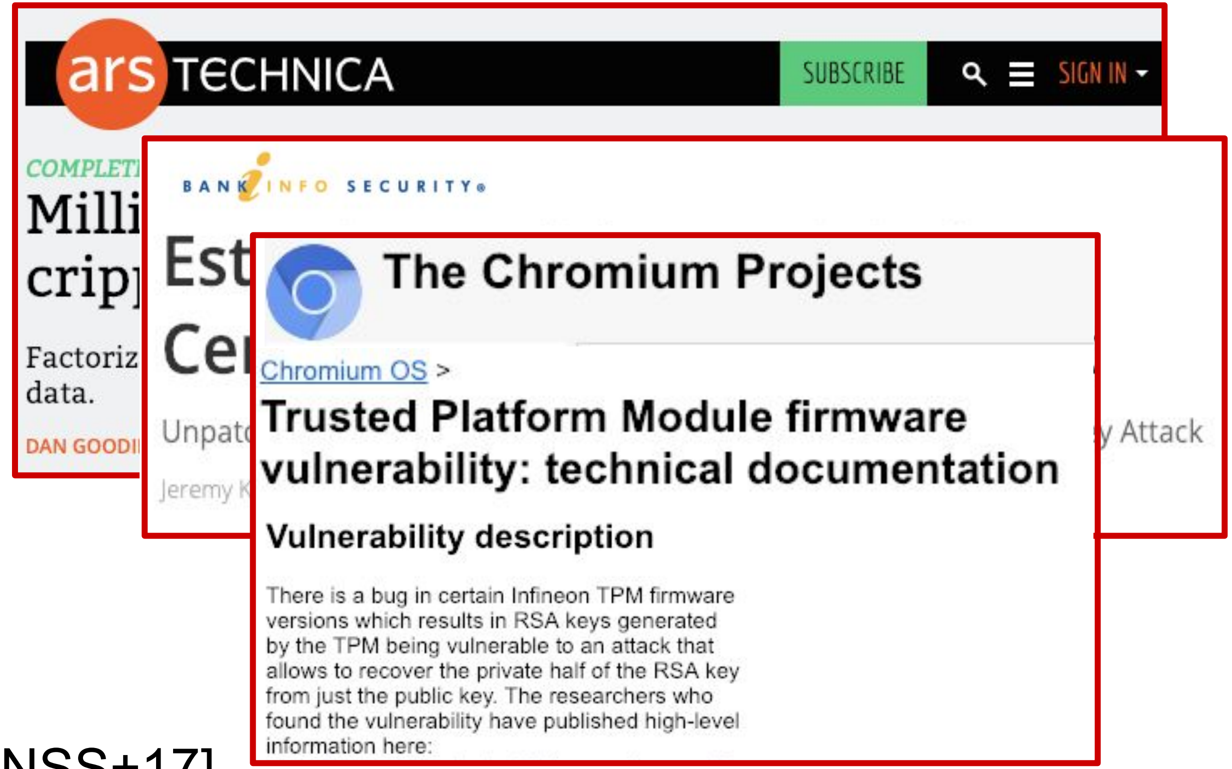


[NSS+17]

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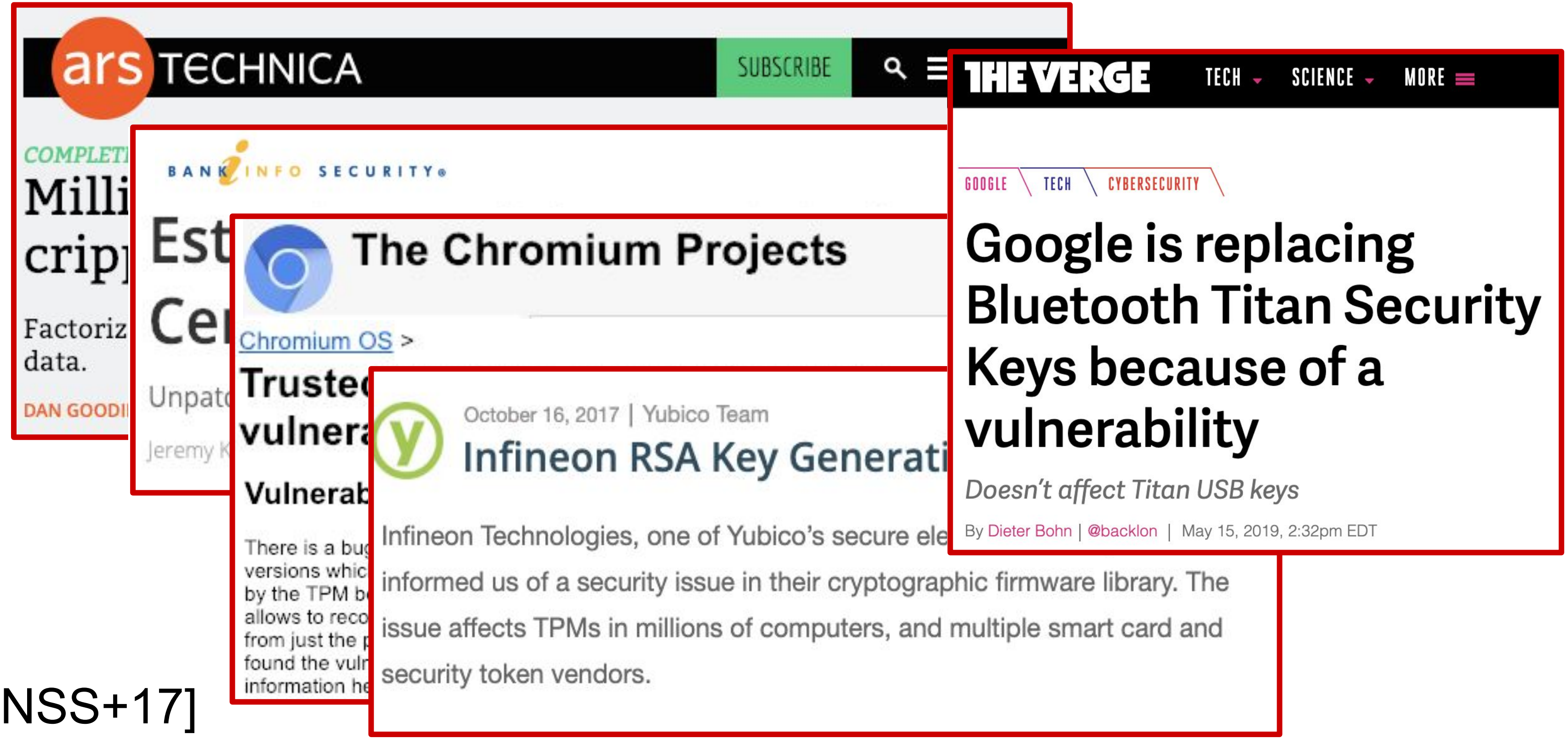


[NSS+17]

# Security threat #2: Supply-chain tampering

ars TECHNICA | SUBSCRIBE | SIGN IN

*AT LEAST THEY PICK UP THE EXTRA SHIPPING —*

## Photos of an NSA “upgrade” factory show Cisco router getting implant

Servers, routers get “beacons” implanted at secret locations by NSA’s TAO team.

SEAN GALLAGHER - 5/14/2014, 12:30 PM

(TS//SI//NF) Left: Intercepted packages are opened carefully; Right: A “load station” implants a beacon

MOTHERBOARD

CHINA | By Joseph Cox | Aug 31 2018, 5:05am

## 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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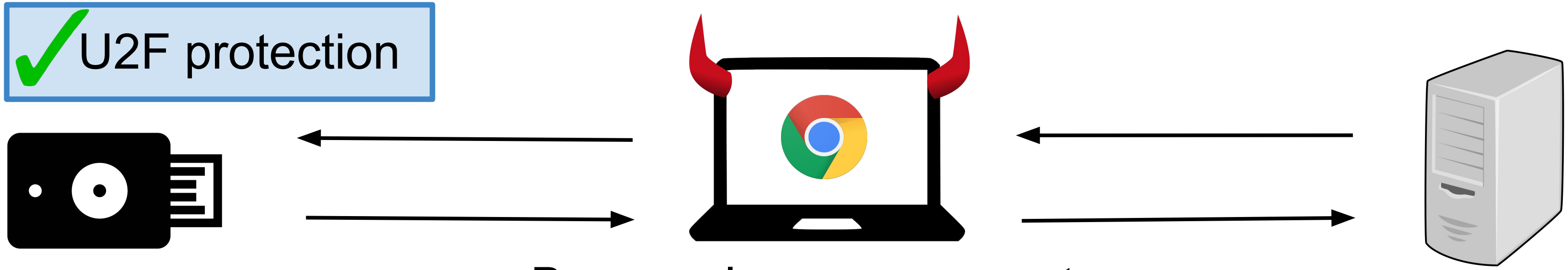
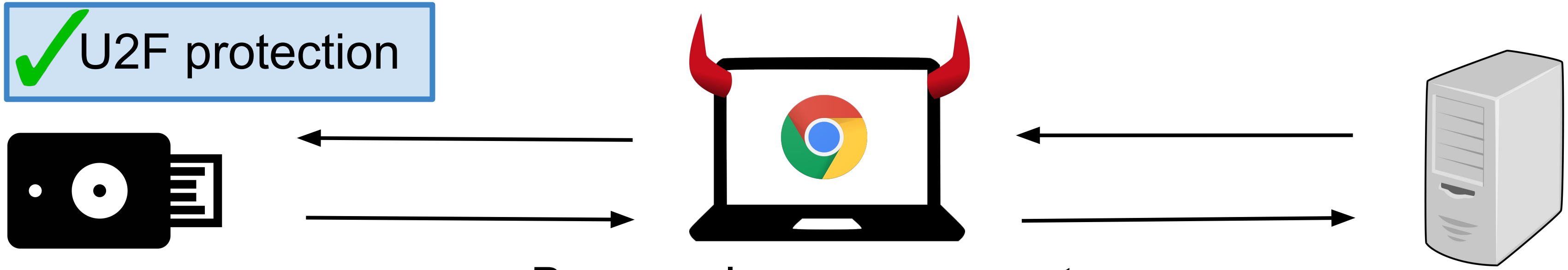
✓U2F protection



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

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- **Backwards-compatible** with U2F server
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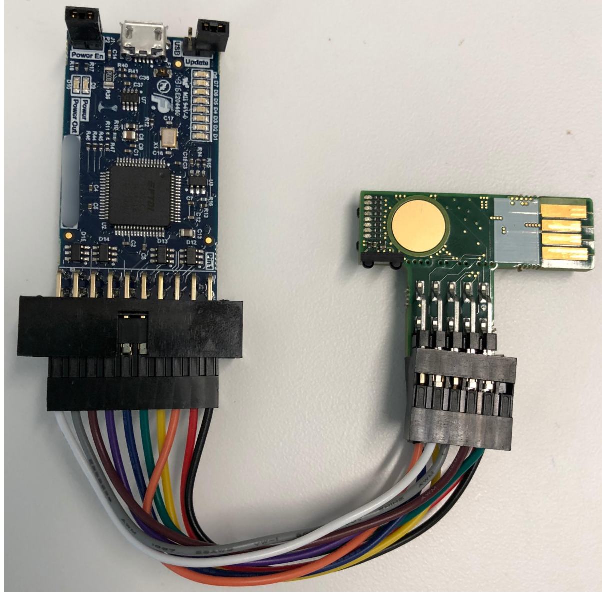
- **Practical** on commodity hardware tokens
  - Evaluated on Google hardware

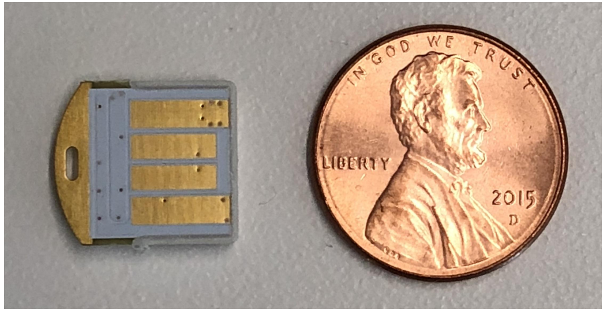
Design principles:

- 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

# U2F protocol steps

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]

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

# True2F protocol steps

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

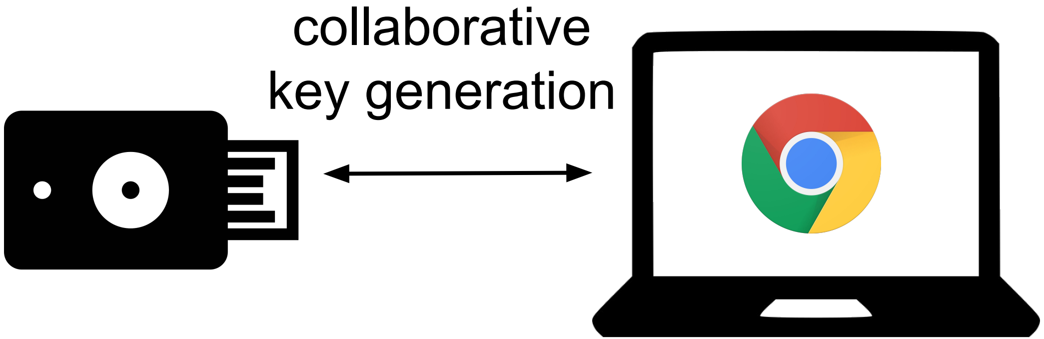
- ➔ **Ensure token master secret incorporates good randomness.**

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

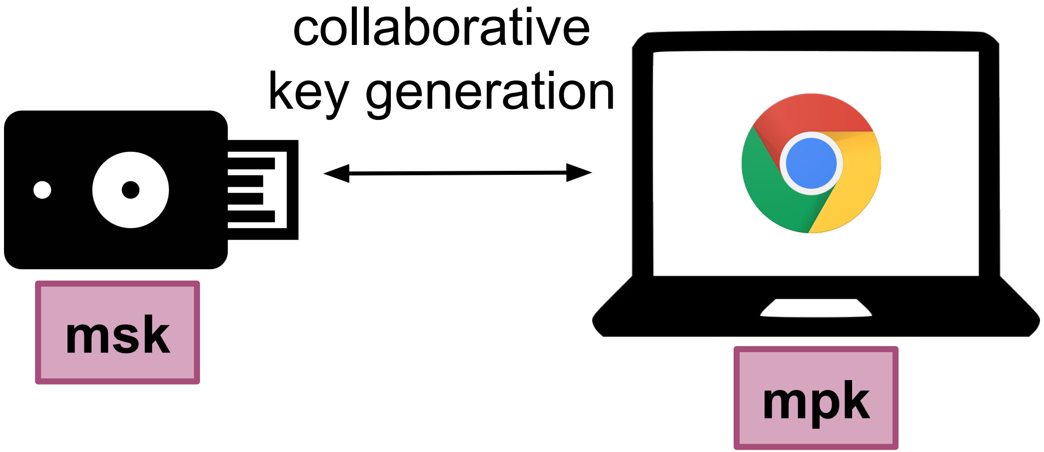
2. Authentication (logging into an account) [Modified]

*Principle:* Both browser and token contribute randomness to the protocol.

# Step #0: Initialization

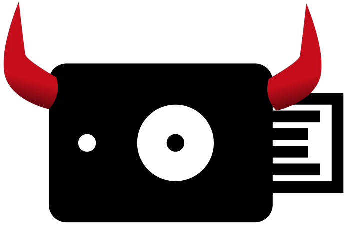


# Step #0: Initialization



# Initialization: Security properties

The token cannot bias mpk.



**msk**

**mpk**

[GJKR99], [CMBF13]

# Initialization: Security properties

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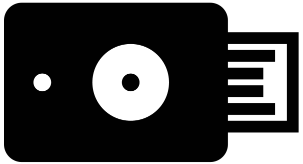

msk

mpk

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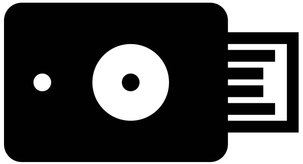

Our protocol reduces the number of group operations by 3x compared to [CMBF13] (see paper).

# True2F protocol steps

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

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**1. Registration (associating a token with an account)** [Modified]
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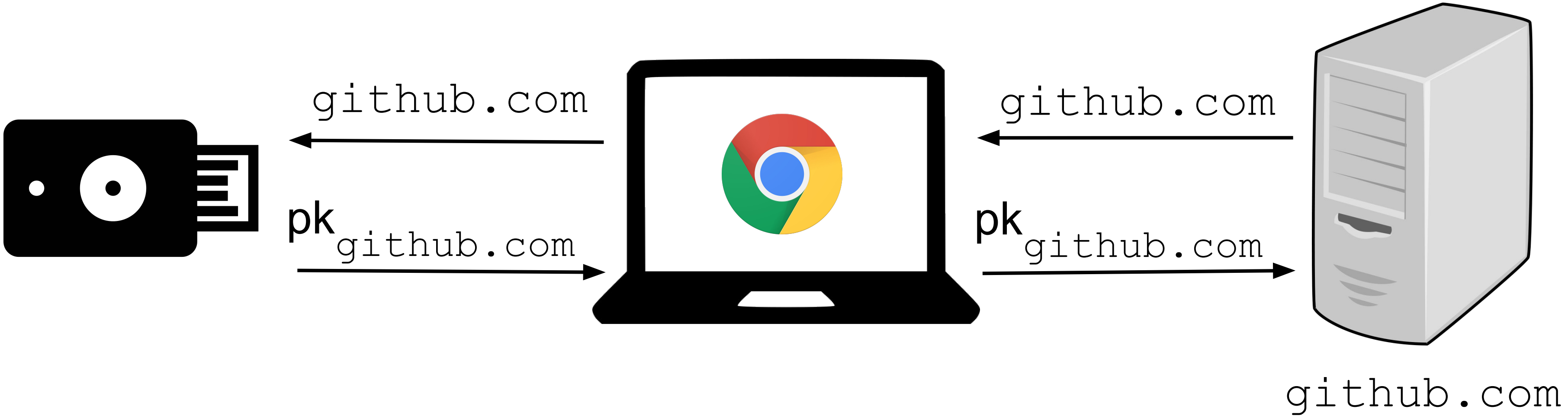
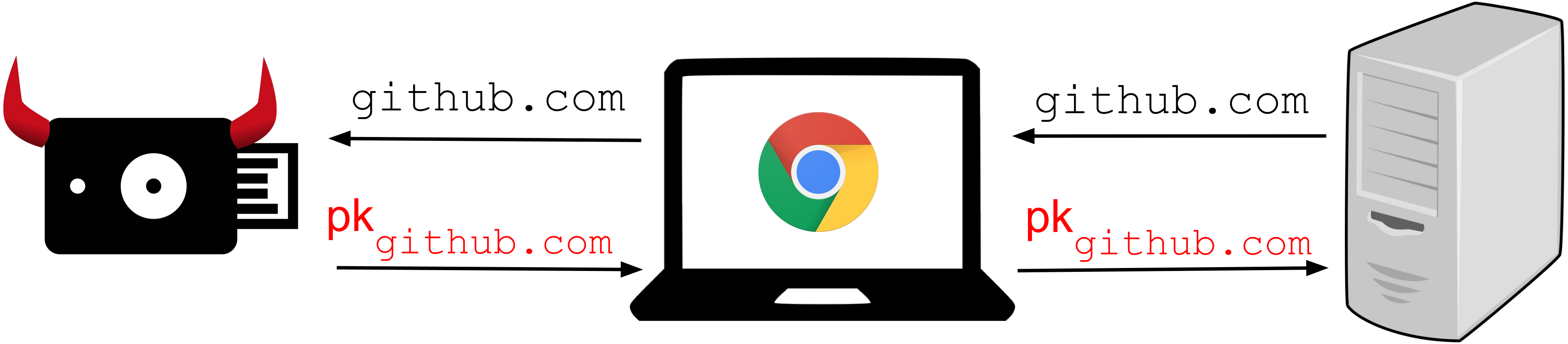
*Principle:* Browser can verify all deterministic token operations.

# Step #1: U2F Registration

Associate a token with an account.



# Security threat #1: Implementation bugs in token

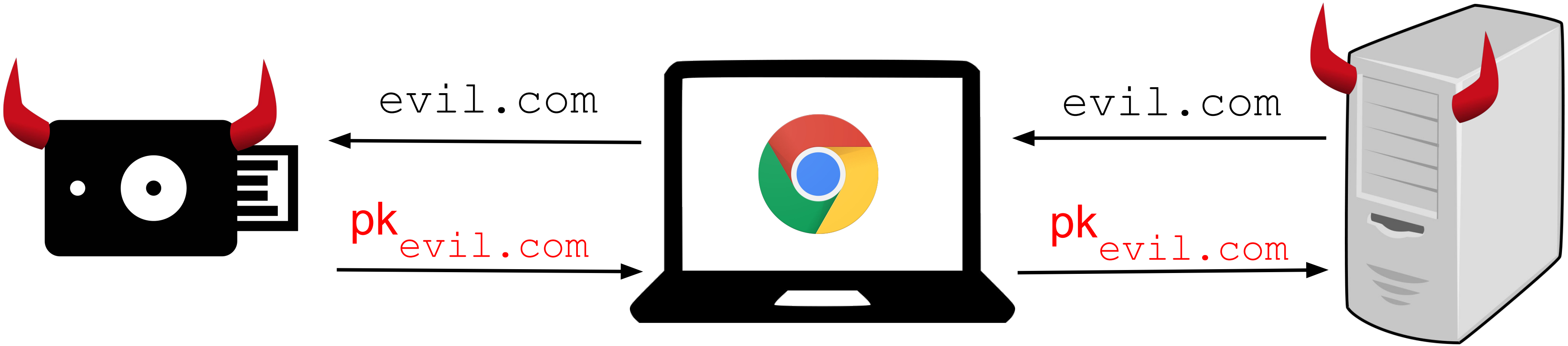



github.com

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

Bad randomness in embedded devices:
[EZJ+14], [LHA+14], [NDWH14], [YRS+09]

# Security threat #2: Supply-chain tampering




evil.com

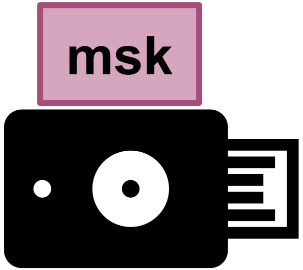
$pk_{\texttt{evil.com}} \leftarrow f(sk_{\texttt{github.com}})$

$sk_{\texttt{github.com}} \leftarrow f^{-1}(pk_{\texttt{evil.com}})$

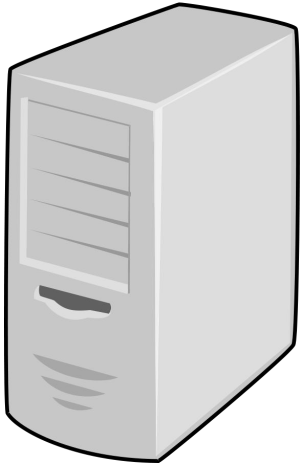
# Verifiable Identity Families (VIFs)


Derive server-specific keypairs in a **deterministic** and **verifiable** way from a master keypair.

# Verifiable Identity Families (VIFs)





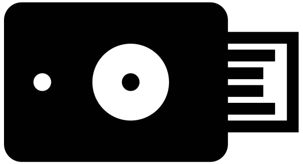


Formally, we prove that VIFs are **unique**, **verifiable**, **unlinkable**, and **unforgeable**.

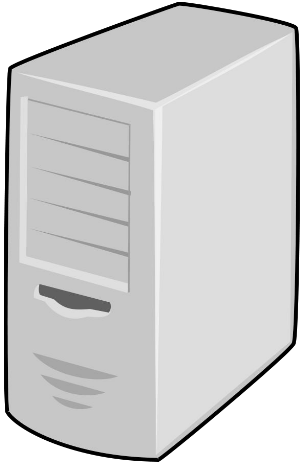
# Contribution: Simple (weak) VIF construction

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

**msk**



**mpk**



`github.com`

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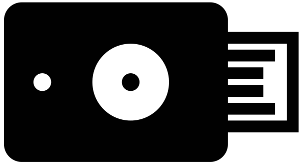
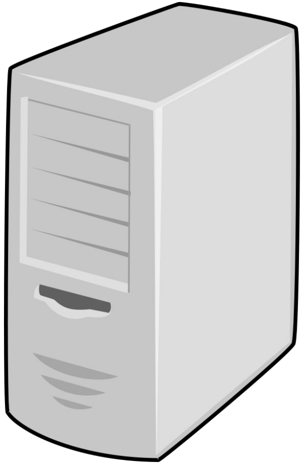


$\mathsf{mpk} = X = g^x \in \mathbb{G}$



github.com

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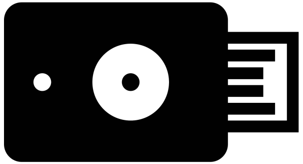
$k = H(X)$



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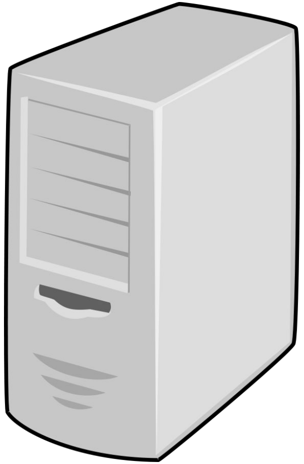

github.com

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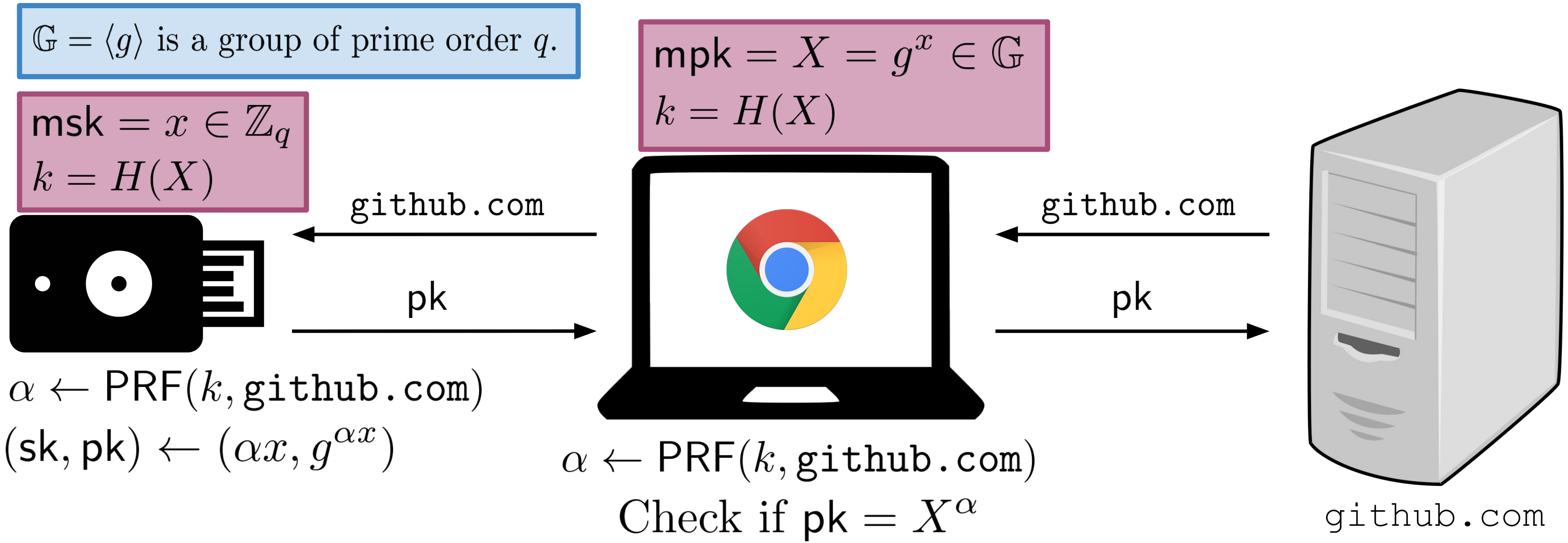

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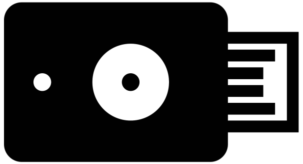
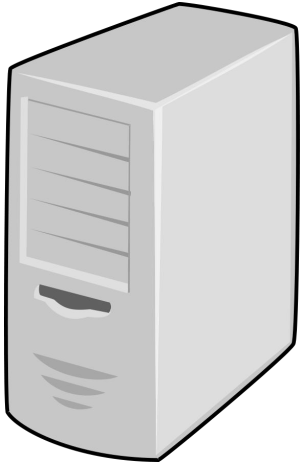


$\leftarrow$ `github.com`

$\mathsf{pk}$ $\rightarrow$

$\leftarrow$ `github.com`

$\mathsf{pk}$ $\rightarrow$



$\alpha \leftarrow \mathsf{PRF}(k, \texttt{github.com})$
$(\mathsf{sk}, \mathsf{pk}) \leftarrow (\alpha x, g^{\alpha x})$

$\alpha \leftarrow \mathsf{PRF}(k, \texttt{github.com})$
Check if $\mathsf{pk} = X^{\alpha}$

`github.com`

✓ **Unique:** The token can produce the unique keypair for `github.com`.

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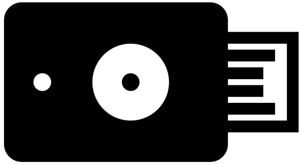

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`github.com` ←
pk →

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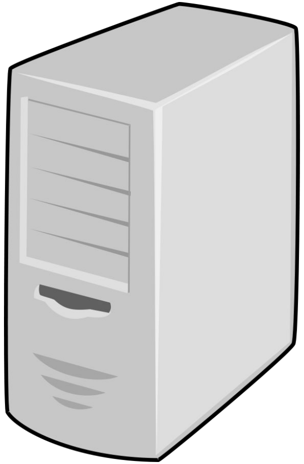

`github.com`

✓**Verifiable:** The token can prove to the browser that $\mathsf{pk}_{\texttt{github.com}}$ is really the unique public key for `github.com`.

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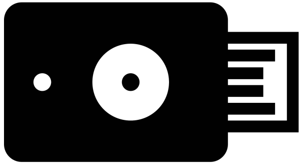
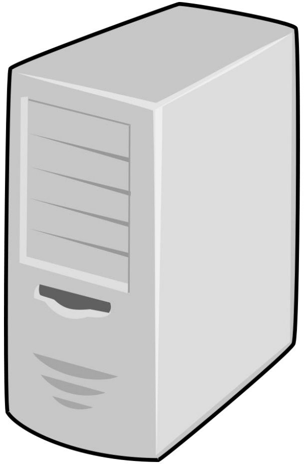


`github.com`

pk

`github.com`

pk



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`github.com`

✓**Unforgeable:** The browser cannot forge a signature under $\mathsf{pk}_{\texttt{github.com}}$.

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✓**Weak unlinkability:** `github.com` cannot distinguish $\mathsf{pk}_{\texttt{github.com}}$ from a random ECDSA public key.

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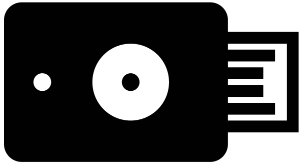
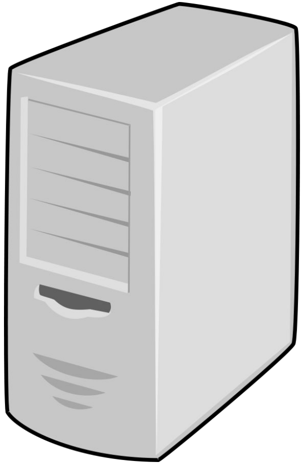


github.com ←

pk →

github.com ←

pk →



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github.com

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

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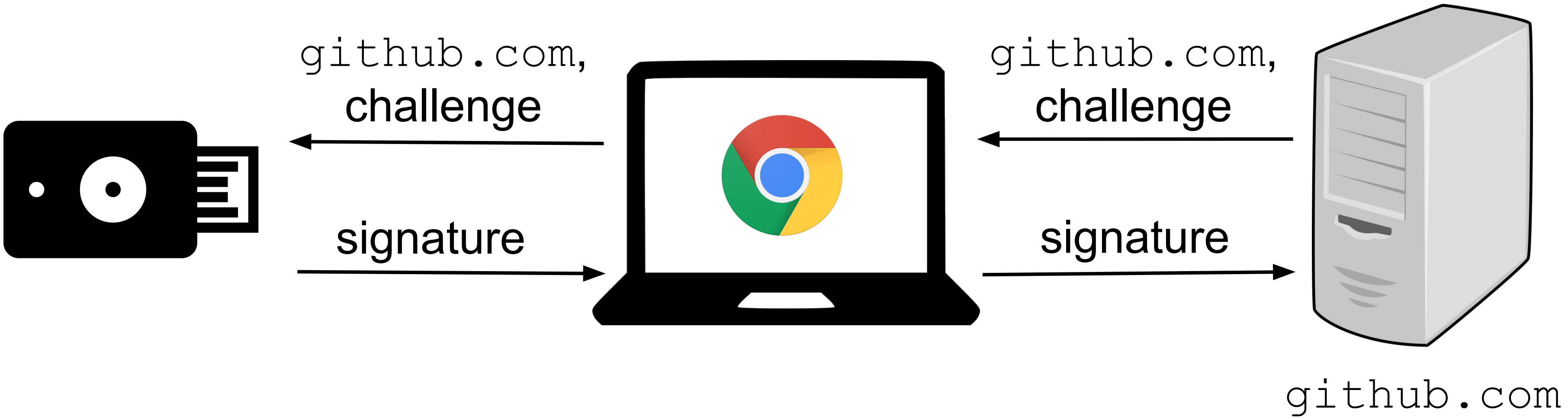
**2. Authentication (logging into an account)** [Modified]
   ➔ **Ensure authentication leaks no data.**

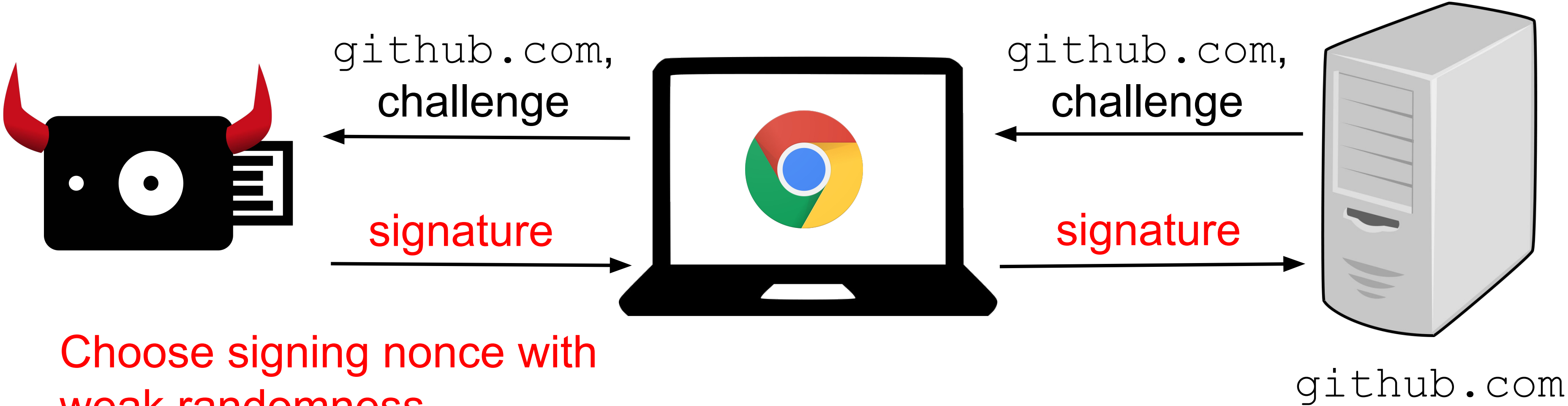
*Principle:* Both browser and token contribute randomness to the protocol.

# Step #2: U2F Authentication

Log into an account.



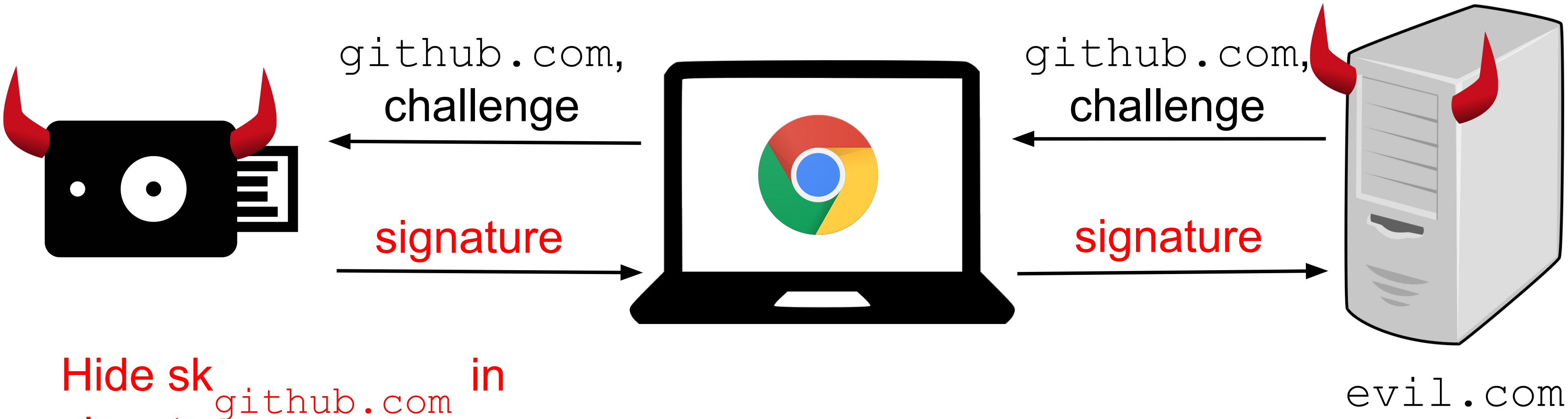
# Security threat #1: Implementation bugs in token




Choose signing nonce with
weak randomness

Bad randomness in embedded devices:
[EZJ+14], [LHA+14], [NDWH14], [YRS+09]

# Security threat #2: Supply-chain tampering




Hide sk github.com in signature

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]

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

➔ Ensure authentication leaks no data.

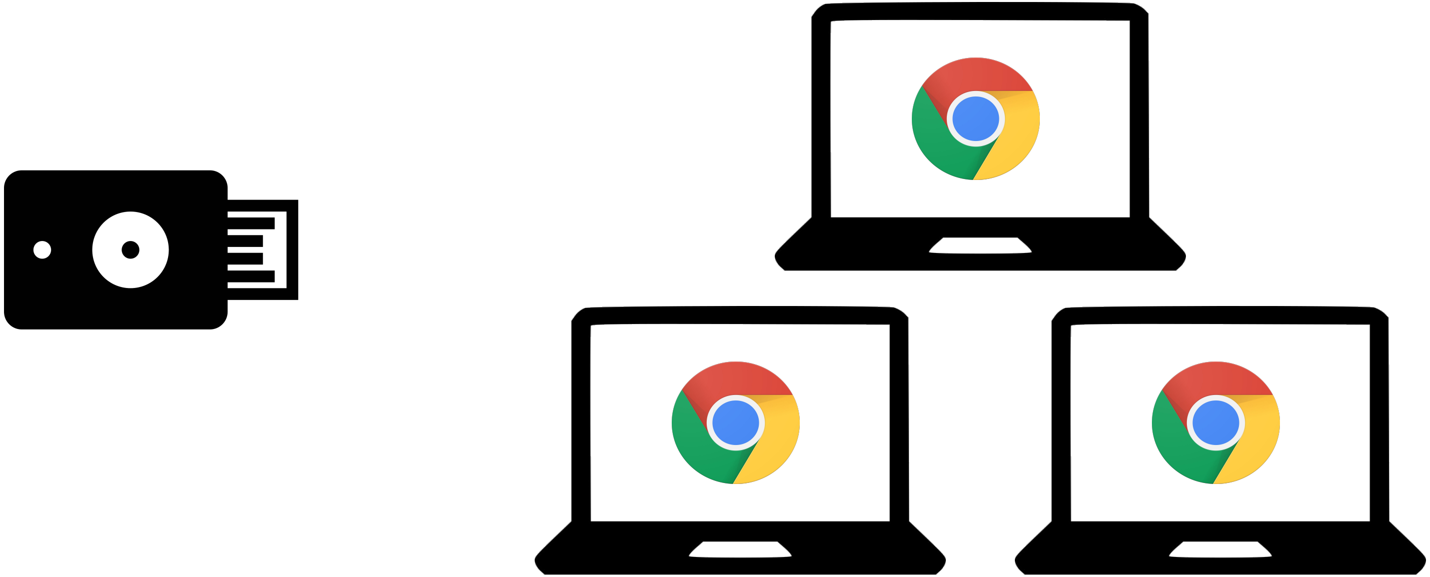
# Other contributions (see paper)

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

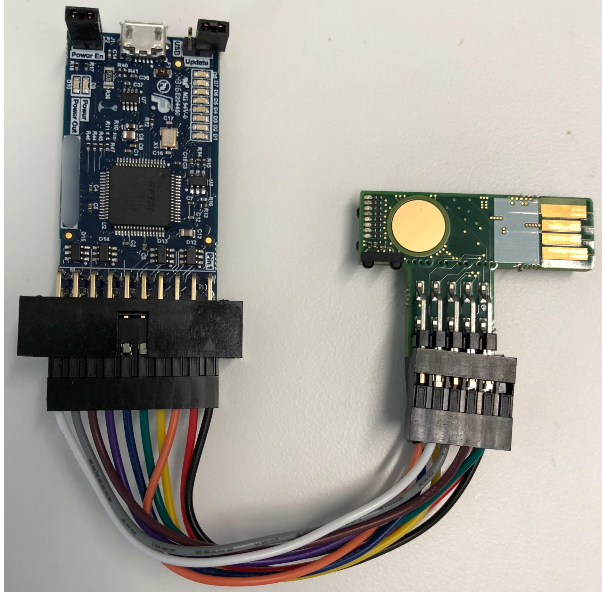
- Flash-optimized data structure for storing U2F authentication counters
  - Provides stronger unlinkability than many existing U2F tokens
  - “Tear-resistant” and respects constraints of token flash

# Multiple Browsers

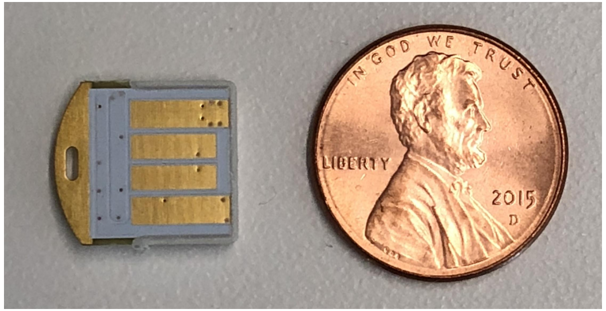
1. Token gives mpk to browser (protect against bugs)
2. Sync mpk across browser instances



# True2F evaluation



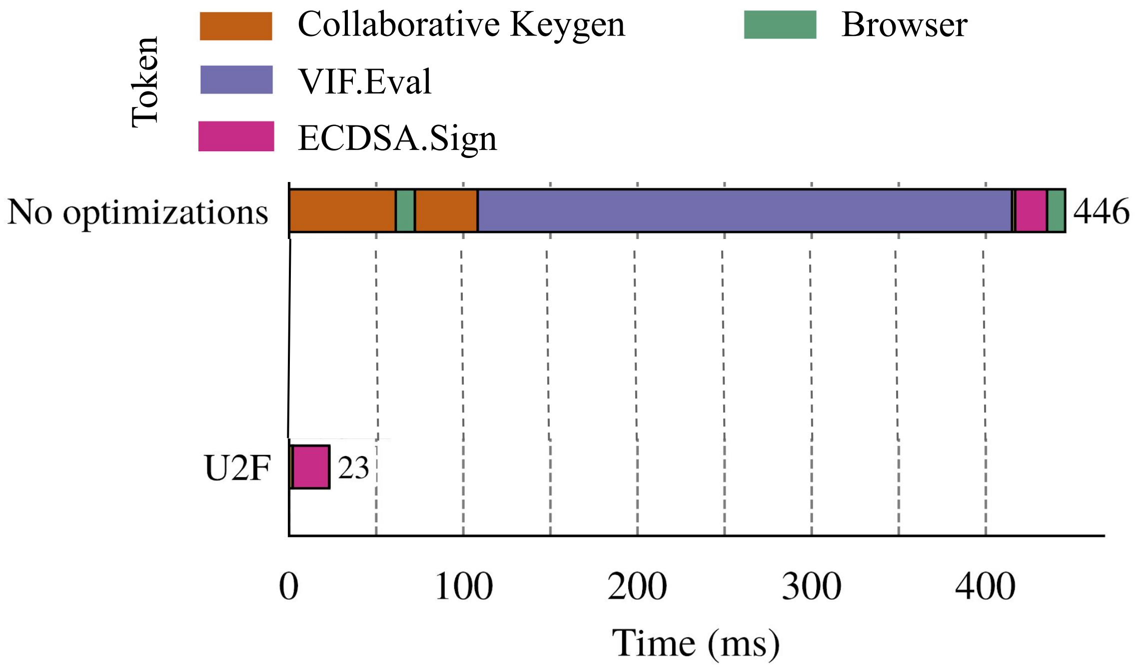
Google development board running True2F.



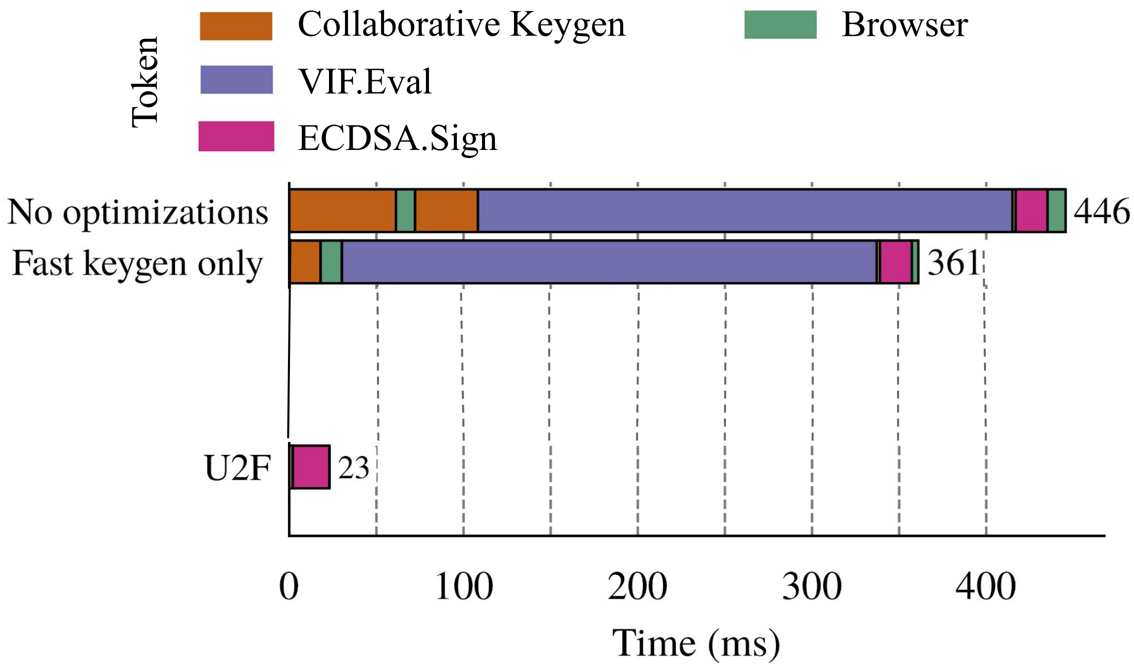

Google production USB token with same hardware specs.

ARM SC-300 processor clocked at 24 MHz

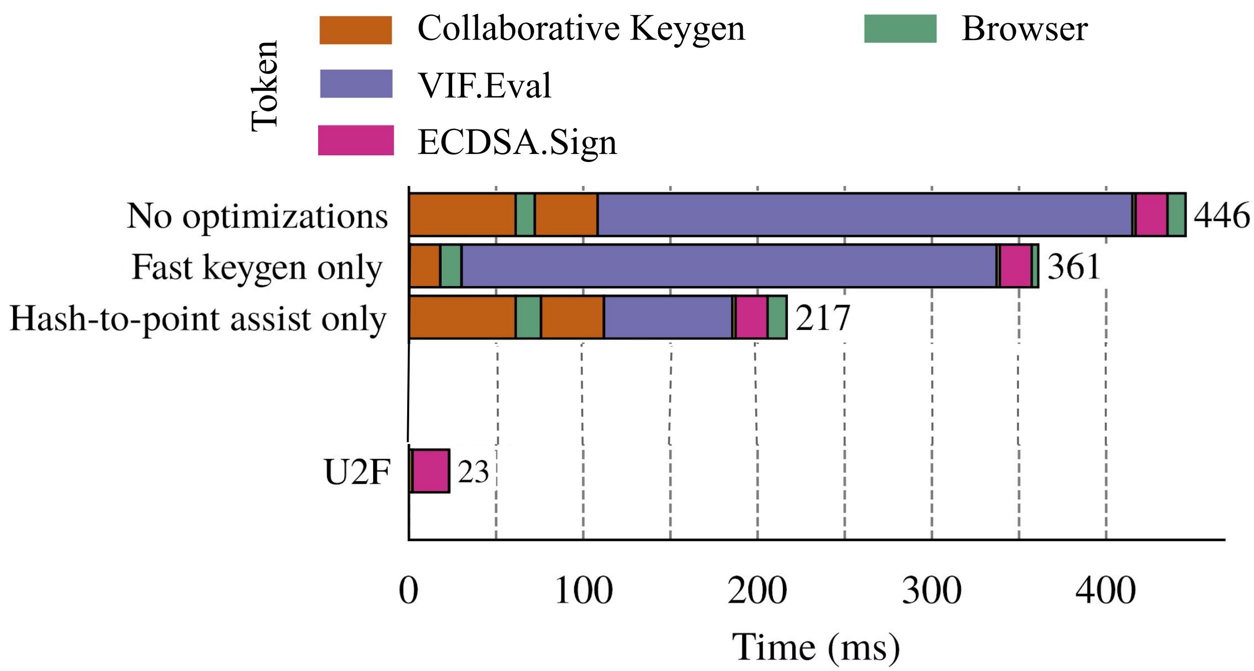
# True2F imposes minimal authentication overhead



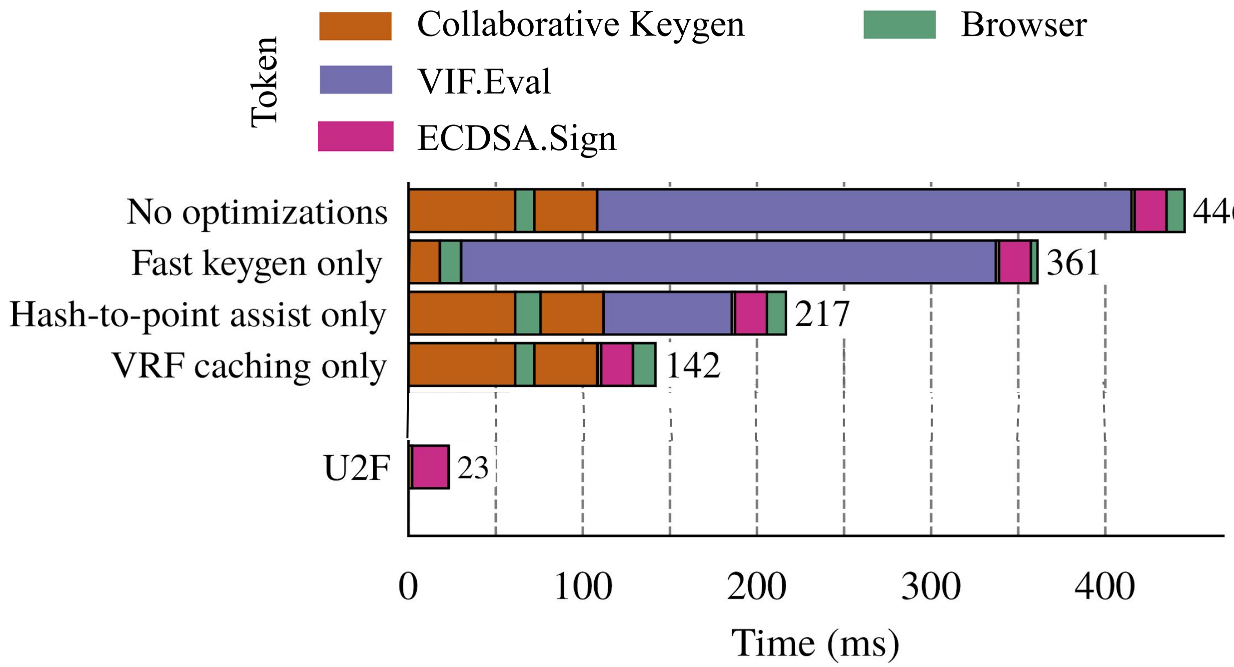
# True2F imposes minimal authentication overhead



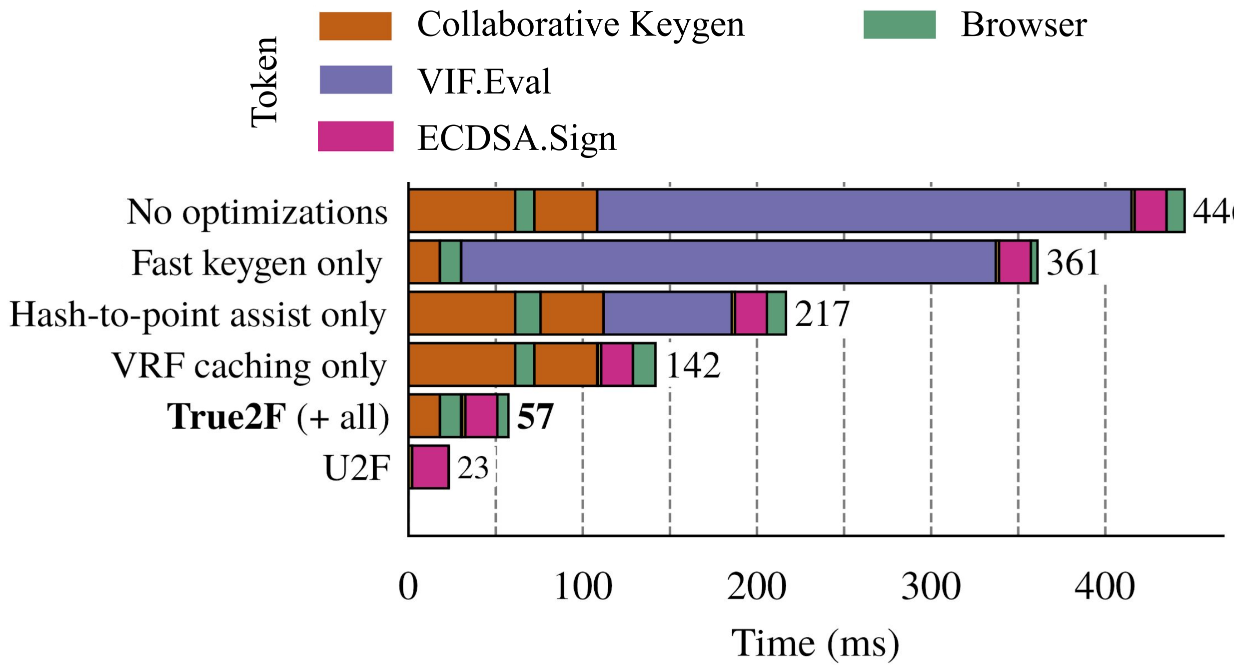
# True2F imposes minimal authentication overhead



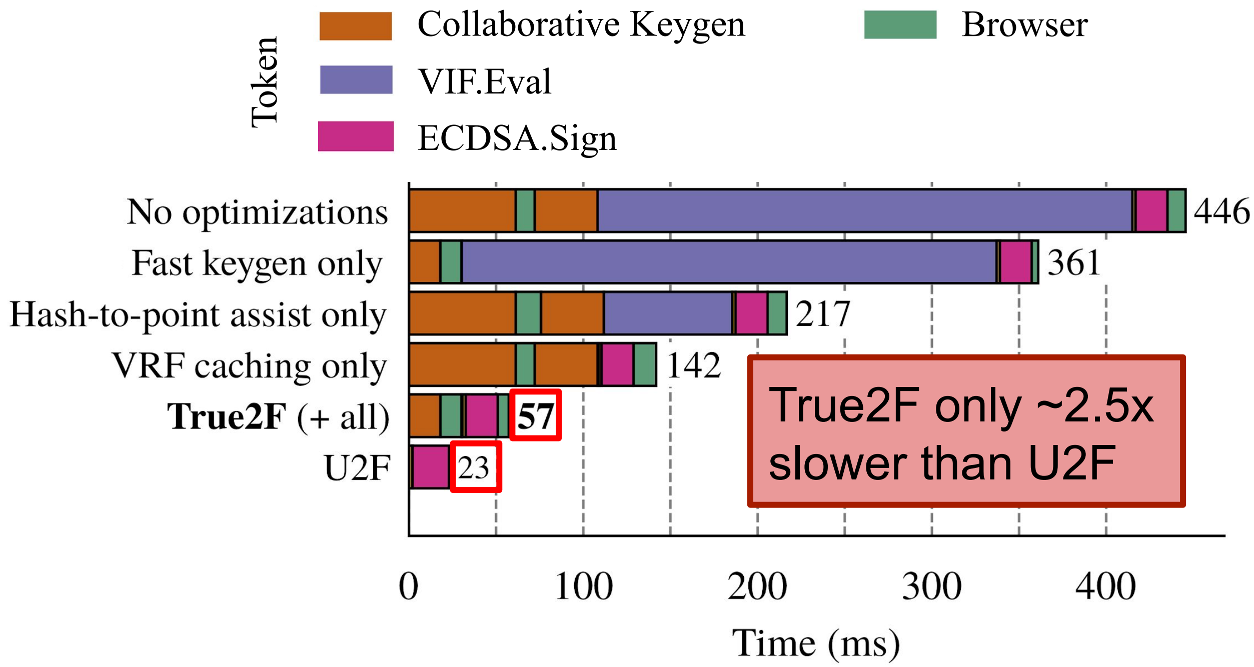
# True2F imposes minimal authentication overhead



# True2F imposes minimal authentication overhead

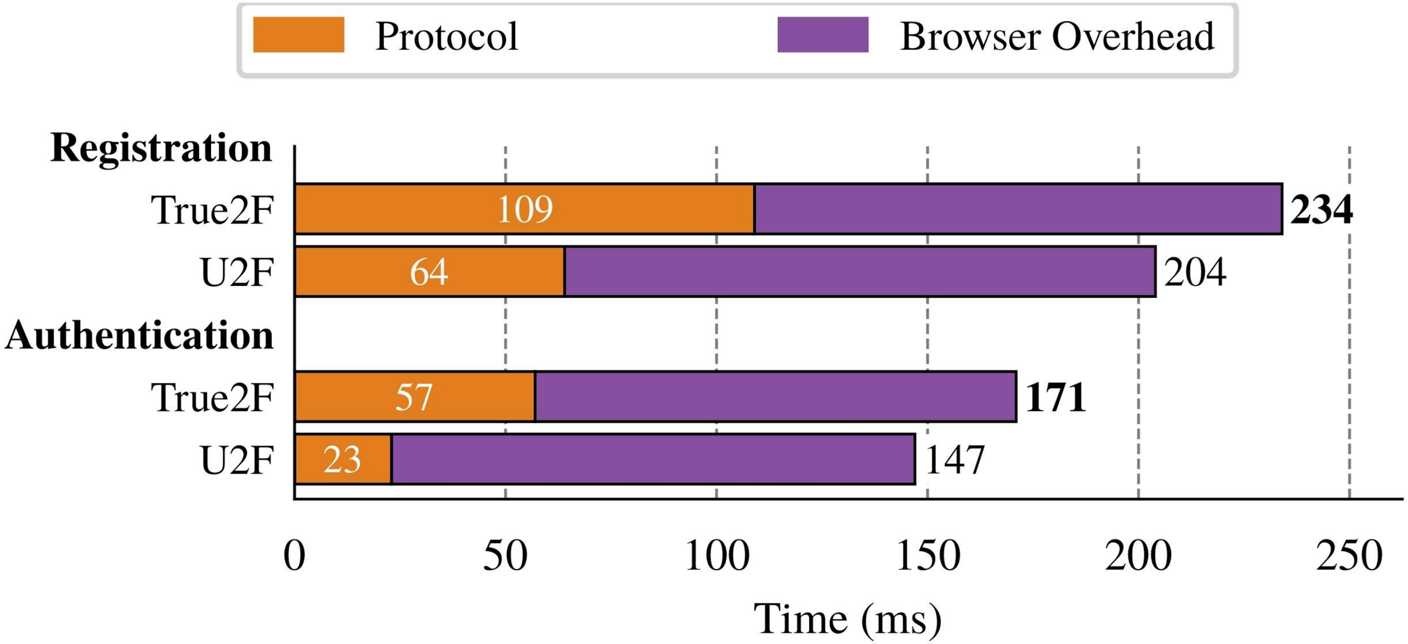


# True2F imposes minimal authentication overhead

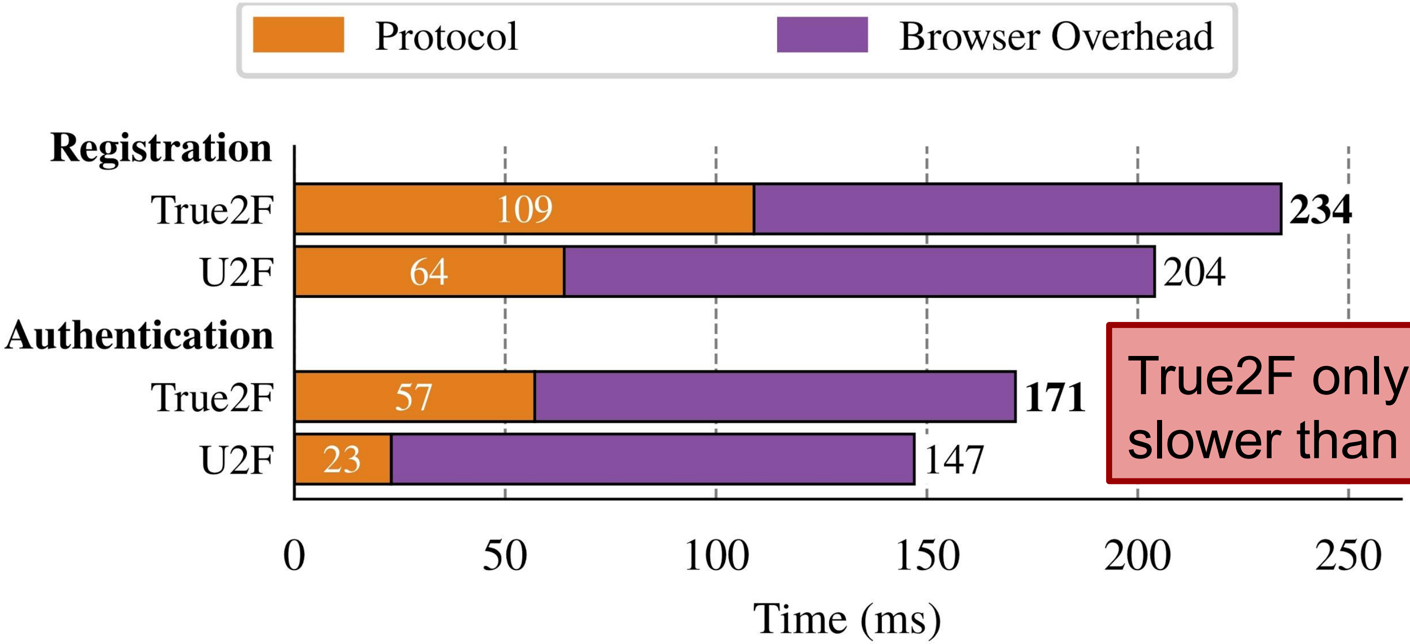



True2F only ~2.5x slower than U2F

# 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

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