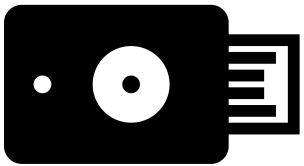
Making U2F Resistant to Implementation Bugs and Supply-Chain Tampering

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

Stanford and Google

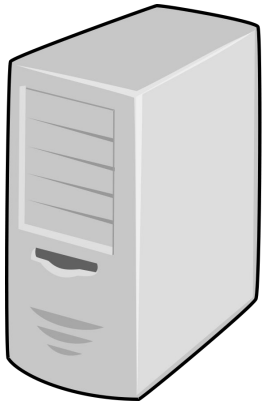
To appear at IEEE Security & Privacy 2019

U2F defends against phishing and browser compromise



Token
(authenticator)

Host



Relying Party

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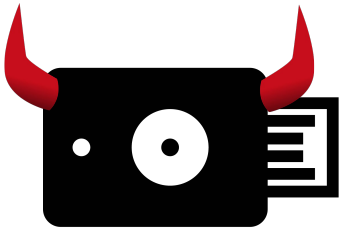

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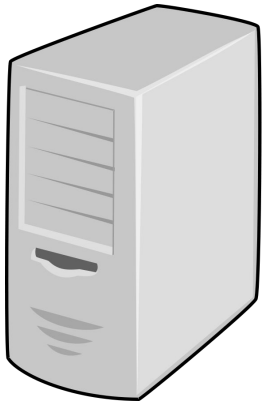

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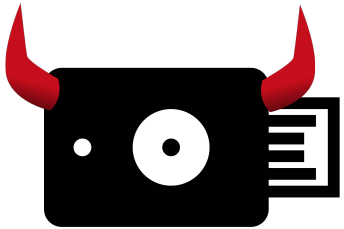

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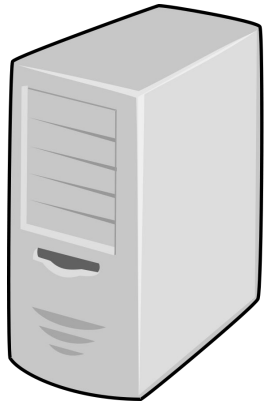

Relying Party

1. Implementation bugs
2. Supply-chain tampering

U2F Shortcoming #1: Implementation bugs

ars TECHNICA SUBSCRIBE SIGN IN

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

U2F Shortcoming #1: Implementation bugs

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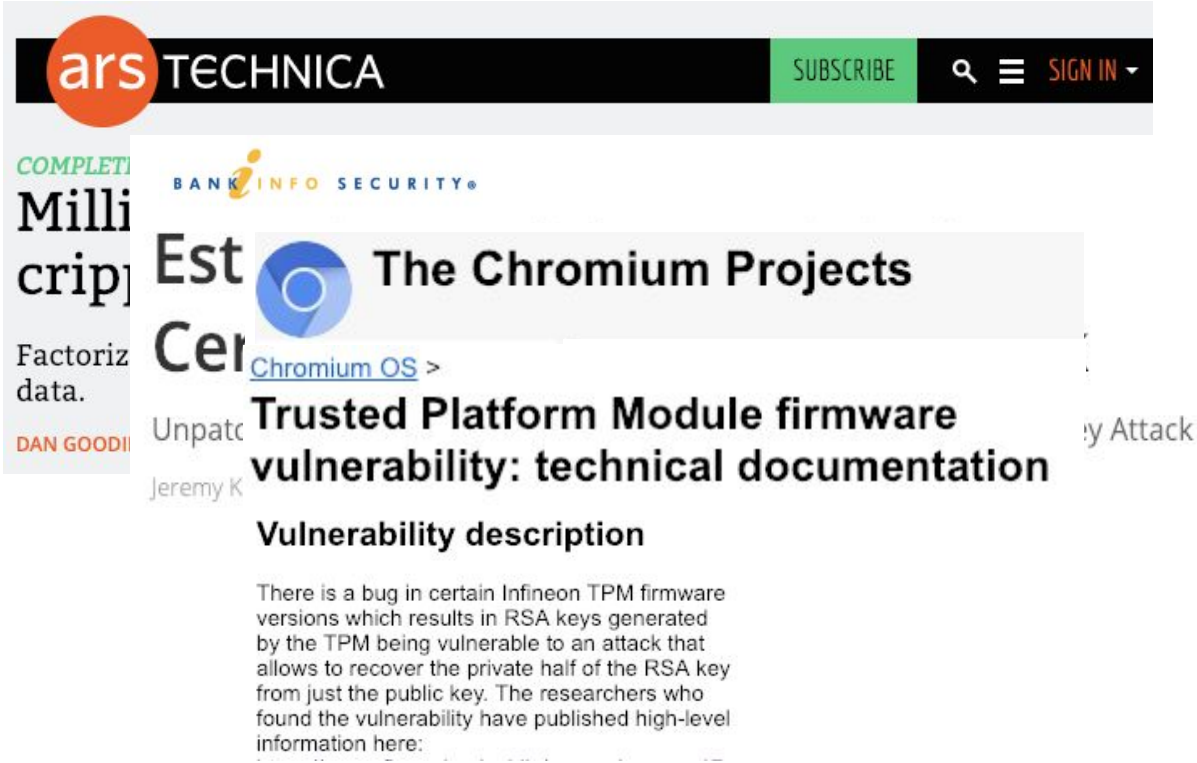

U2F Shortcoming #2: Supply-chain tampering

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.

Our proposed enhancement of U2F

Goals:

- Augment U2F to protect against **faulty tokens**
- **Backwards-compatible** with U2F relying parties
- **Practical** on commodity hardware tokens

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Design principles:

- Both host and token **contribute randomness** to the protocol.
- **Host can verify** all deterministic token operations.

U2F protocol steps

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

Proposed protocol steps

0. Initialization (after purchasing a token)
1. Registration (associating a token with an account)
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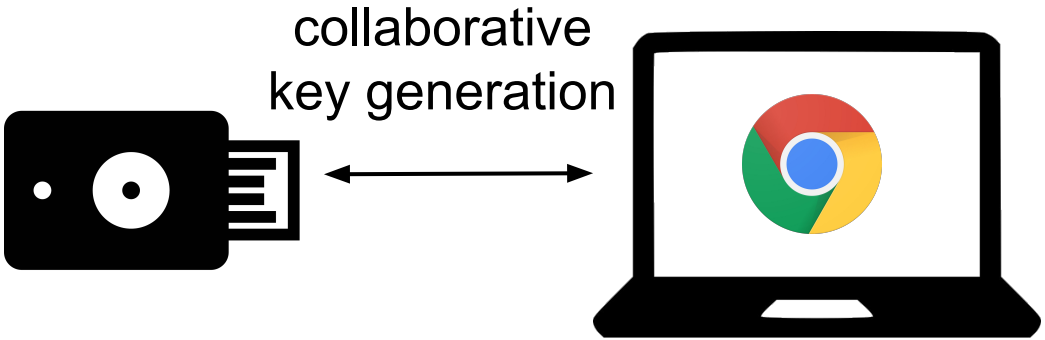

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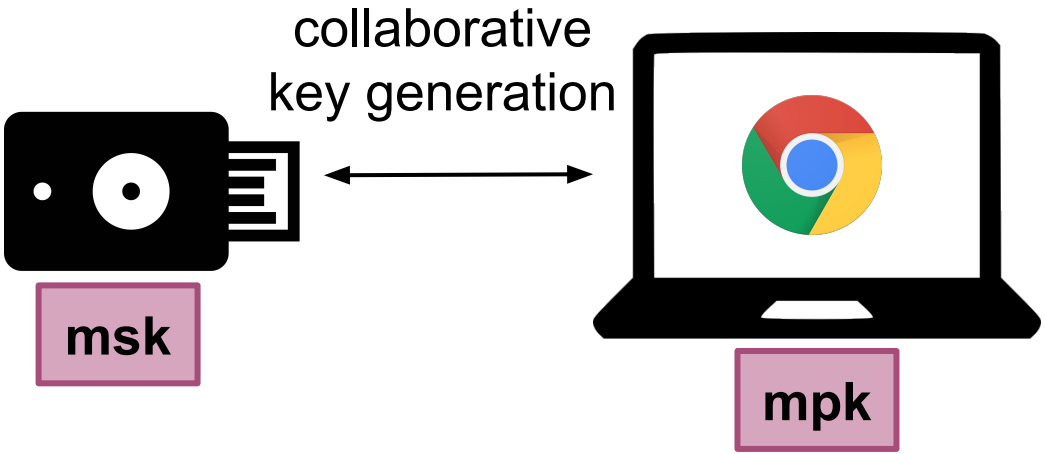

Initialization properties

The token cannot bias mpk.

msk

mpk

[CMBF13]

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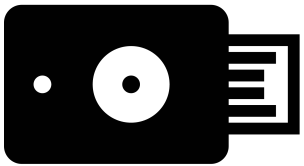

msk

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[CMBF13]

Initialization protocol using collaborative key generation

$\mathbb{G} = \langle g \rangle$ is a group of prime order q.
ECDSA keypairs have the form $(x, g^x) \in \mathbb{Z}_q \times \mathbb{G}$.

$r \xleftarrow{R} \mathbb{Z}_q$
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$c \leftarrow H(v, r)$

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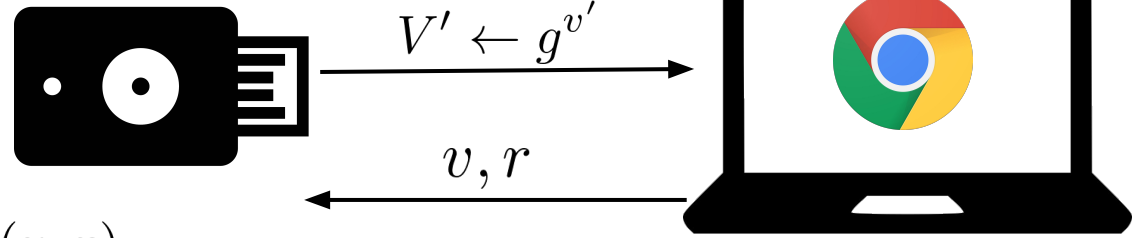

v, r

$\text{mpk} \leftarrow V' \cdot g^v$
$= g^{v+v'}$

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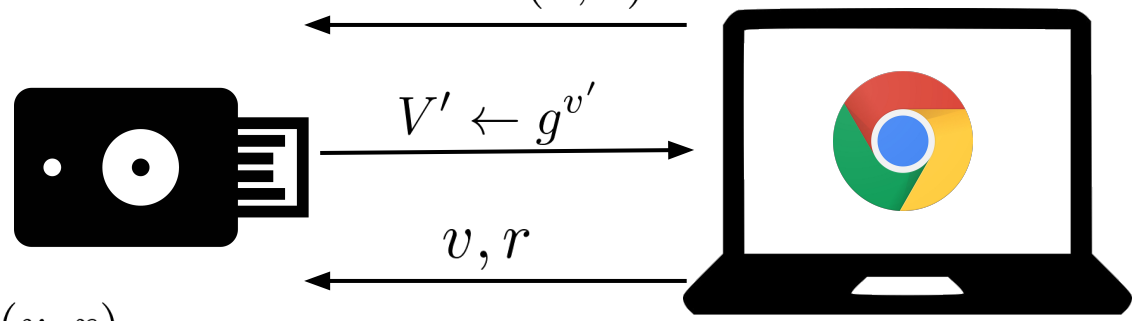

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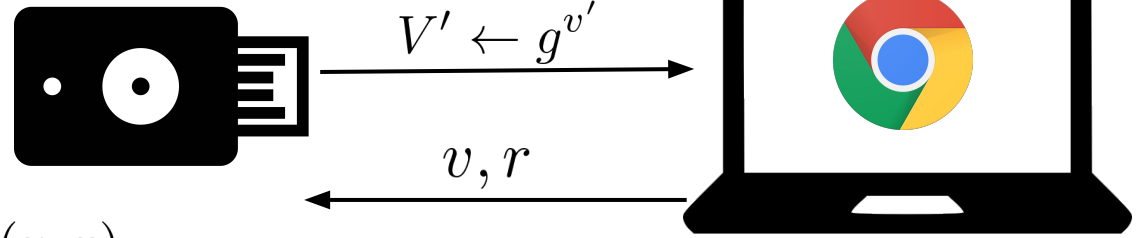

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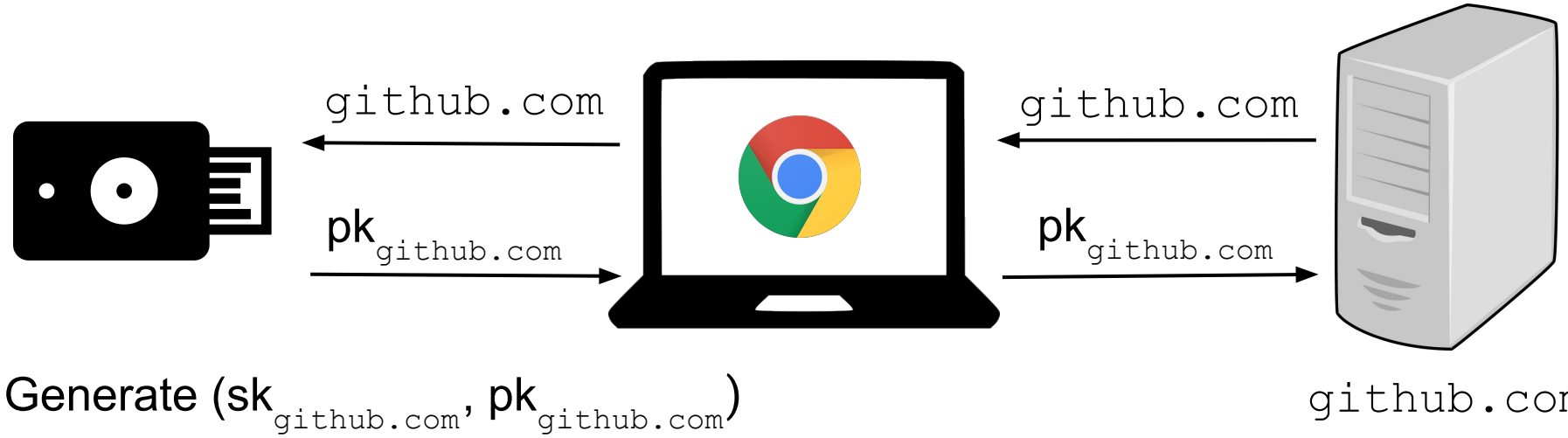
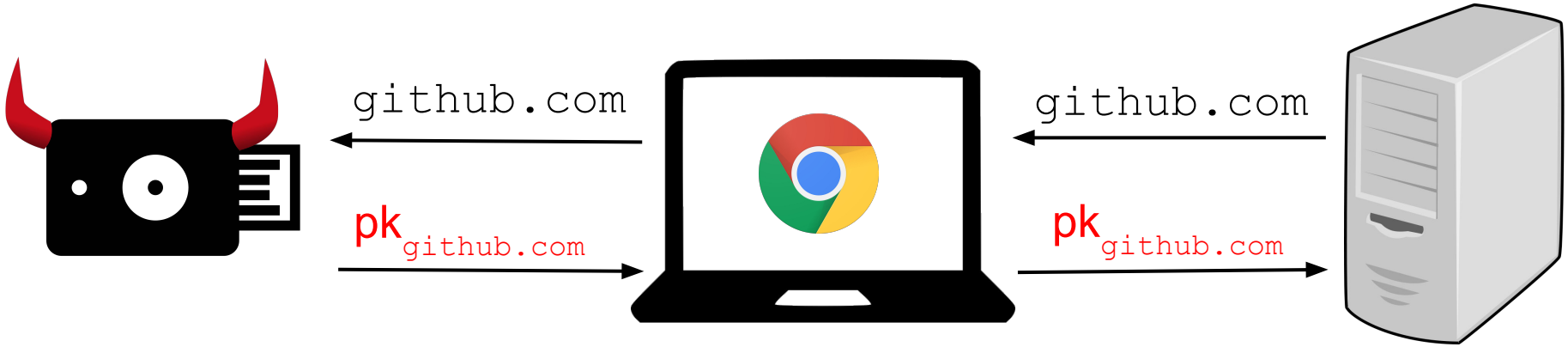
U2F Registration

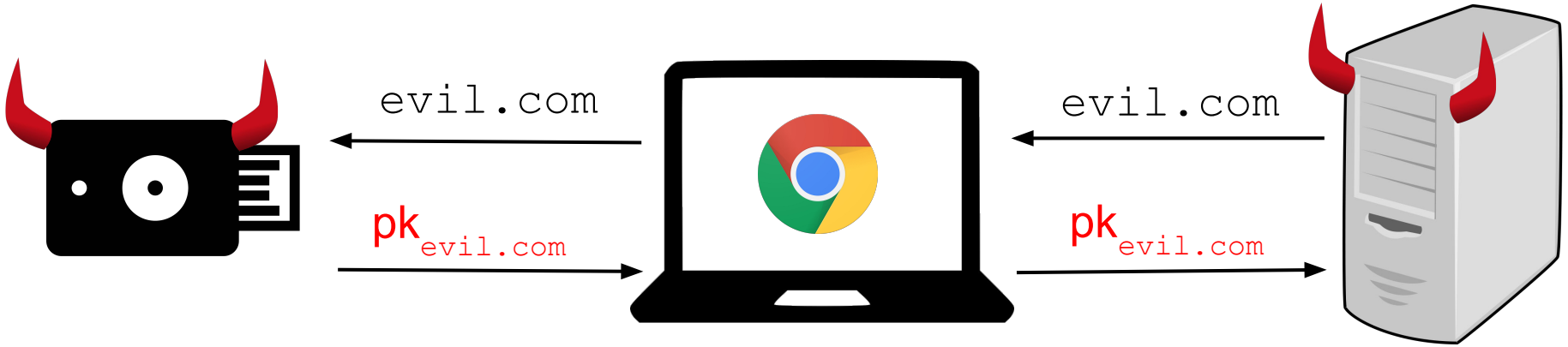


Implementation bug at registration



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

Supply-chain tampering at registration



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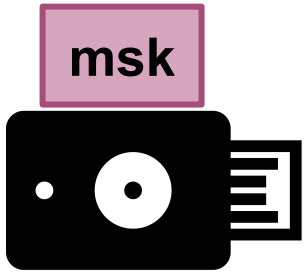

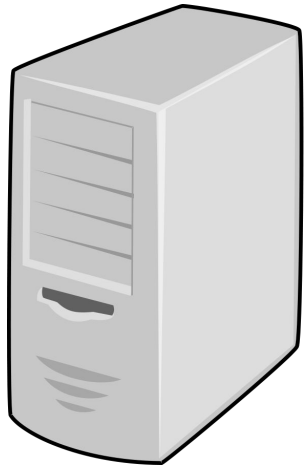

Derive per-account keypairs in a **deterministic** and **verifiable** way from the master keypair.

Registration properties

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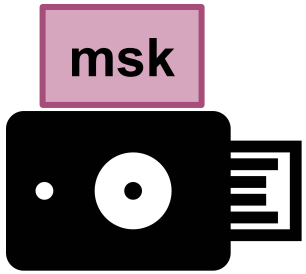

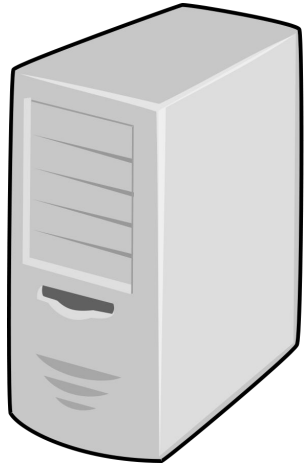

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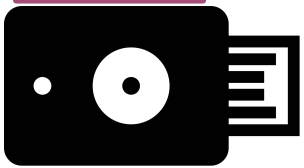

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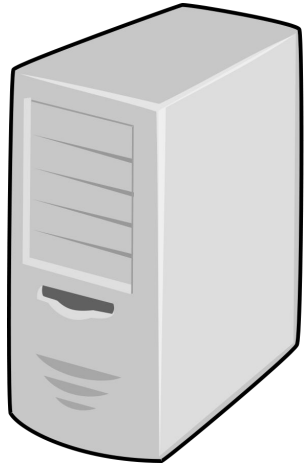

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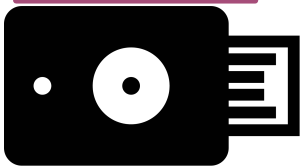

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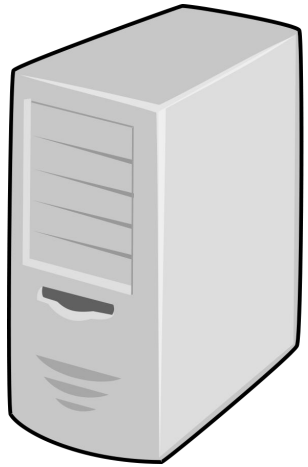

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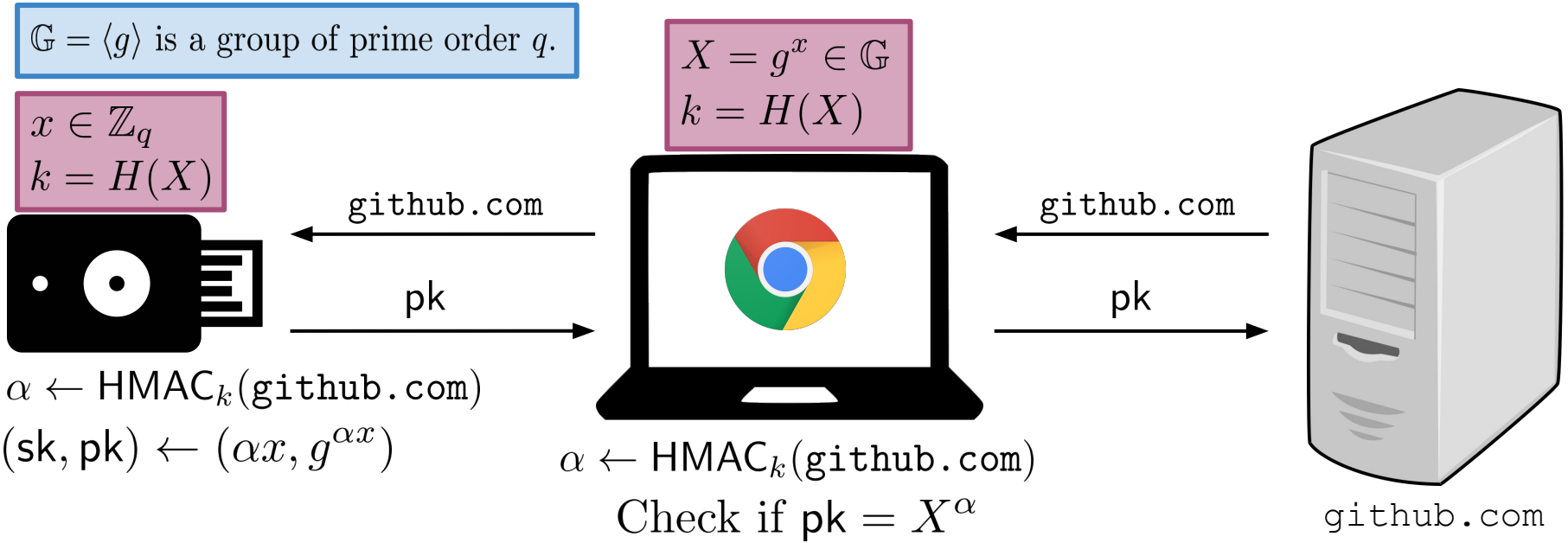

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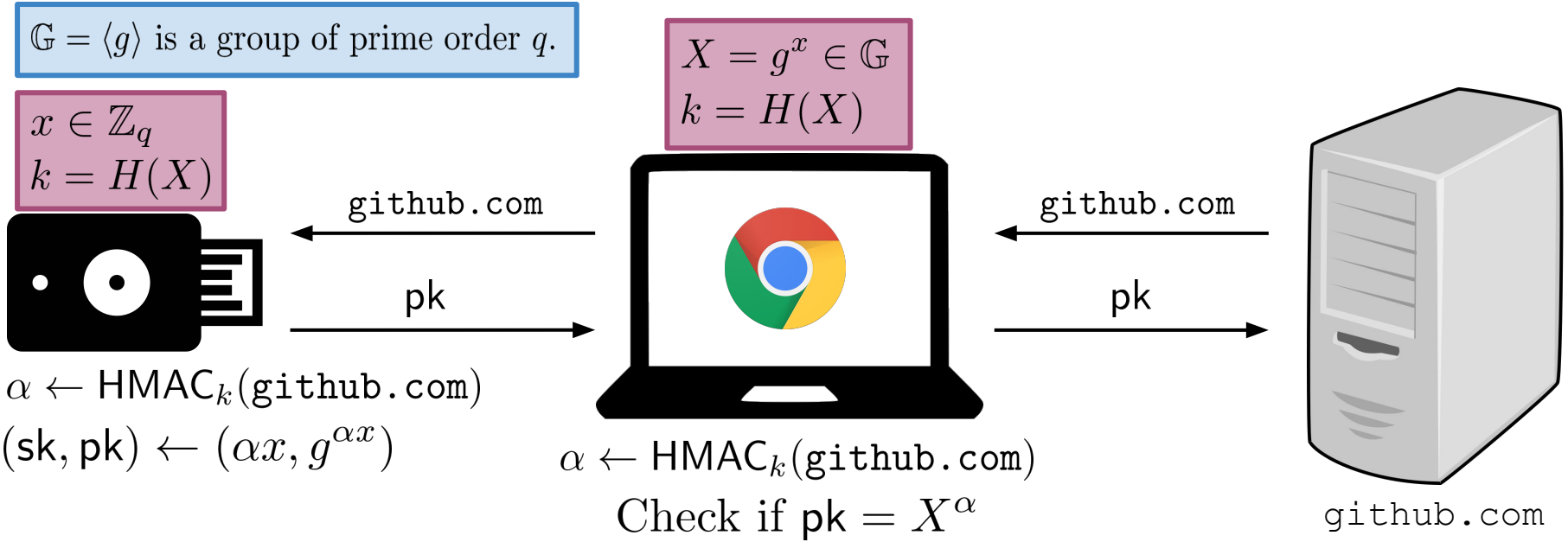

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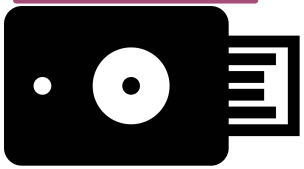

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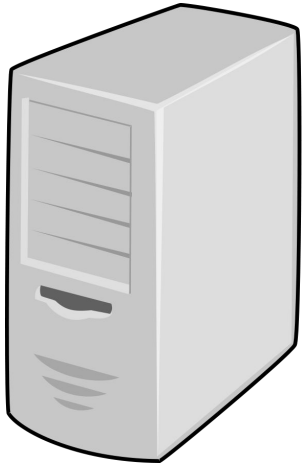

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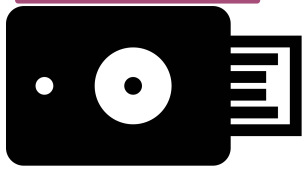

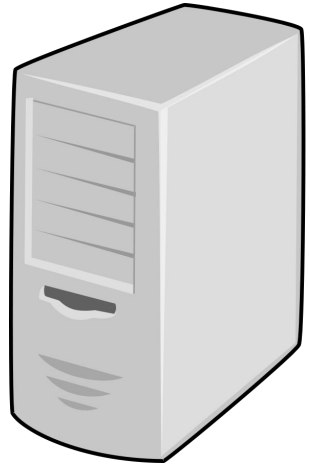

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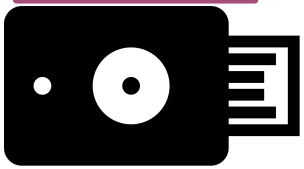

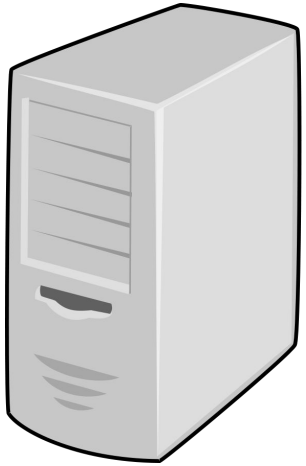

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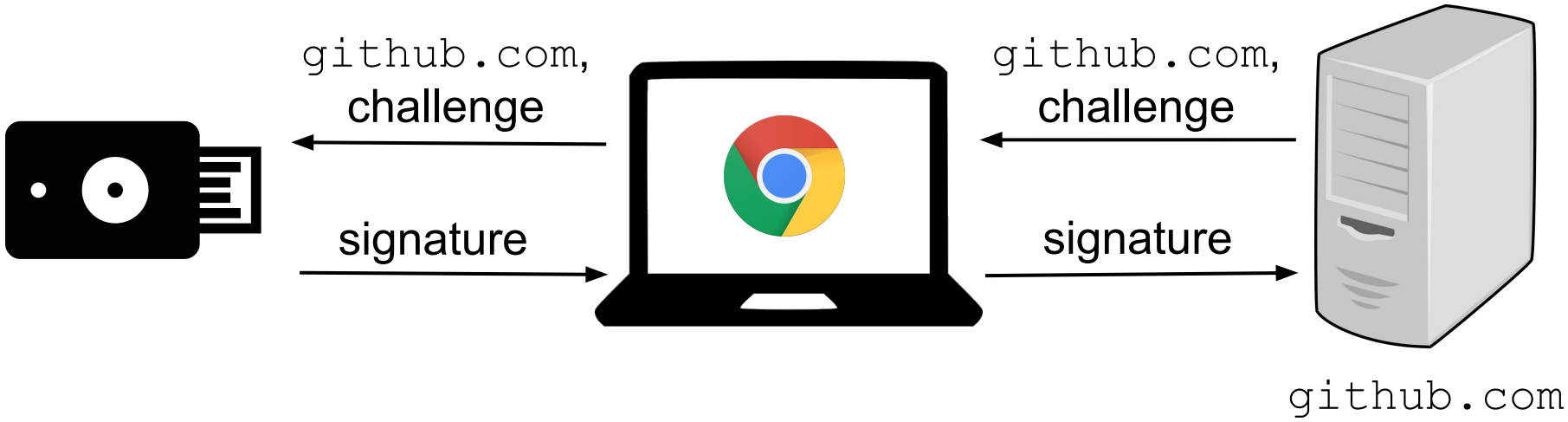
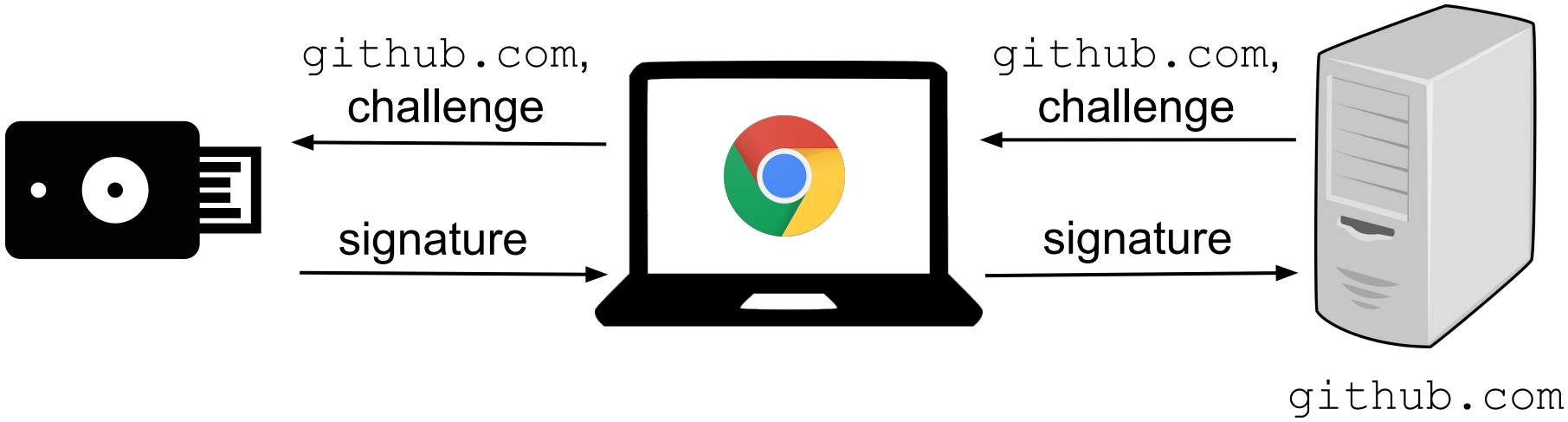


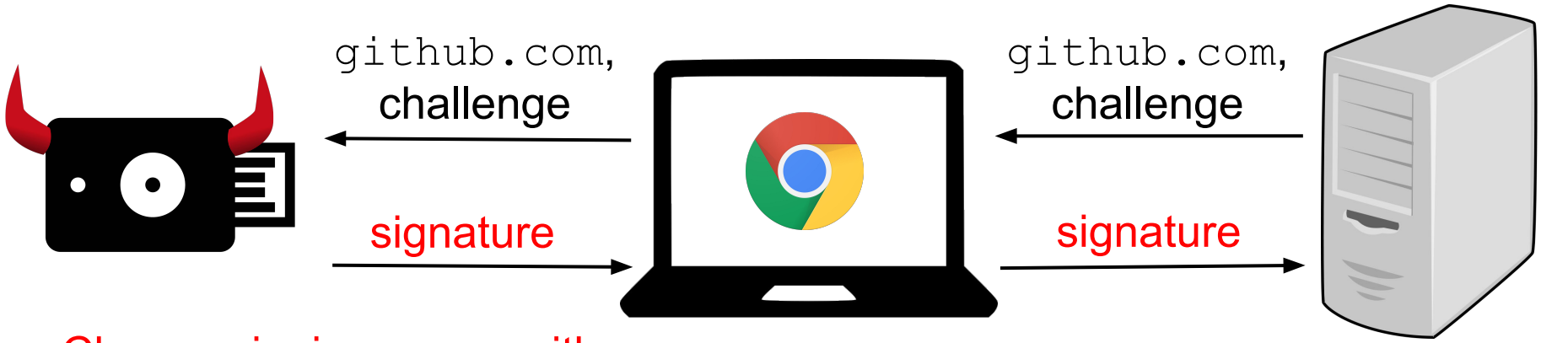
U2F Authentication



ECDSA signatures are randomized:

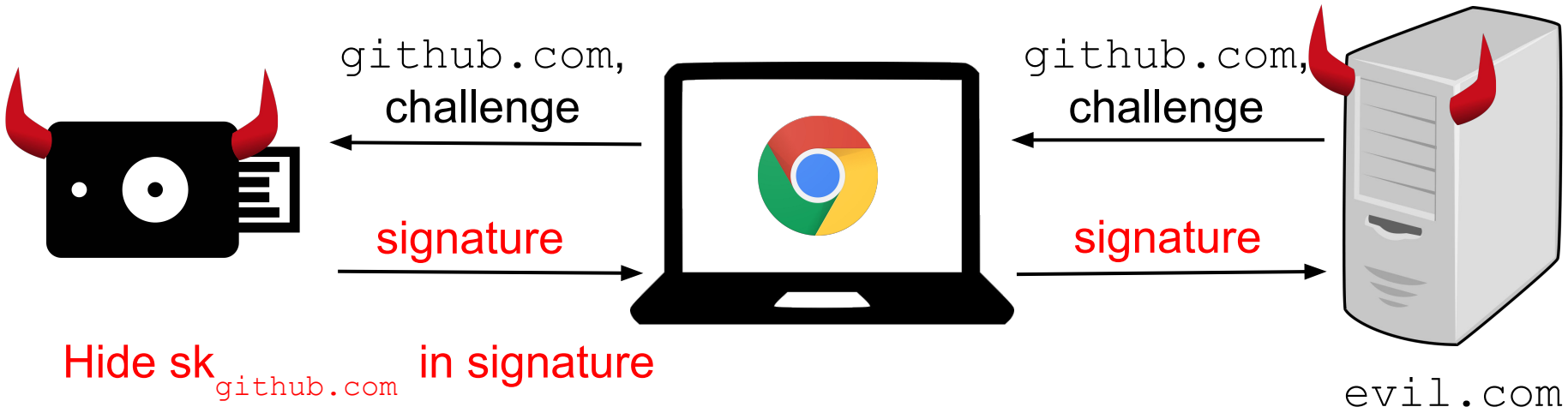
1. Signing nonce
2. Malleability (2 valid signatures)

Implementation bug at authentication



Choose signing nonce with weak randomness

Supply-chain tampering at authentication



Subliminal channels: [Sim84], [Des88]
Unique signatures: [BLS04]

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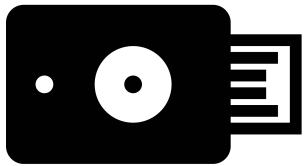

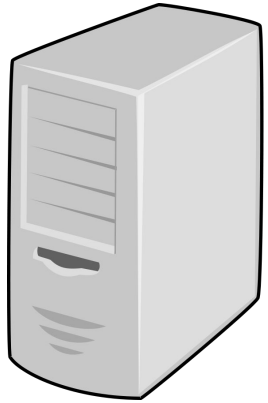

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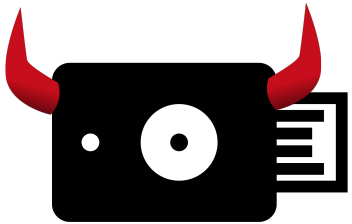
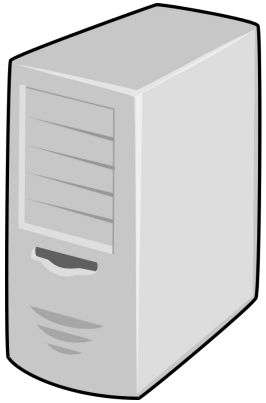
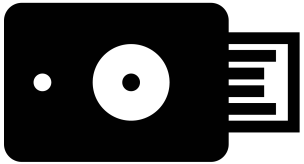


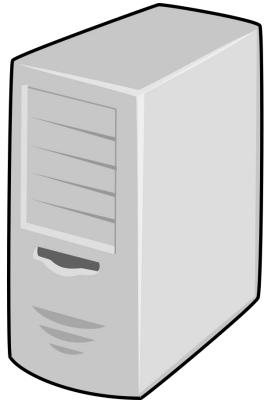


Exfiltration resistance: Token cannot exfiltrate any bits of information in signature.

[AMV15], [MS15], [DMS16]

Authentication properties



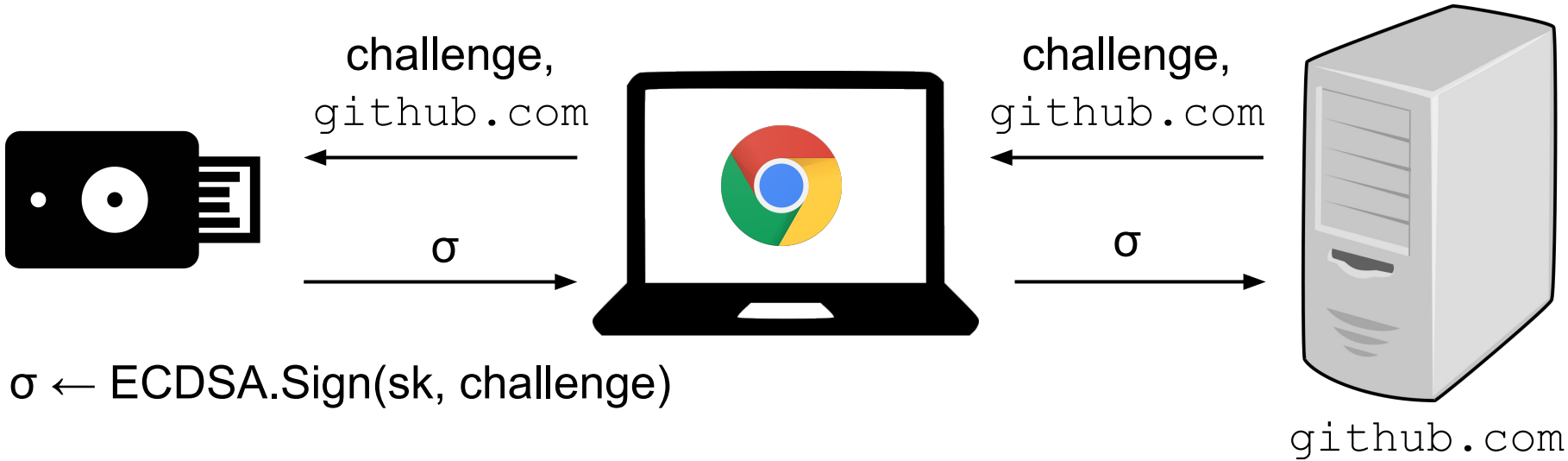


Exfiltration resistance: Token cannot exfiltrate any bits of information in signature.

Zero knowledge: Host “learns nothing” except a valid signature.

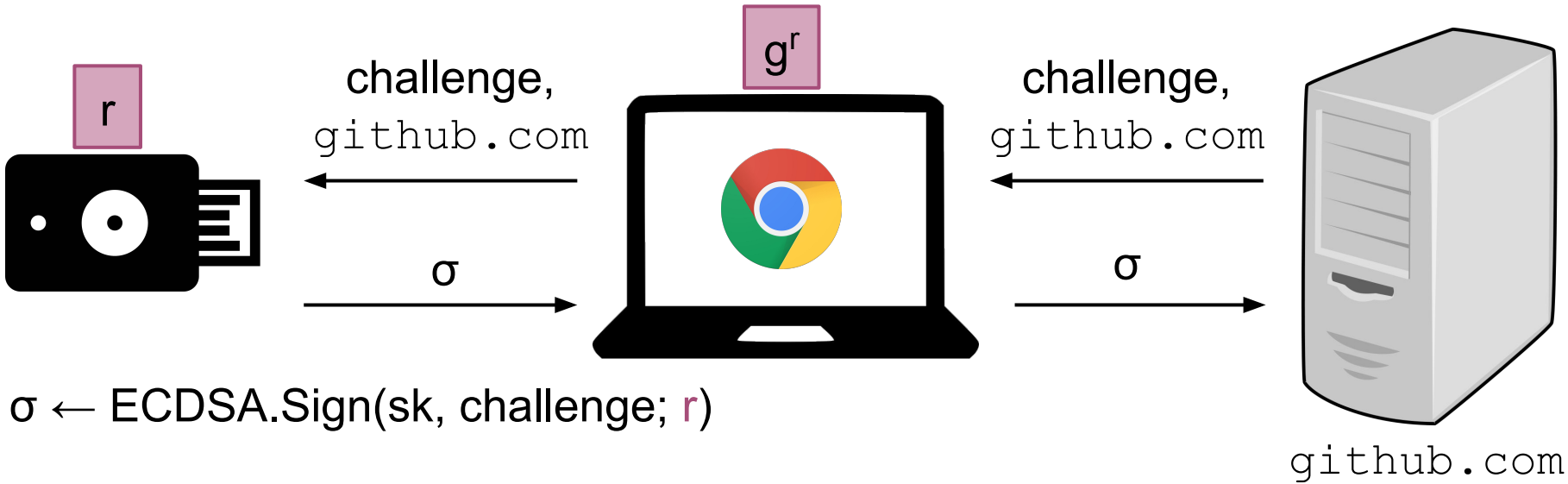
[AMV15], [MS15], [DMS16]

Authentication construction idea



σ ← ECDSA.Sign(sk, challenge)

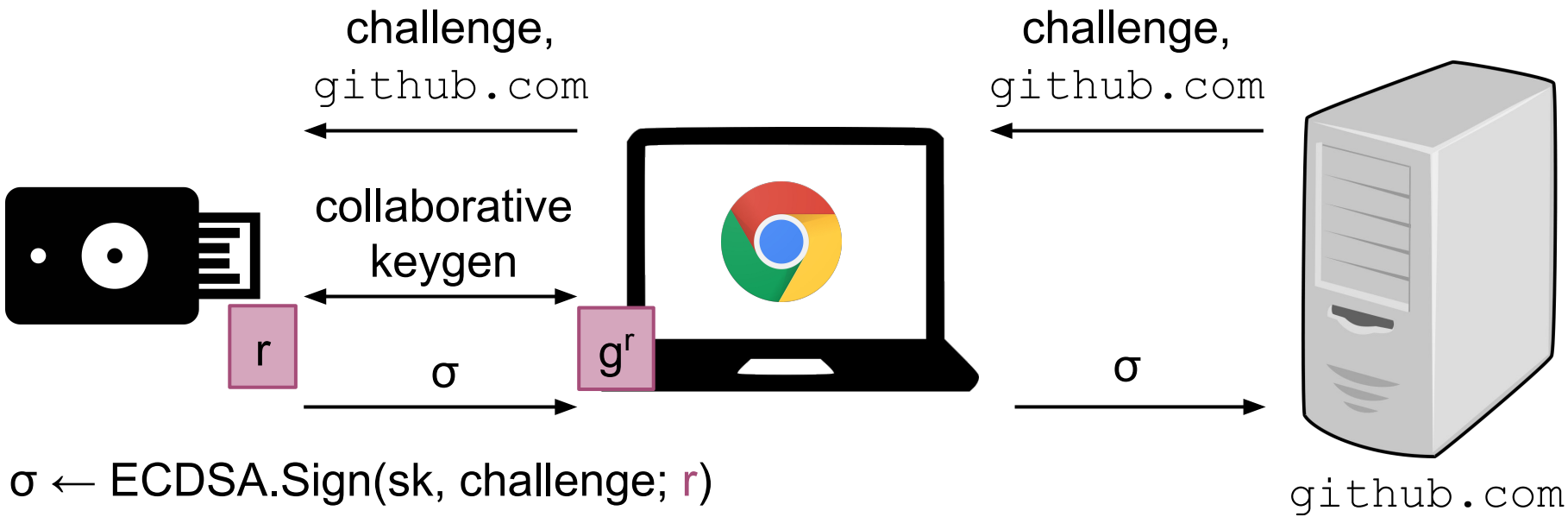
Authentication construction idea



σ ← ECDSA.Sign(sk, challenge; r)

Use g^r to verify that r is used in σ.

Authentication construction idea



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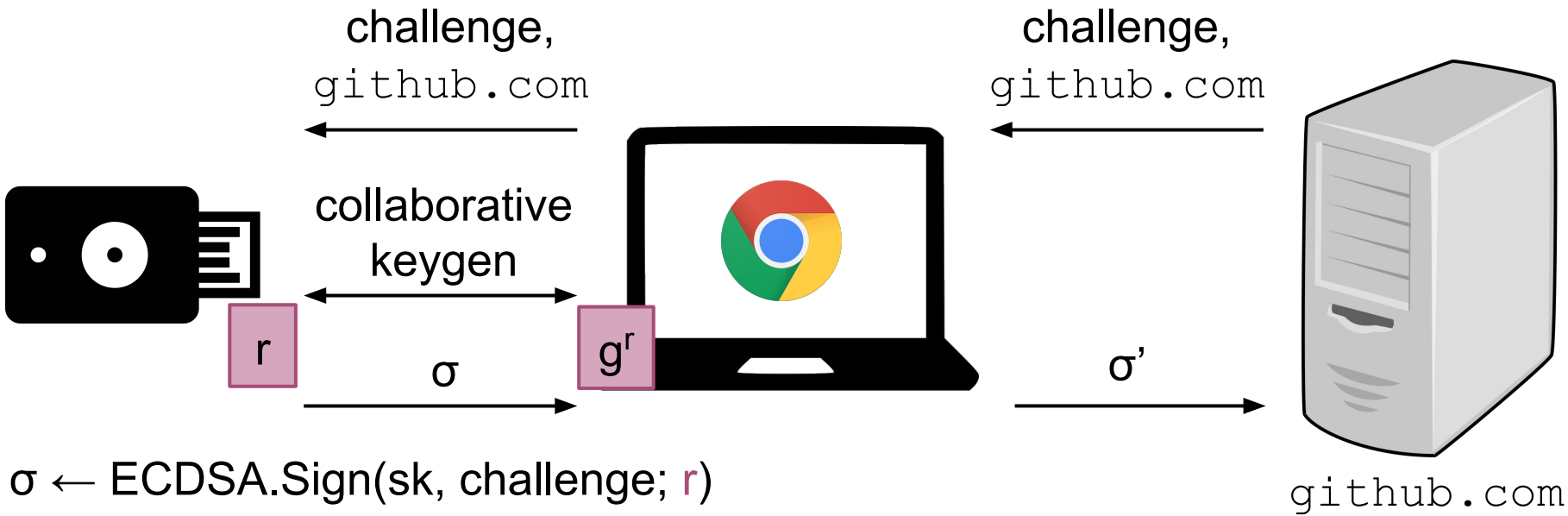
Authentication construction idea



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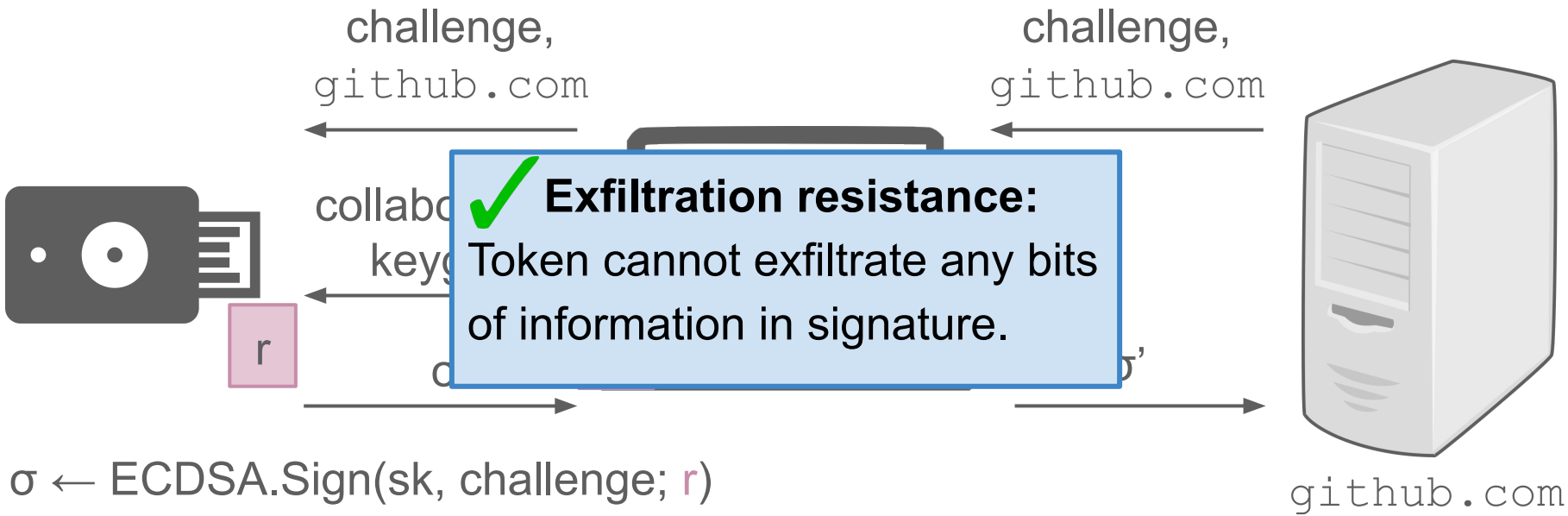
Randomly choose σ' from two
valid signatures.

Authentication construction idea



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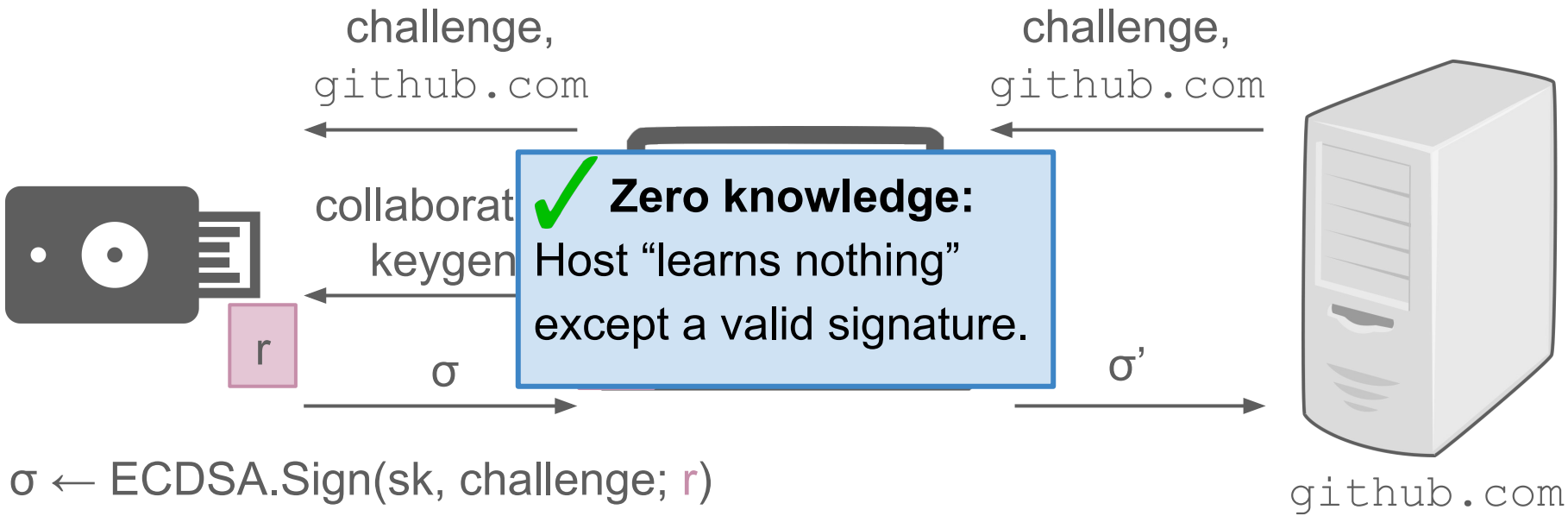


σ ← ECDSA.Sign(sk, challenge; r)

Use g^r to verify that r is used in σ.
Randomly choose σ' from two
valid signatures.

Proposed protocol steps

✓0. Initialization (after purchasing a token)

✓1. Registration (associating a token with an account)

✓2. Authentication (logging into an account)

“Out-of-protocol” covert channels

Our protocol defends against “in-protocol” covert channels.

What about “out-of-protocol” covert channels?

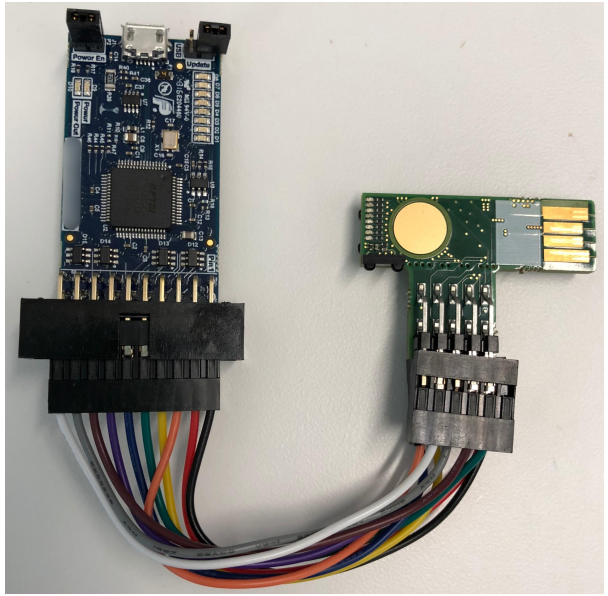
1. Timing: can be prevented by host
2. Failure: discard bad tokens
3. Malware
4. Other

[Hu92], [CBS04]

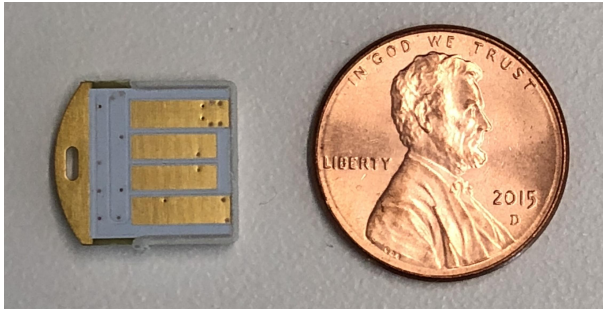
Other contributions (see paper)

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

Implementation



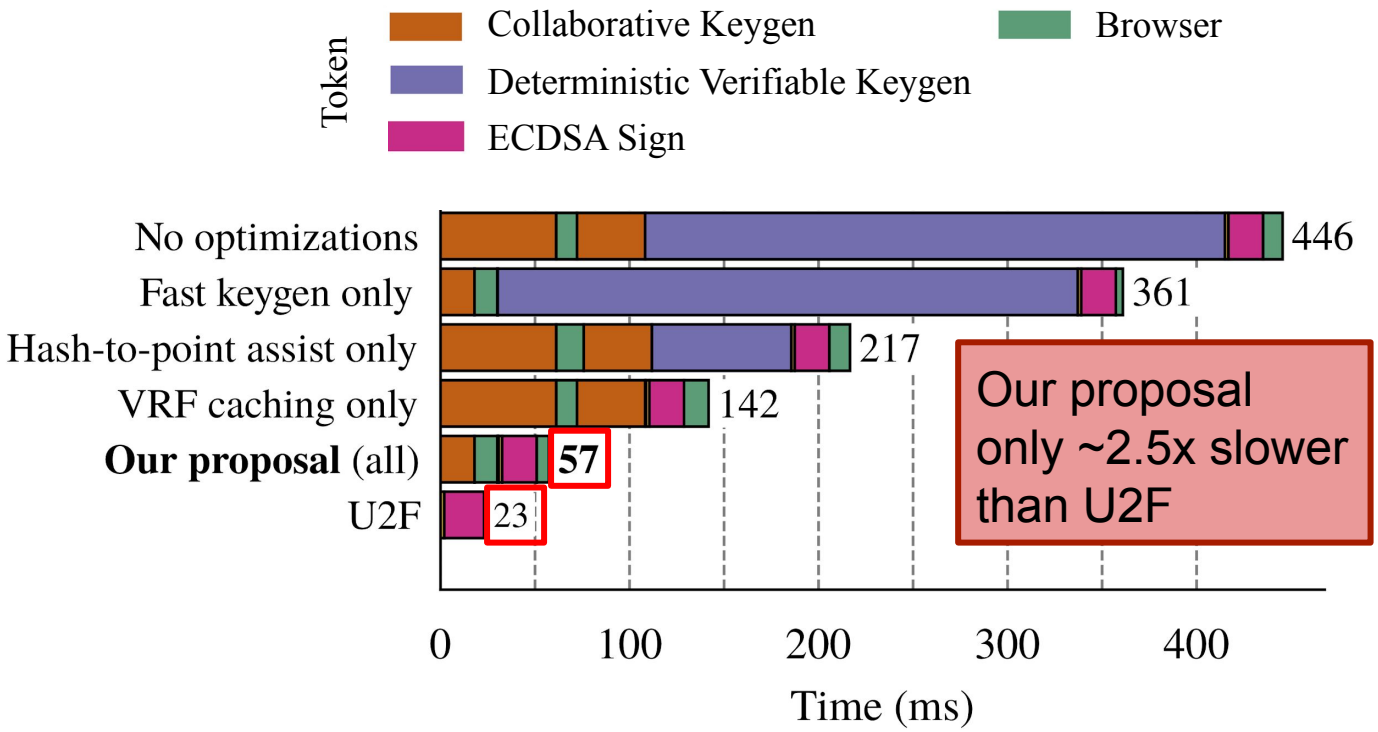
Google development board running our protocol.



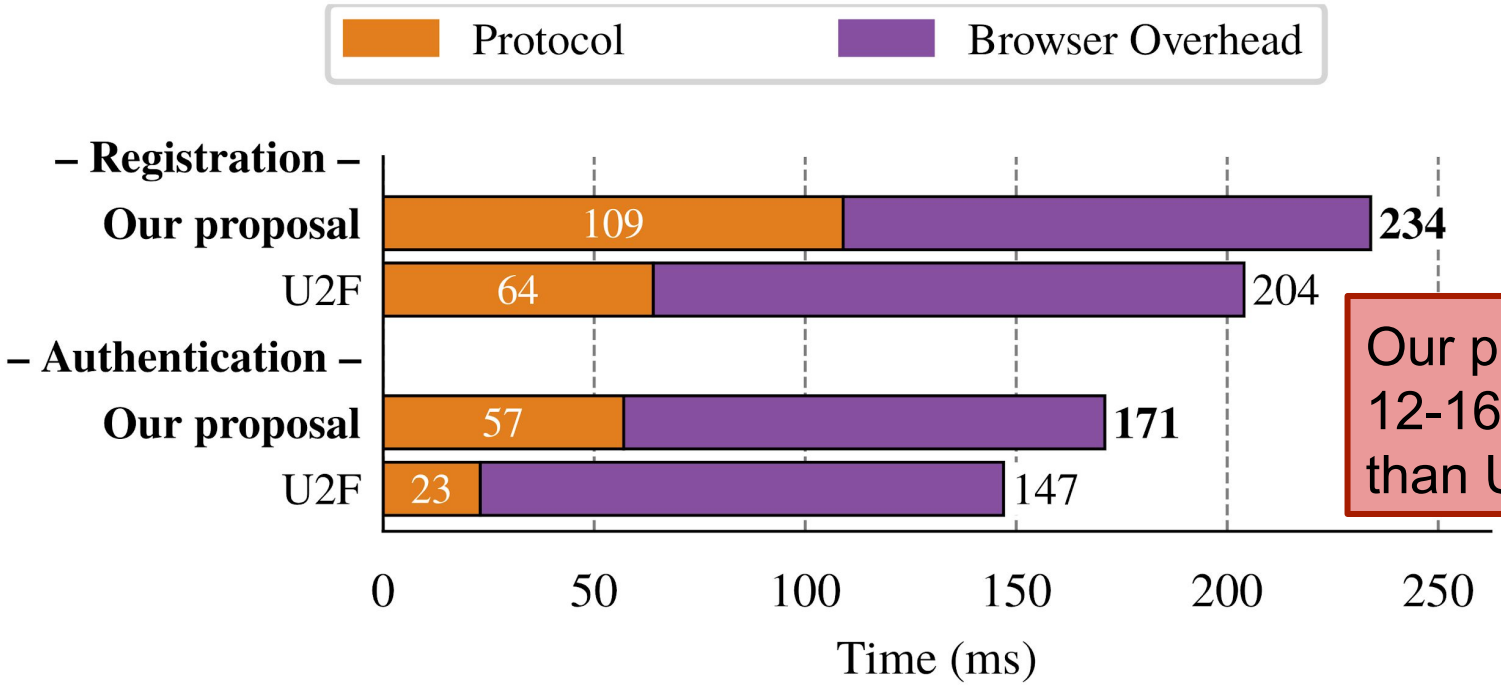
Google production USB token with same hardware specs.

ARM SC-300 processor clocked at 24 MHz

Minimal authentication overhead



Comparatively small end-to-end slowdown



Our protocol only 12-16% slower than U2F

Deployment considerations

Deployment considerations

How does the browser UI change?

- *Initialization*: prompt user to initialize unknown token
- *Errors:* warn user on token failure

Deployment considerations

How does the browser UI change?

- *Initialization*: prompt user to initialize unknown token
- *Errors:* warn user on token failure

How to support multiple browsers?

- Token gives mpk and counter to browser (protect against bugs)
- Sync mpk and counter across browser instances

CTAP2

- Cryptographic constructions carry over to CTAP2 (ECDSA P256).
- Core ideas remain, but still need full analysis.

Withstand untrustworthy hardware

Our proposal

- Augments U2F to protect against **faulty tokens**
- **Backwards-compatible** with U2F relying parties

Practical to deploy: performant on commodity hardware tokens

What is the next step?

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https://arxiv.org/abs/1810.04660
Paper to appear at IEEE S&P 2019

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Table 7: Cost of various operations on the token, averaged over 100 runs, and the expected number of each operation required per authentication attempt. "HW?" indicates use of the token's crypto accelerator.

Operation	**HW?**	**Time** (µs)	**Ops. per auth.**					
			No opts.	+ Fast keygen	+ VRF caching	+ Hash assist	**True2F** (+ all)	U2F
SHA256 (128 bytes)	Y	19	5	5	3	5	3	1
$x + y \in \mathbb{Z}_q$	N	36	17	16	2	15	1	0
$x \cdot y \in \mathbb{Z}_q$	N	409	9	8	2	11	1	0
$g^x \in \mathbb{G}$	Y	17,400	7	5	3	7	1	0
ECDSA.Sign	Y	18,600	1	1	1	1	1	1
$g \cdot h \in \mathbb{G}$	N	25,636	1	0	1	1	0	0
$\sqrt{x} \in \mathbb{Z}_q$	N	105,488	2	2	0	0	0	0