Password-Hardened Encryption Revisited

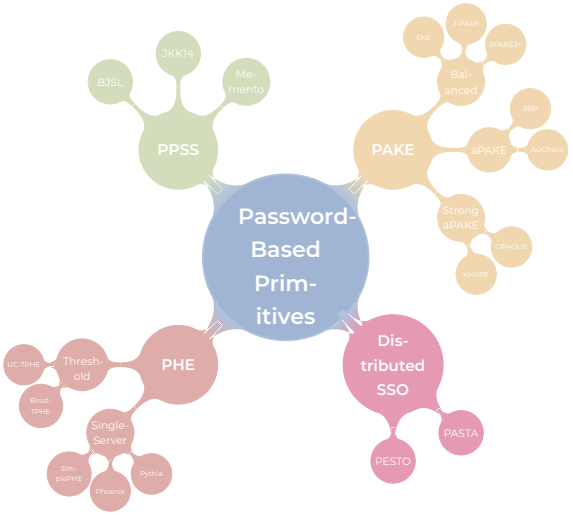
Ruben Baecker, Paul Gerhart, and Dominique Schröder

Why Password Hardened Encryption?

We found an attack...

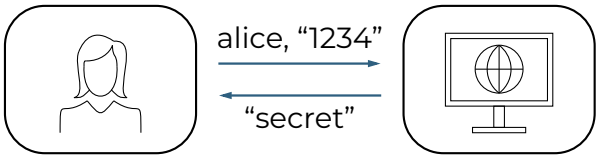
...caused by an insufficient security model

Password-Based Primitives



The Problem with **Database Breaches**

$\mathsf{H}(\text{“1234”}, 2181) = b481$



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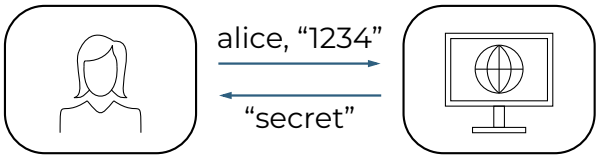

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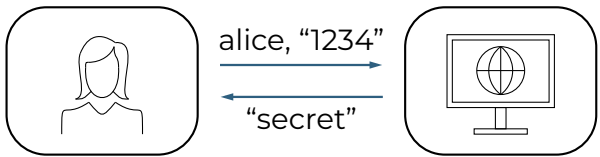

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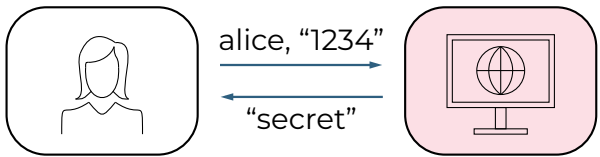

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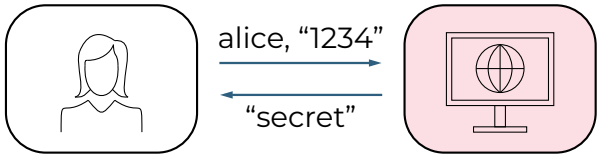

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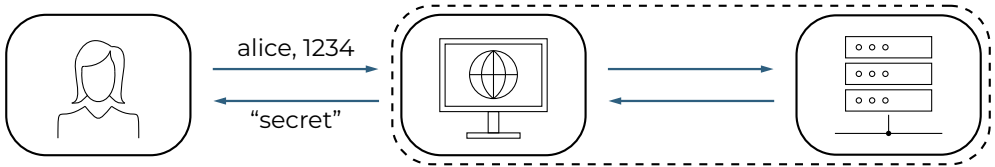
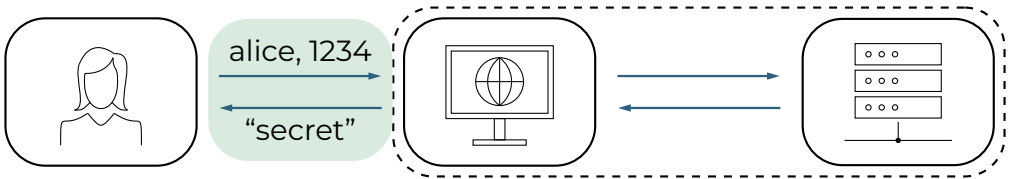
PHE: Distributing Trust

ECSJR'15 (USENIX), SFSB'16 (CCS), LESC'17 (USENIX), LERCMS'18 (USENIX), BELSSZ'20 (CCS)



PHE: **Oblivious** To The User

- The user does not have to do crypto
- The user-server interface is unchanged
- PHE protects **ALL** users



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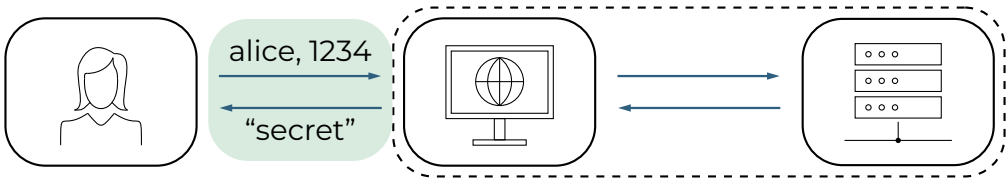

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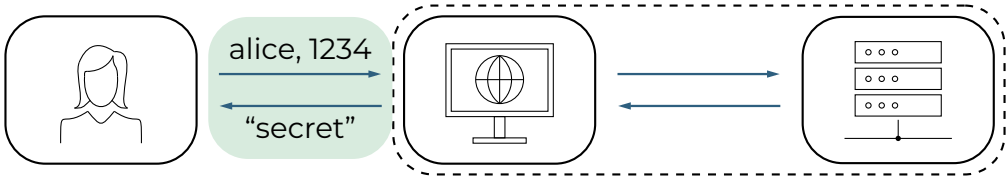

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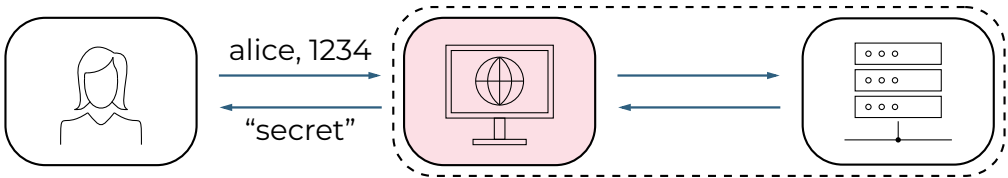
- Online interaction with ratelimiter necessary for password validation and decryption
- Ratelimiter rate-limits authentication attempts on a **per-user** basis



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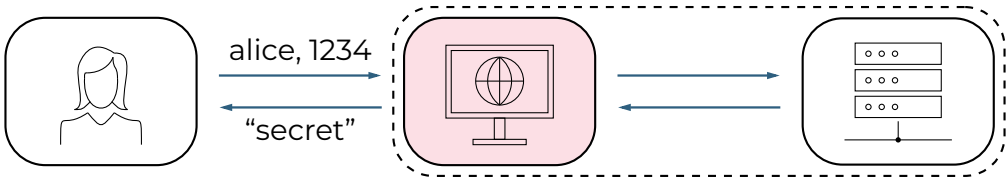

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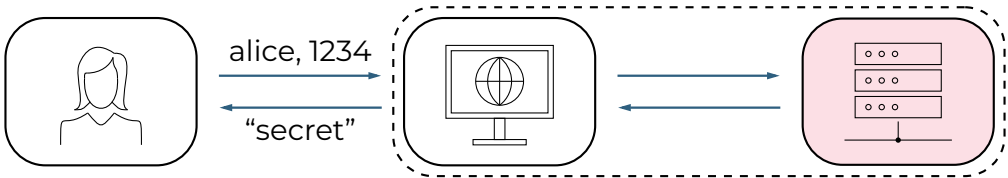
- Ratelimiter learns **nothing** about the password or the encrypted message
- Ratelimiter cannot convince the server of a wrong outcome
- Ratelimiter operates in a **zero-trust** fashion
- Ratelimiter only requires **constant** storage



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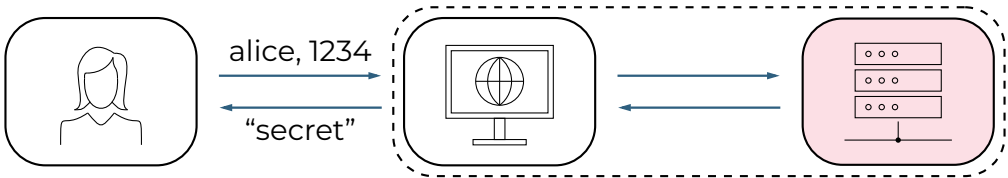

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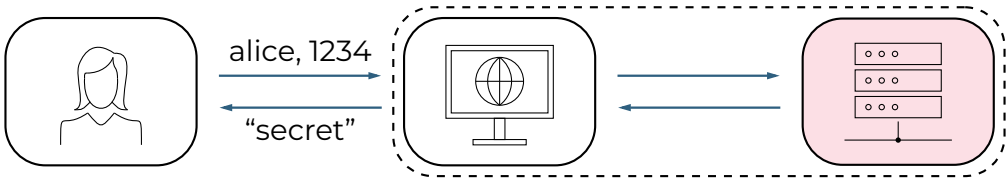

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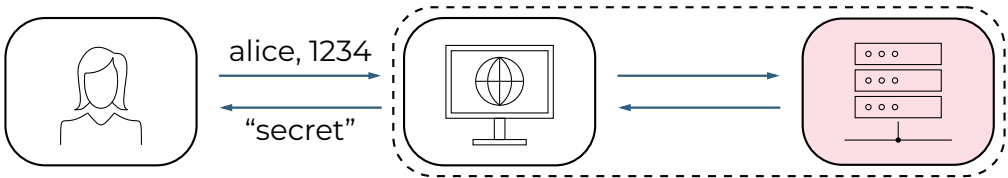
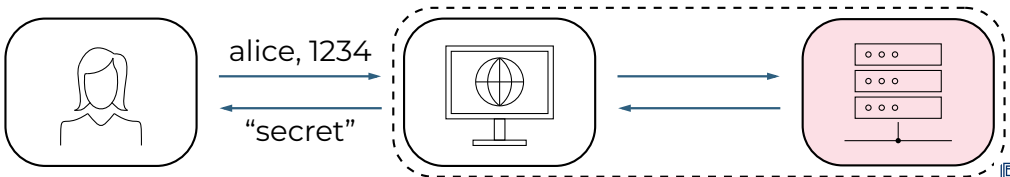


PHE: **Restoring Security** After Corruption

- After one corruption, we're back to a **single point of failure**
- Key rotation resets corruptions
- Provides security even against **alternating corruptions**
- Key rotation is best practice in the industry and required by PCI-DSS and NIST standards
- Requires no user interaction and is of constant communication size



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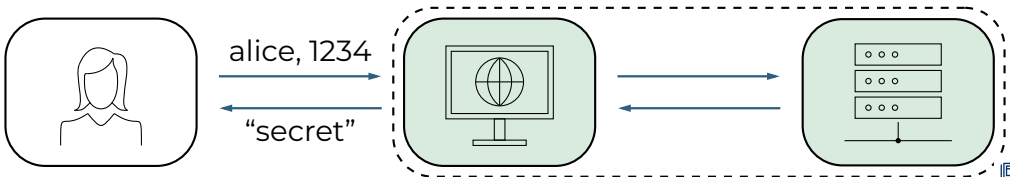

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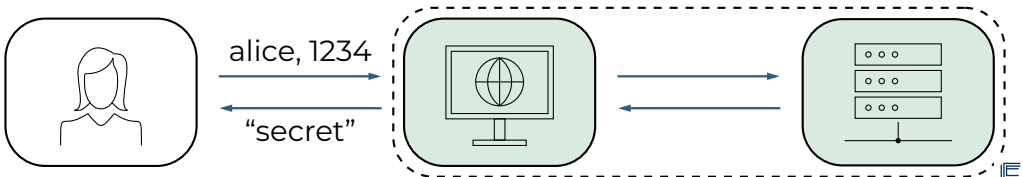

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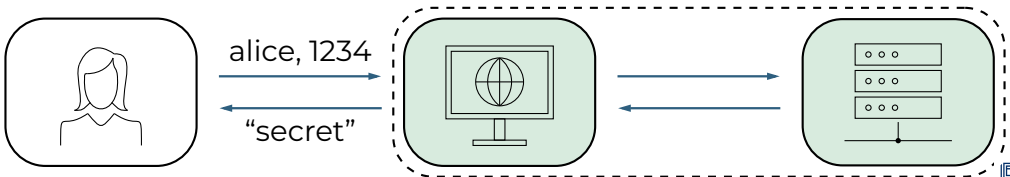

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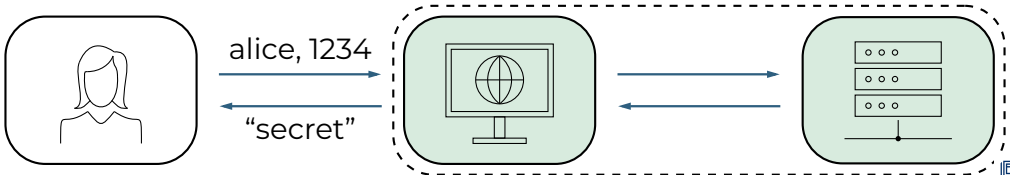

Why Password Hardened Encryption?

We found an attack...

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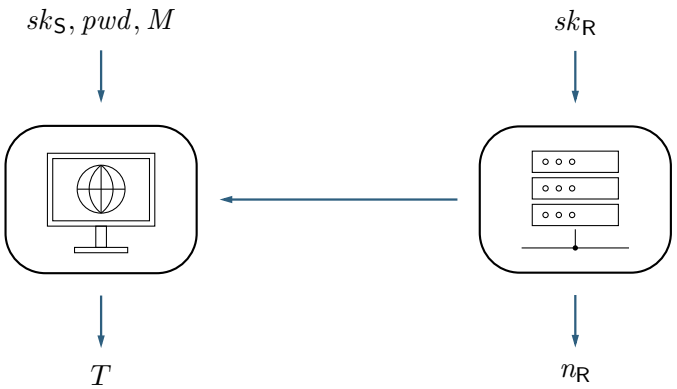
Simple PHE – LERCMS'18

$$T = (t_0, t_1, n_{\mathsf{S}}, n_{\mathsf{R}})$$
$$t_0 = F^0_{sk_{\mathsf{S}}}(pwd, n_{\mathsf{S}}) \cdot F^0_{sk_{\mathsf{R}}}(n_{\mathsf{R}})$$
$$t_1 = F^1_{sk_{\mathsf{S}}}(pwd, n_{\mathsf{S}}) \cdot F^1_{sk_{\mathsf{R}}}(n_{\mathsf{R}}) \cdot M$$

- t_0 is used for the password check
- t_1 hides the message
- commercialized by Virgil Security

FAU

Simple PHE **Encryption**



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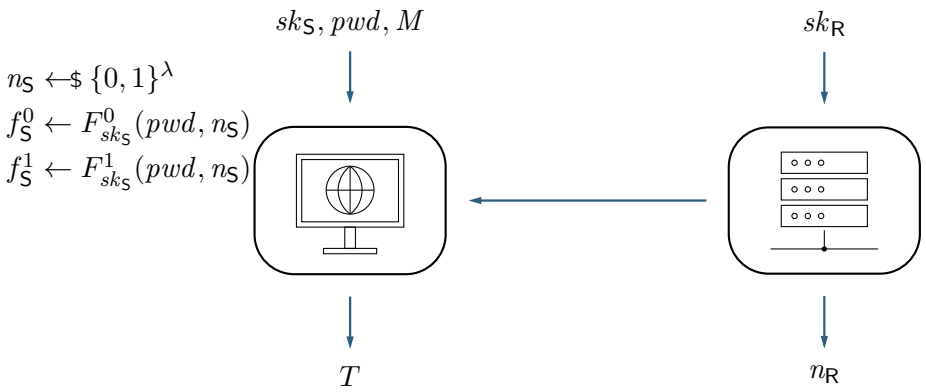

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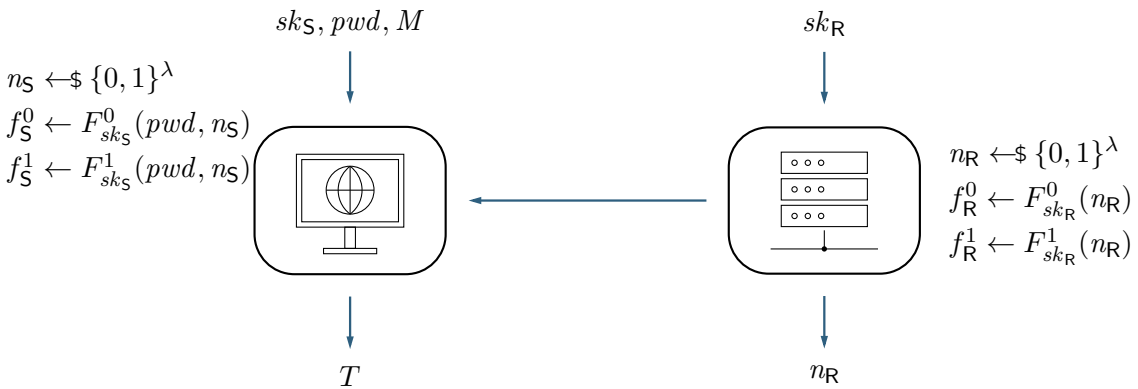

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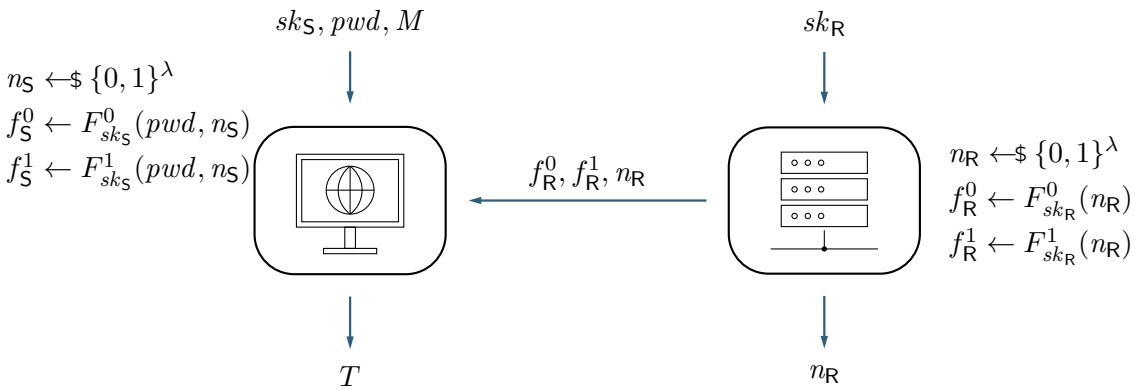

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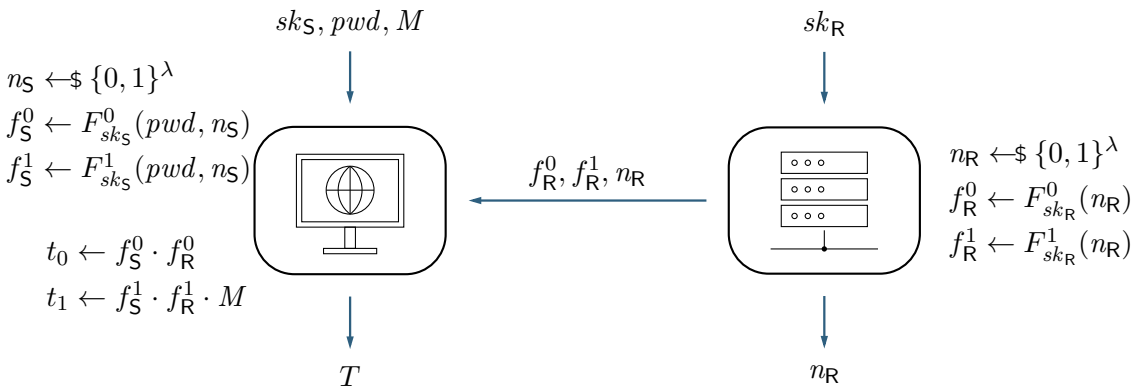

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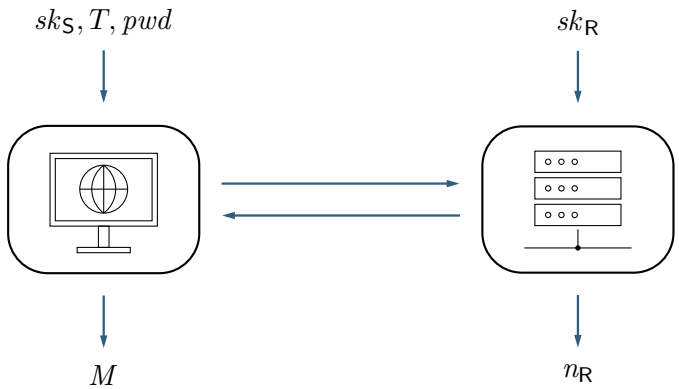

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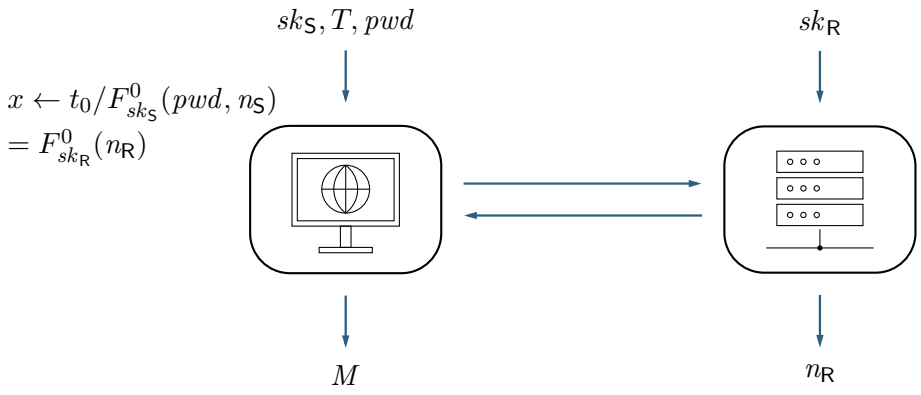

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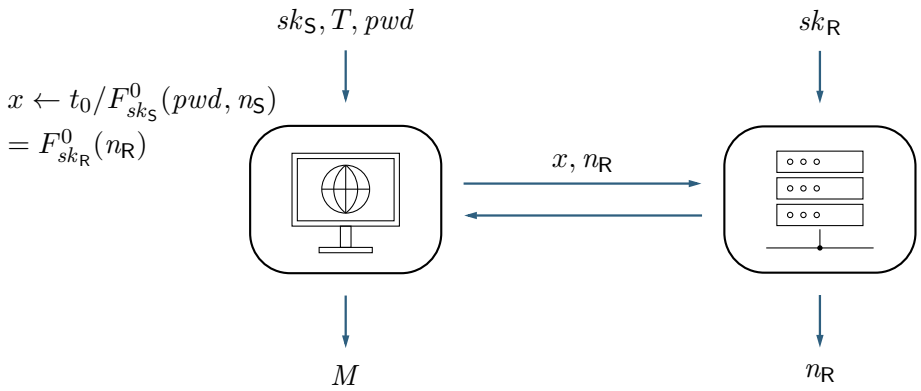

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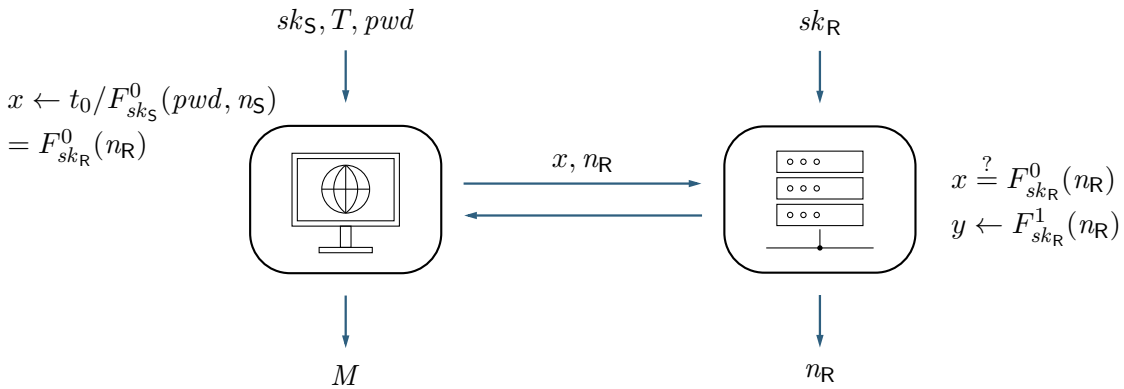

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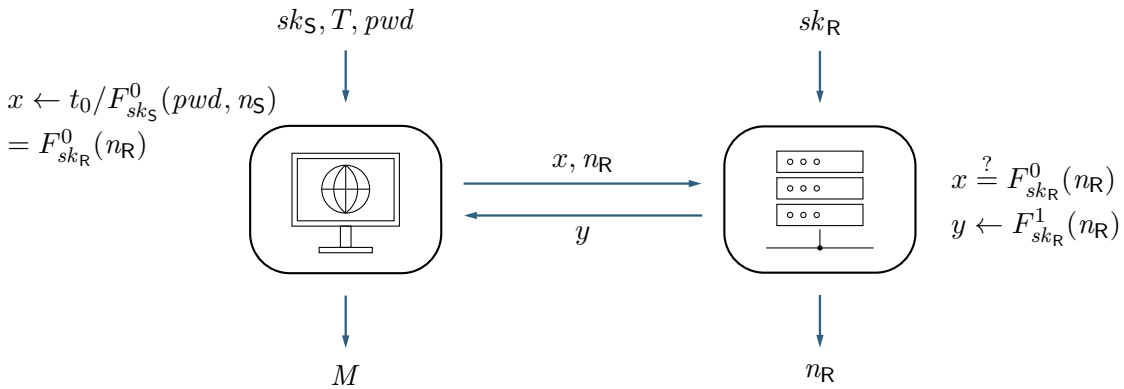

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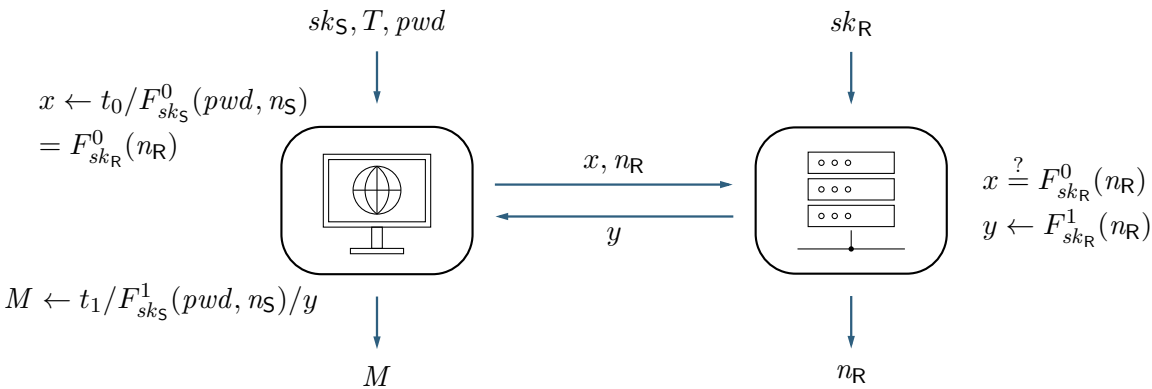

The Attack: Malicious Ratelimiter

Step 0: The target user is already enrolled with the secure password secPW

$$t_0^{\mathsf{hon}} = F^0_{sk_\mathsf{S}}(\mathsf{secPW}, n_\mathsf{S}^{\mathsf{hon}}) \cdot F^0_{sk_\mathsf{R}}(n_\mathsf{R}^{\mathsf{hon}})$$
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Step 1: Corrupt the ratelimiter and enroll malicious user with known password malPW reusing $n_\mathsf{R}^{\mathsf{hon}}$

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The Attack: Malicious Server

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Step 3: Extract $F^0_{sk_R}(n_R^{hon})$ from $t_0^{mal} = F^0_{sk_S}(\mathsf{malPW}, n_S^{mal}) \cdot F^0_{sk_R}(n_R^{hon})$

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Step 4: Extract $F^0_{sk_S}(\mathsf{secPW}, n_S^{hon})$ from $t_0^{hon} = F^0_{sk_S}(\mathsf{secPW}, n_S^{hon}) \cdot F^0_{sk_R}(n_R^{hon})$

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FAU

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FAU

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$$F^0_{sk_\mathsf{R}}(n^{\mathsf{hon}}_\mathsf{R}) \leftarrow F^0_{sk_\mathsf{S}}(\mathsf{malPW}, n^{\mathsf{mal}}_\mathsf{S}) \cdot F^0_{sk_\mathsf{R}}(n^{\mathsf{hon}}_R) / F^0_{sk_\mathsf{S}}(\mathsf{malPW}, n^{\mathsf{mal}}_\mathsf{S})$$

Step 4: Extract $F^0_{sk_\mathsf{S}}(\mathsf{secPW}, n^{\mathsf{hon}}_\mathsf{S})$ from $t_0^{\mathsf{hon}} = F^0_{sk_\mathsf{S}}(\mathsf{secPW}, n^{\mathsf{hon}}_\mathsf{S}) \cdot F^0_{sk_\mathsf{R}}(n^{\mathsf{hon}}_\mathsf{R})$

$$F^0_{sk_\mathsf{S}}(\mathsf{secPW}, n^{\mathsf{hon}}_\mathsf{S}) \leftarrow F^0_{sk_\mathsf{S}}(\mathsf{secPW}, n^{\mathsf{hon}}_\mathsf{S}) \cdot F^0_{sk_\mathsf{R}}(n^{\mathsf{hon}}_\mathsf{R}) / F^0_{sk_\mathsf{R}}(n^{\mathsf{hon}}_\mathsf{R})$$

Step 5: Brute-force secPW from $F^0_{sk_\mathsf{S}}(\mathsf{secPW}, n^{\mathsf{hon}}_\mathsf{S})$

FAU

Why Password Hardened Encryption?

We found an attack...

...caused by an insufficient security model

Treating Attack Vectors in **Isolation**

- **Hiding:** A corrupt server does not learn an encrypted message
- **Partial Obliviousness:** A corrupt ratelimiter does not learn an encrypted message
- **Soundness:** A corrupt ratelimiter cannot convince the server of an incorrect outcome
- **Forward Security:** An updated ciphertext after key rotation is indistinguishable from a newly generated one

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A **Unified** Hiding Definition

$\mathcal{A}$ does not learn an encrypted message

- as a **corrupt server**
  (previously covered by Hiding)
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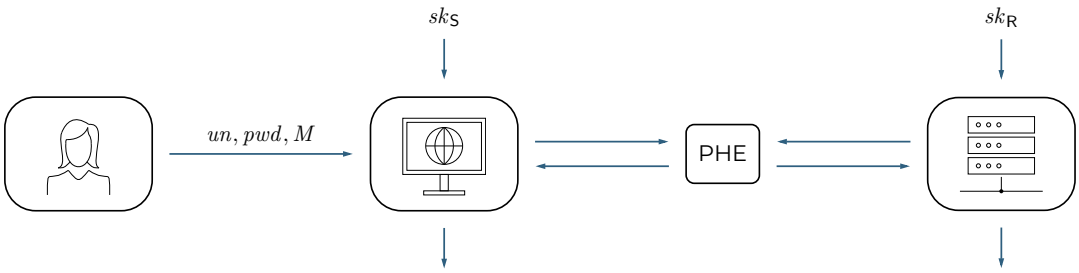
We also proposed the fastes PHE ever

HildeGUARD

Two conceptual changes enable faster PHE

FAU

Standard PHE



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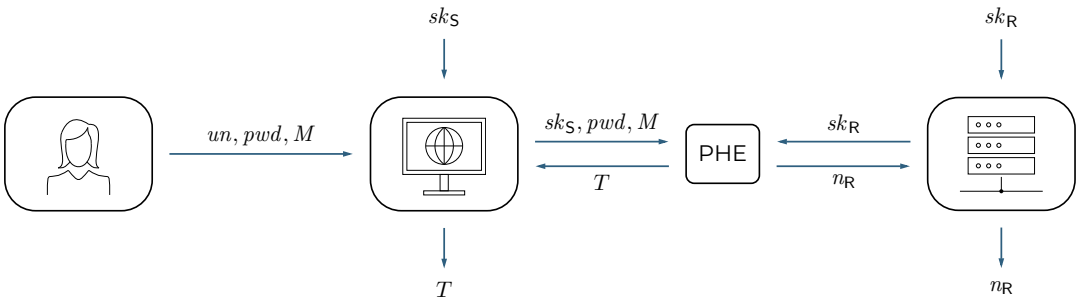
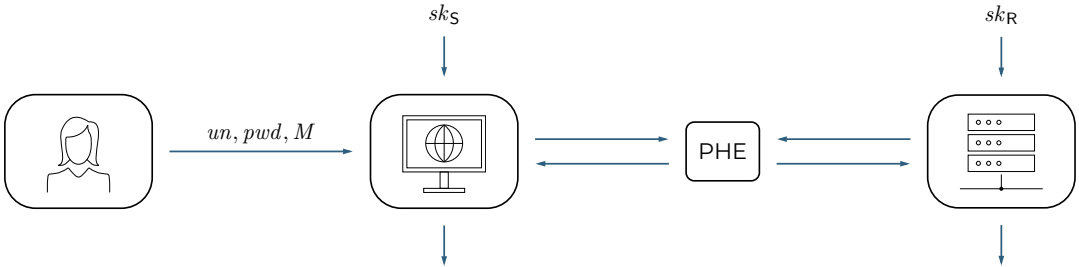


How PHE is used **in practice**



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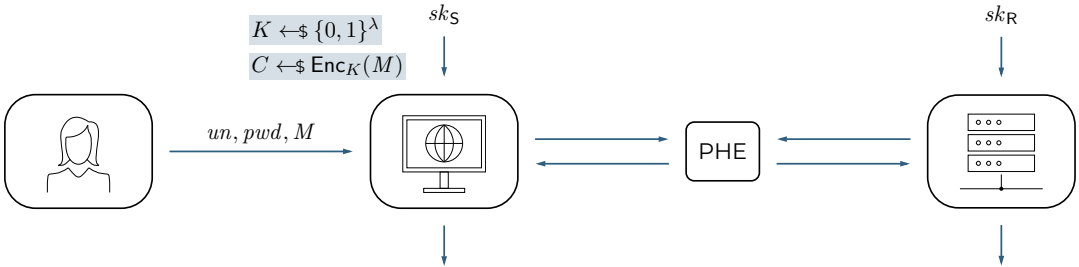

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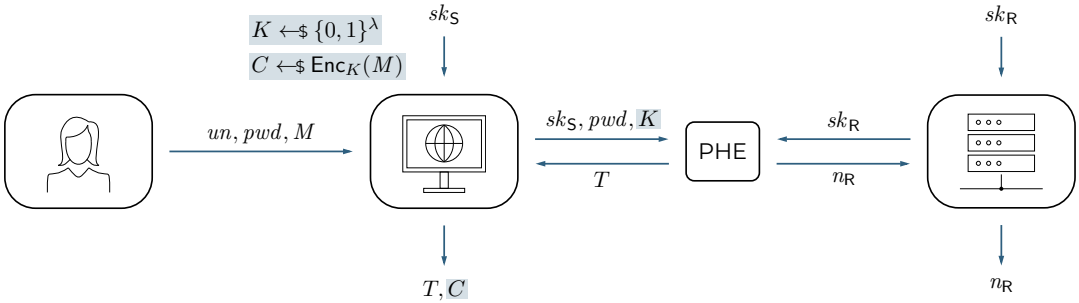
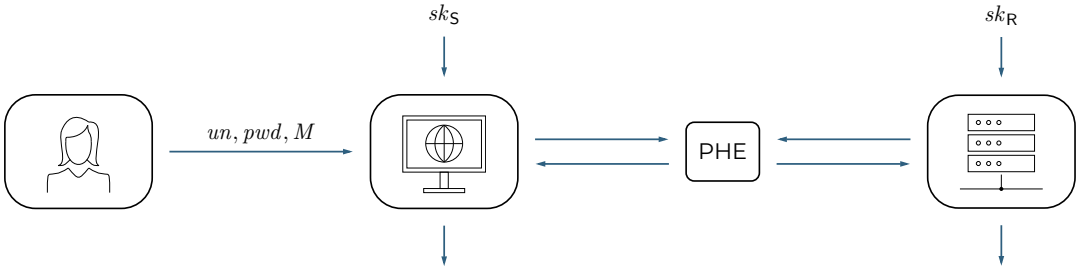


Encapsulation-style PHE



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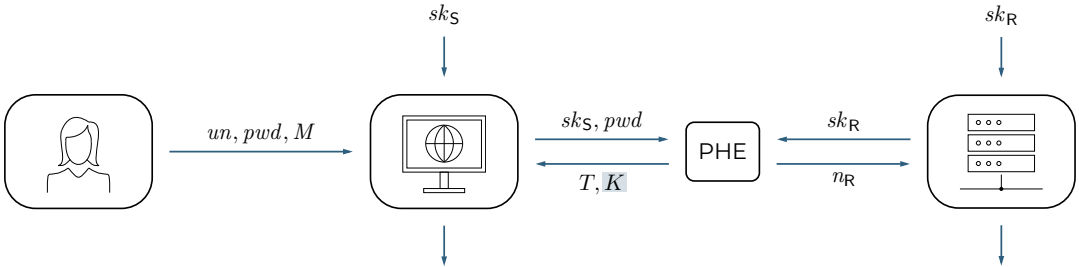

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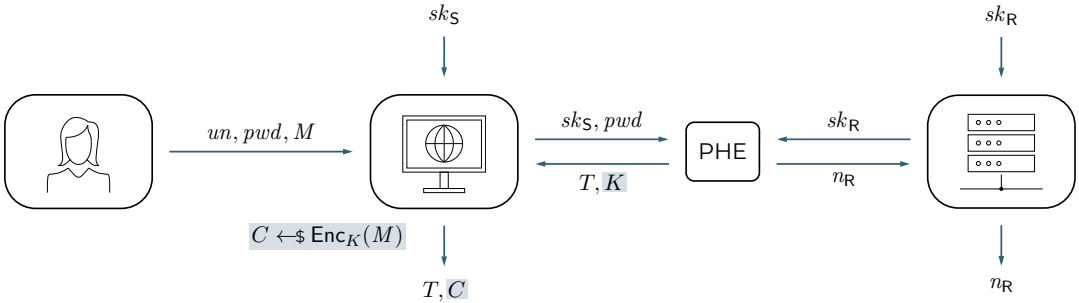

Soundness vs. Binding

Soundness (LERCMS'18)

- $\mathcal{A}$ has **two-time** oracle access
- $\mathcal{A}$ wins if **different** $M \neq M'$ are returned for the **same** pwd
- or if the **same** M is returned for **different** $pwd \neq pwd'$

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Why Binding suffices

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  - No key: **Trivially** achievable
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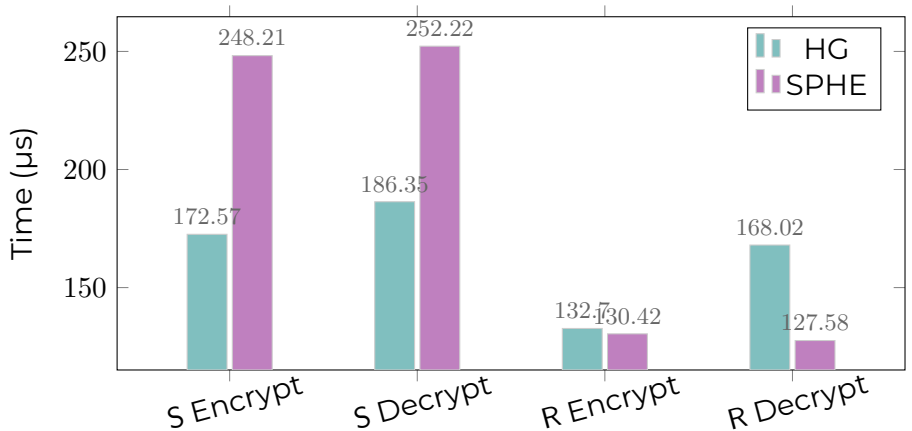
Performance Evaluation

Implemented in Rust using curve25519_dalek

Tested on MacBook Pro (M3 Pro with 36GB unified memory)



Thanks for your attention!

ruben-baecker.de

Password-Hardened Encryption Revisited
Ruben Baecker, Paul Gerhart, and Dominique Schröder
ia.cr/2025/1453

Universally Composable Password-Hardened Encryption
Behzad Abdolmaleki, Ruben Baecker, Paul Gerhart, Mike Graf, Mojtaba Khalili, Daniel Rausch, and Dominique Schröder
ia.cr/2025/1647

HildeGUARD: The Decryption Protocol

A slightly simplified enrollment record

$$T = \mathsf{Enc}_{sk_\mathsf{S}}(t_0, t_1, n)$$
$$t_0 = F^0_{sk_\mathsf{R}}(n) \cdot \mathsf{H}(pwd, n)$$
$$t_1 = F^1_{sk_\mathsf{R}}(n) \cdot K$$

Decryption:

- S obtains $F^0_{sk_\mathsf{R}}(n)$ from t_0 using pwd; R recomputes $F^0_{sk_\mathsf{R}}(n)$
- Perform a PAKE using $F^0_{sk_\mathsf{R}}(n)$ as the password
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