A Plausible Attack on the Adaptive Security of Threshold Schnorr Signatures

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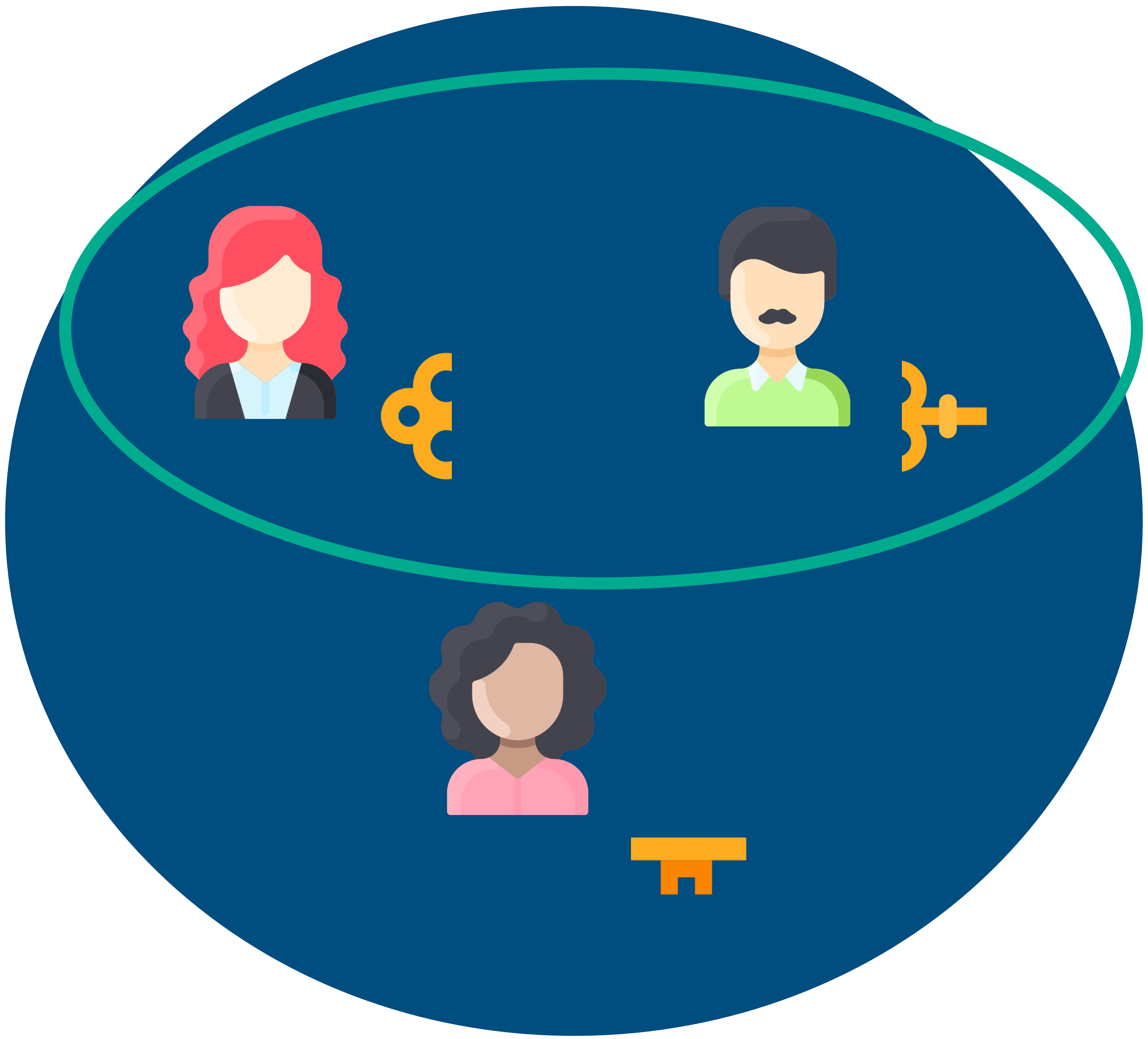
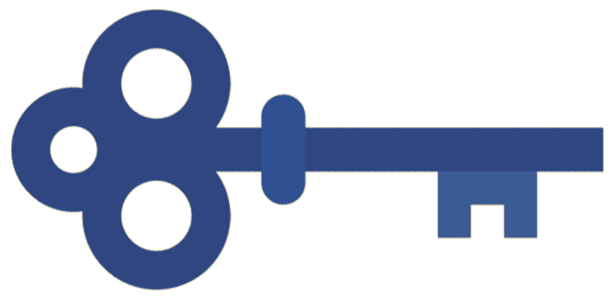
Threshold Signatures





Public Key PK

- $t+1$-out-of-n
- trusted key generation or DKG to produce PK

$(2,3)$ Example

NIST Threshold Standardization

NIST | COMPUTER SECURITY RESOURCE CENTER CSRC

NIST IR 8214C (2nd Public Draft)

NIST First Call for Multi-Party Threshold Schemes

Date Published: March 27, 2025

Comments Due: May 30, 2025 (public comment period is CLOSED)

Email Questions to: nistir-8214C-comments@nist.gov

(Single-Party) Schnorr Signatures

Signer:

$sk \leftarrow \mathbb{Z}_p, PK \leftarrow g^{sk}$

Icons by flaticon.com

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To sign a message m:

$r \leftarrow \mathbb{Z}_p,\ R \leftarrow g^r$

$c \leftarrow H(PK, m, R)$

$z \leftarrow r + c \cdot sk$

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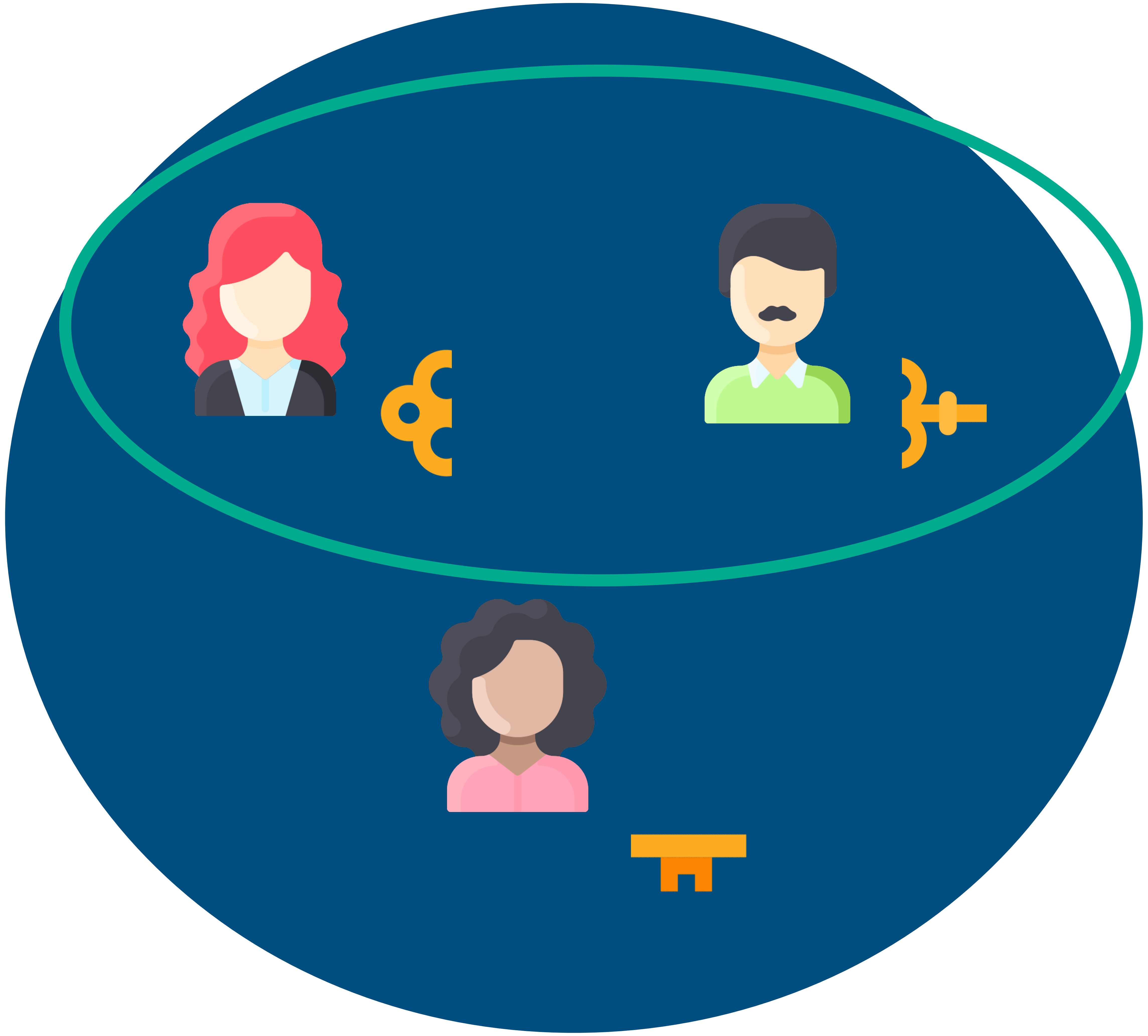

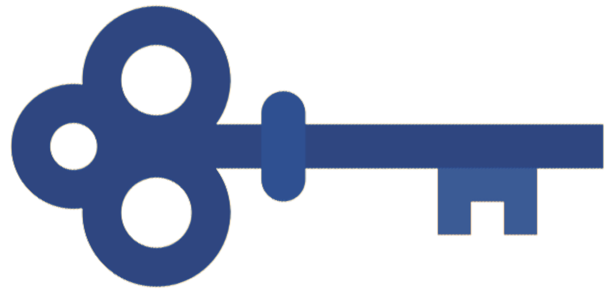

Public Key PK

- final signature $sig = (R, z)$ verifies as Schnorr signature under PK

$(2,3)$ Example

Remember ROS attacks?

ROS Attacks

- ROS problem first stated in Schnorr's original paper
- many threshold, blind, and multi-signatures were shown insecure
- ROS attacks fundamentally rely on concurrency
- most recent showing a polynomial-time attack for greater than $0.725\log(p)$ (e.g., ≈180) concurrent sessions
- a birthday problem

Our Attack

- similar to ROS, we construct an attack where the forgery amounts to a linear combination of parties' public values
- uniquely, our attack allows a forgery *based on public key shares alone* - no partial signatures are required
- unlike ROS attacks, the attack works *even for a single signing session*

The Problem P

- we define a search problem P and show a concrete, efficient attack if P is easy to solve

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- similar to ROS, P does not rely on group elements or operations (field elements only)
- unlike ROS, P is not stated in terms of a random oracle

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- *full* adaptive security is the analogue of static security ($t_c = t$ corruptions)

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    - e.g., Shamir secret sharing, DL-based DKGs like Pedersen, Gennaro et al.
3. Final signature is compatible with Schnorr verification: $R \cdot PK^c = g^z$

Affected Schemes

- FROST, FROST2, FROST3
- SimpleTSig
- Sparkle, Sparkle+
- Lindell'22
- Classic S.
- GKMN'21 (deterministic)
- Arctic (deterministic)

<u>Robust (G.O.D.):</u>

- ROAST
- SPRINT
- HARTS
- GJKR'07
- Stinson-Strobl'01

Non-Affected Schemes

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"On the Adaptive Security of Key-Unique Threshold Signatures"

eprint 2025/943

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- adversary sets $R^* = PK^{\alpha_0} PK_1^{\alpha_1} \cdots PK_n^{\alpha_n}$ for random $\alpha_0, \alpha_1, \ldots, \alpha_n \in \mathbb{Z}_p$

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- compute $\overrightarrow{w} = c^* \vec{v}_0 + \sum_{i=0}^{n} \alpha_i \vec{v}_i$ where $c^* = H(PK, m^*, R^*)$

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- $\overrightarrow{w} = c^* \vec{v}_0 + \sum_{i=0}^{n} \alpha_i \vec{v}_i = \sum_{j \in CS} \beta_j \vec{v}_j$
- finally, computes $z^* = \sum_{j \in CS} \beta_j sk_j$

Attack Success

$(n, t+1)$	$t_c = t$	$t_c = t-1$	$t_c = t-2$	$t_c = t-3$
(64,43)	195.84	446.97	698.2	949.52
(128,86)	137.87	388.92	640.02	891.17
(196,131)	75.41	326.45	577.53	828.64
(512,342)	0.0	37.25	288.28	539.32
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Table 2. The probability that our attack succeeds is 2^{-x} for x given in the table, with $p \approx 2^{252}$, where x is computed as in Theorem 2. Here, n is the total number of potential signers, $t+1$ is the threshold, and t_c is the corruption threshold.

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Implications of Our Results

Our results have two striking implications:

1. If P is easy to solve, all schemes meeting Conditions 1-3 are statically secure but not adaptively secure

   Would be first such separation for any natural protocol, solving a long-standing open problem in MPC

   Moreover, would apply to a large class of schemes and would hold even in the strongest idealized models: the AGM and the GGM

Implications of Our Results

2. The full adaptive security of these schemes cannot be proven without an assumption that implies the hardness of some instances of P

   Such an assumption would likely go beyond assumptions about the group and ROs since P is not defined in terms of them

   Moreover, this extends to corruption thresholds below $t_c = t$

Call to Action

- attack is “plausible” because we do not know if the problem P is easy to solve or not
- some preliminary analysis, but further investigation needed

On the Adaptive Security of FROST

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FROST

- Flexible Round-Optimized Schnorr Threshold signatures
- 2 rounds
  - 1 offline pre-processing round, 1 online signing round
  - static security in the ROM under AOMDL
  - OMDL: Given $(X_0, X_1, \ldots, X_t)$ and t queries to a DL solution oracle $\mathcal{O}^{DL}(X)$, output $t+1$ discrete logs $(x_0, x_1, \ldots, x_t)$
  - AOMDL: falsifiable variant of OMDL

Threshold Schnorr Signatures

How to share sk ?

How to share r ?

$$z \leftarrow r + c \cdot sk$$

$$sig = (R, z)$$

FROST

- To sign a message m, party P_i
  - Round 1: samples $r_i, s_i \xleftarrow{\$} \mathbb{Z}_p$, sets $R_i \leftarrow g^{r_i}$, $S_i \leftarrow g^{s_i}$, and outputs R_i, S_i

$m, \mathcal{S} \rightarrow$

  - Round 2: computes
    - $a_i \leftarrow H'(i, PK, m, \{R_i, S_i\}_{i \in \mathcal{S}})$
    - $R = \Pi_{i \in \mathcal{S}} R_i \cdot S_i^{a_i}$
    - $c \leftarrow H(PK, m, R)$
    - $z_i \leftarrow r_i + a_i \cdot s_i + c \cdot \lambda_i^{\mathcal{S}} \cdot sk_i$
    - outputs z_i

$z = \Sigma_{i \in \mathcal{S}} z_i$

$sig = (R, z)$

$R \cdot PK^c \stackrel{?}{=} g^z$

Optimizations FROST2 / FROST3

- FROST2 computational optimization of FROST
- FROST3 improves communication complexity of FROST2
- we prove adaptive security of all 3 variants

IRTF FROST Standardization

Internet Research Task Force (IRTF)
Request for Comments: 9591
Category: Informational
ISSN: 2070-1721

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June 2024

The Flexible Round-Optimized Schnorr Threshold (FROST) Protocol for Two-Round Schnorr Signatures

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3. Unconditional hardness of LDVR for interesting values above $t/2$

The LDVR Problem

MAIN $\mathsf{Expt}_{\mathcal{A}}^{(t_c,t,n)\text{-ldvr}}(\kappa)$

$\mathsf{ctr} := 0$

$(p, st) \leftarrow_\$ \mathcal{A}(\kappa)$

// $2^\kappa < p < 2^{\kappa+1}$, p prime

for $j \in \{0, \ldots, n\}$ **do**

  $\boldsymbol{v}_j := (1, j, \ldots, j^t) \in \mathbb{Z}_p^{t+1}$

$(\mathrm{CS}, i^*) \leftarrow_\$ \mathcal{A}^{\mathcal{O}}(st)$

// $\mathrm{CS} \subseteq \{1, \ldots, n\}, |\mathrm{CS}| \le t_c, i^* \in [\mathsf{ctr}]$

$$\boldsymbol{w} := c_{i^*}\boldsymbol{v}_0 + \sum_{j=0}^{n} \boldsymbol{\alpha}_{i^*}[j] \cdot \boldsymbol{v}_j$$

if $\boldsymbol{w} \in \mathsf{span}(\{\boldsymbol{v}_i\}_{i \in \mathrm{CS}})$

  return 1

return 0

$\mathcal{O}(\boldsymbol{\alpha})$

// $\boldsymbol{\alpha} \in \mathbb{Z}_p^{n+1}$

$\mathsf{ctr} := \mathsf{ctr} + 1$

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return c_{ctr}

Fig. 6. The LDVR experiment with parameters $t_c \le t < n$.

The LDVR Problem

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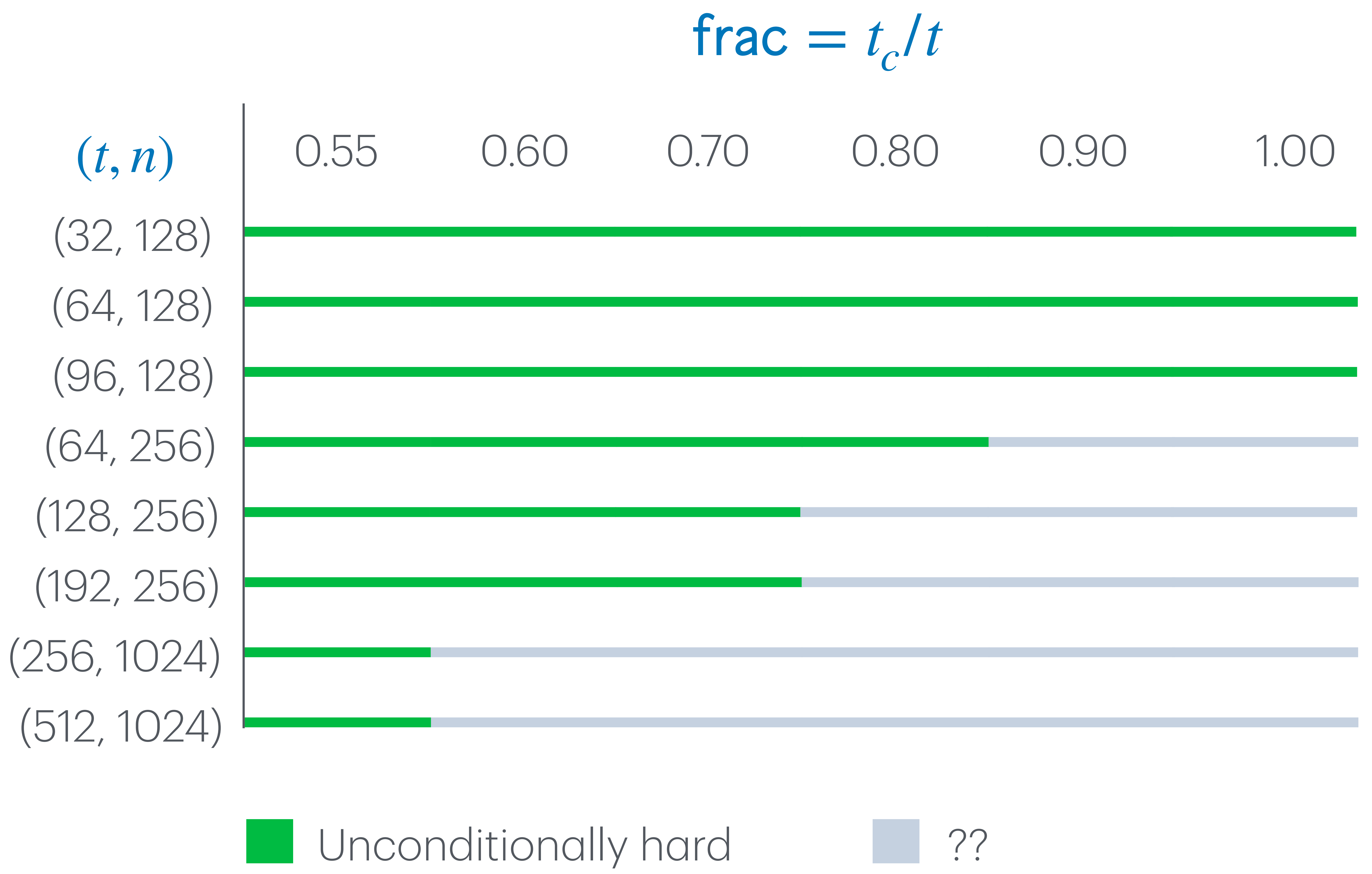
Unconditional Hardness of LDVR



Half Adaptive Security Proof

- FROST/2/3 for up to $t/2$ adaptive corruptions in the ROM under AOMDL
  - same assumptions as static FROST
  - similar structure to static FROST proof

Full Adaptive Security Proof

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- when adversary queries $c^* = H(PK, m^*, R^*)$, it must output representation:

$$R^* = g^{\delta} \cdot \mathsf{PK}^{\beta} \cdot \prod_{k=1}^{n} \mathsf{PK}_k^{\beta_k} \prod_{i=1}^{q_s} R_{i,1}^{\gamma_{i,1}} S_{i,1}^{\gamma'_{i,1}} \cdots R_{i,n}^{\gamma_{i,n}} S_{i,n}^{\gamma'_{i,n}}$$

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Can replace with g and $PK_i's$?

- "Want" this in order to break LDVR

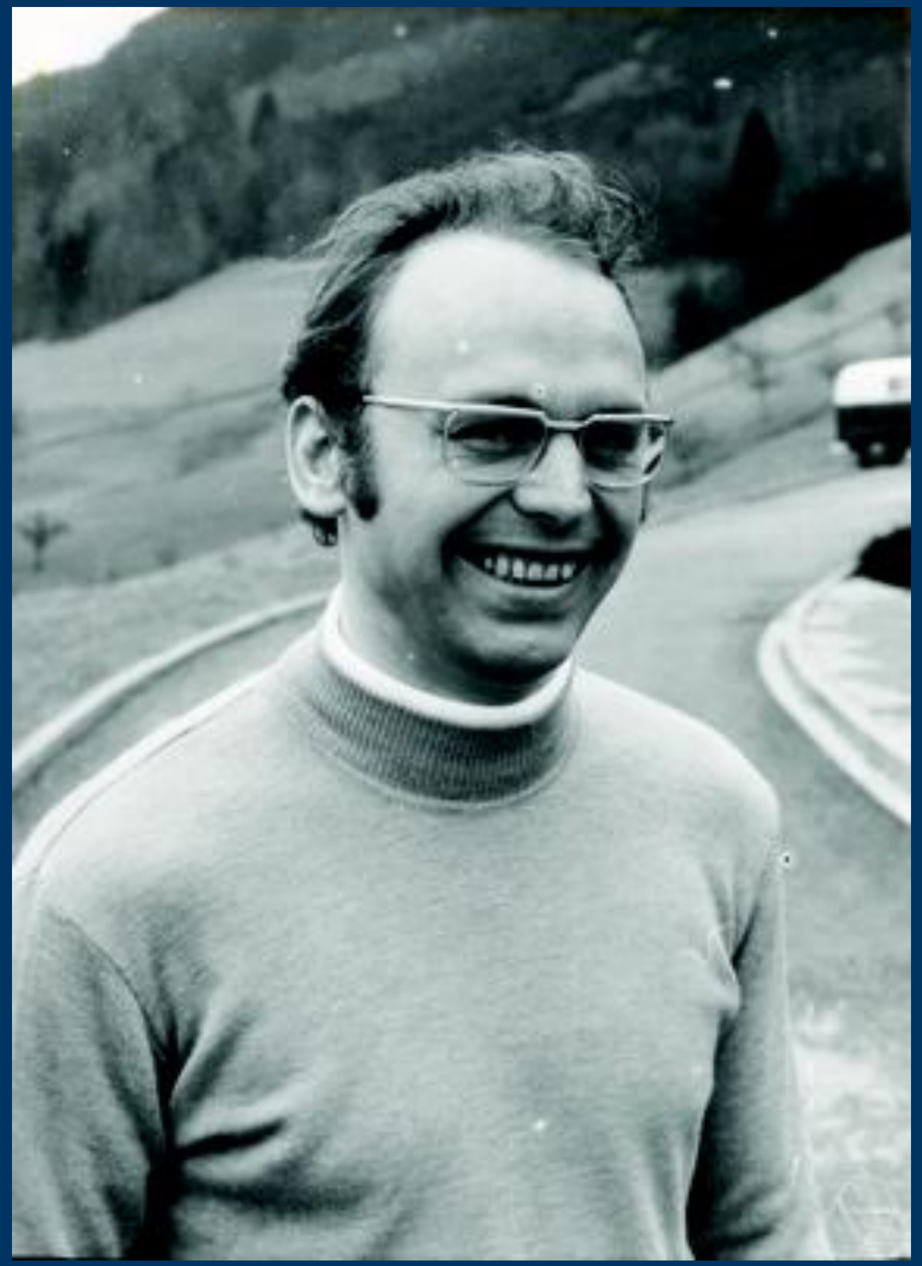
- If no, can break AOMDL instead

Call to Action

- we do not know if P or LDVR is easy or hard (beyond the unconditional bound)
- other schemes may be proven under variants of these assumptions

Plausible Attack

Adaptive FROST



Claus-Peter Schnorr

1943-2025

From the Oberwolfach Photo Collection