Swoosh: Efficient Lattice-Based Non-Interactive Key Exchange

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[2] Ruhr-University Bochum

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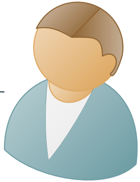
Based on a USENIX 2024 paper with the same title [GdKQ+24].

$(a, g^a) \xleftarrow{\$} \mathsf{Gen}$

$\xrightarrow{g^a}$ $\xleftarrow{g^b}$



$(b, g^b) \xleftarrow{\$} \mathsf{Gen}$

$(g^b)^a \leftarrow \mathsf{SdK}(a, g^b)$

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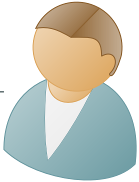

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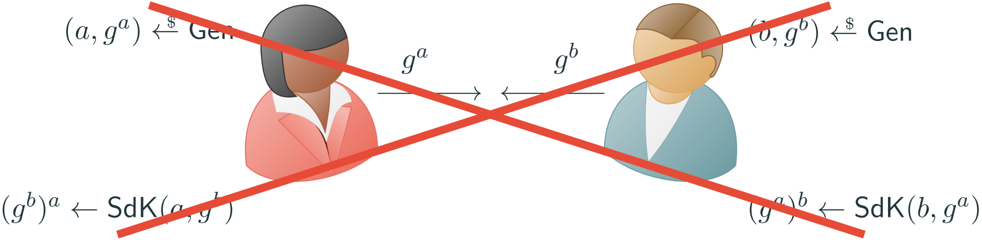
- Diffie-Hellman is widely deployed



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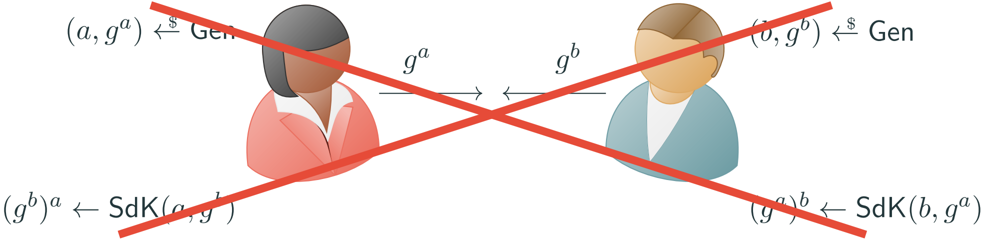
- Need a post-quantum replacement



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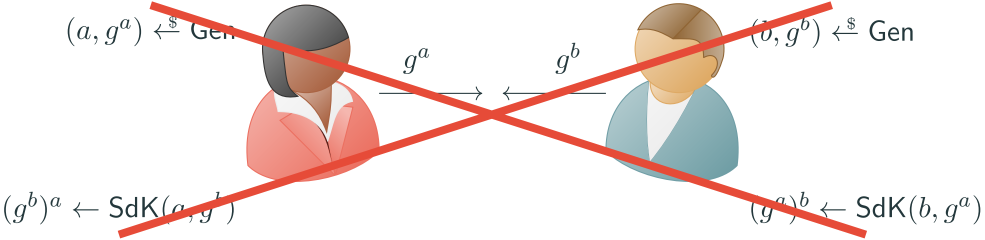
- Need a post-quantum replacement
- Folklore: *"Lattice-based non-interactive key exchange is impractical"*
  - Impossibility results [GKRS20]



- Diffie-Hellman is widely deployed
- Need a post-quantum replacement
- Folklore: *"Lattice-based non-interactive key exchange is impractical"*
  - Impossibility results [GKRS20]
- Our work: *"It's not **that** bad"*

OUTLINE

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- NIKE vs. KEM Applications
- Scheme: Passive-SWOOSH
- Security Model

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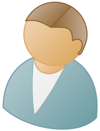
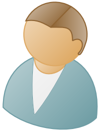
- Scheme: Passive-Swoosh
- Security Model
- Parameter choices
- Implementation details
- Comparison



NON-INTERACTIVE KEY EXCHANGE (NIKE)

$(sk_A, pk_A) \xleftarrow{\$} \mathsf{Gen}$



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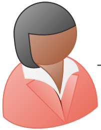
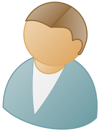


$\xrightarrow{pk_A}$



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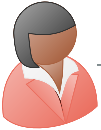

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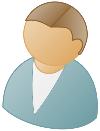

$(sk_B, pk_B) \xleftarrow{\$} \mathsf{Gen}$

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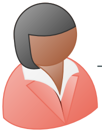
$(sk_A, pk_A) \xleftarrow{\$} \mathsf{Gen}$  $\xrightarrow{pk_A}$ $\xleftarrow{pk_B}$  $(sk_B, pk_B) \xleftarrow{\$} \mathsf{Gen}$

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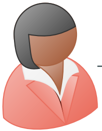

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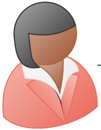

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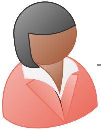

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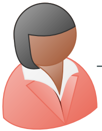

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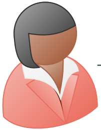

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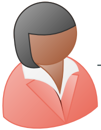

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NON-INTERACTIVE KEY EXCHANGE VS. KEY-ENCAPSULATION MECHANISMS

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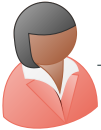

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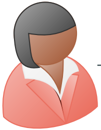
$(sk_A, pk_A) \xleftarrow{\$} \mathsf{Gen}$  $\xrightarrow{pk_A}$ $\xleftarrow{pk_B}$  $(sk_B, pk_B) \xleftarrow{\$} \mathsf{Gen}$

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$(sk_A, pk_A) \xleftarrow{\$} \mathsf{Gen}$  $\xrightarrow{pk_A}$  $(c, k_{BA}) \xleftarrow{\$} \mathsf{Enc}(pk_A)$

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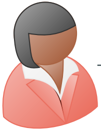

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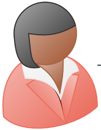

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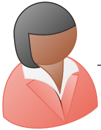
$(sk_A, pk_A) \xleftarrow{\$} \mathsf{Gen}$  $\xrightarrow{pk_A}$ $\xleftarrow{pk_B}$  $(sk_B, pk_B) \xleftarrow{\$} \mathsf{Gen}$

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- Implicit Authentication using static Diffie-Hellman keys
  - OPTLS [KW16]
- Asynchronous key agreement
  - X3DH [MP16]
- Other
  - EDHOC [SMP24]
  - Group OSCORE [TSP+24]
  - More?

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LATTICE-BASED NIKE HAS IMPERFECT CORRECTNESS

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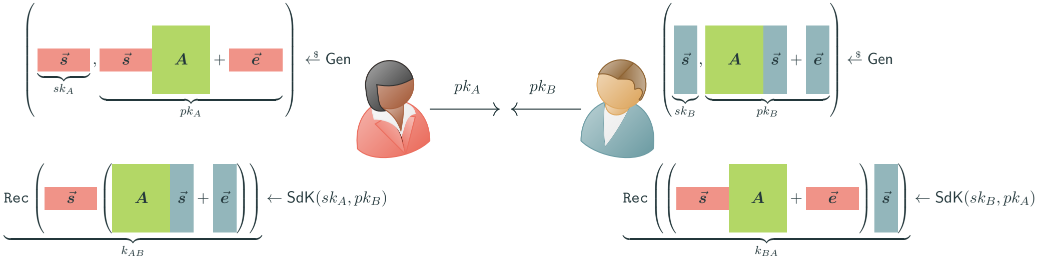
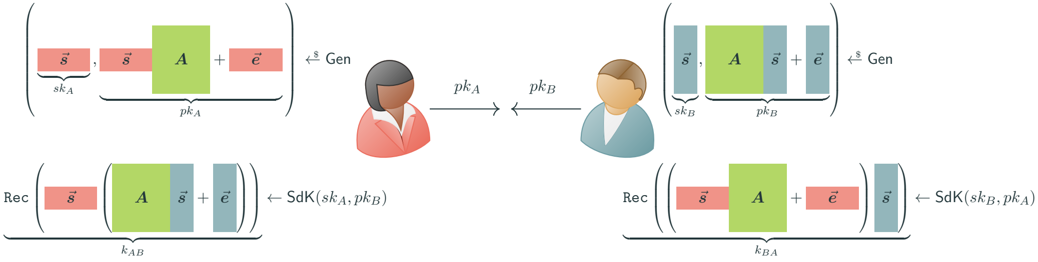


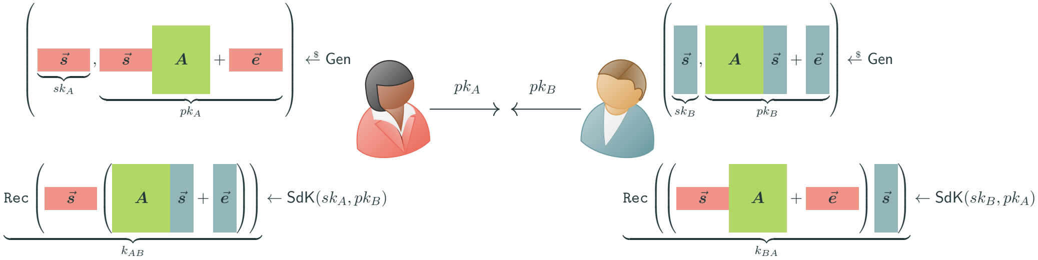


- **Correctness:**

$$\delta := \Pr\left[\mathsf{Rec}\left(\vec{s}\,\boldsymbol{A}\,\vec{s} + \vec{s}\,\vec{e}\right) \neq \mathsf{Rec}\left(\vec{s}\,\boldsymbol{A}\,\vec{s} + \vec{e}\,\vec{s}\right)\right] \leq \frac{4\beta^2 d^2 N}{q}.$$

- **Security:** k_{AB} and k_{BA} look random under the M-LWE assumption.

LATTICE-BASED NIKE HAS IMPERFECT CORRECTNESS



- **Semi-Malicious Correctness:** (we add $\boldsymbol{r} := \mathsf{H}(pk_A, pk_B)$)

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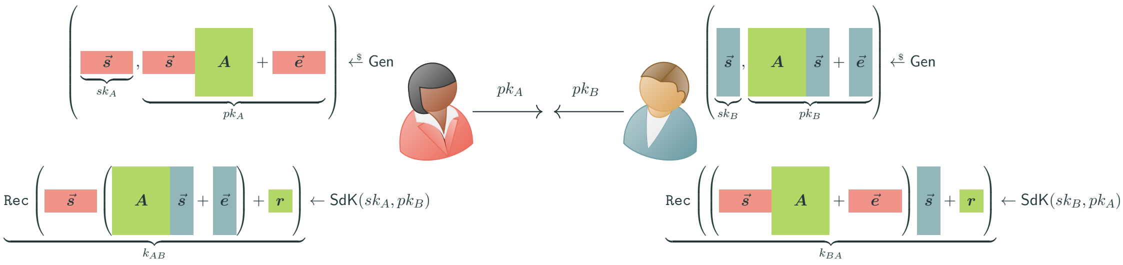

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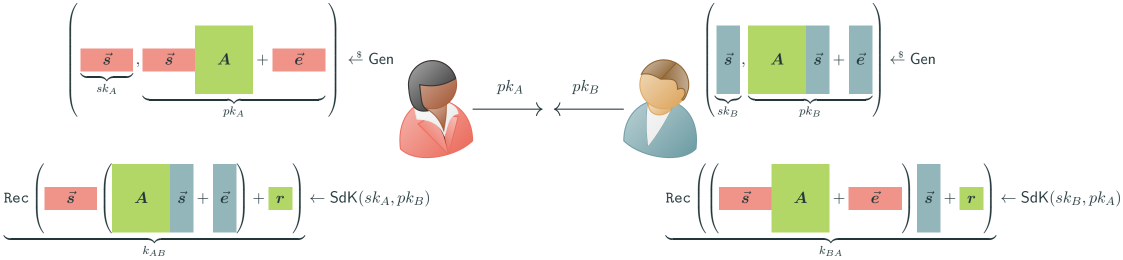

- **Semi-Malicious Correctness:** (we add $r := \mathsf{H}(pk_A, pk_B)$)

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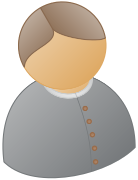
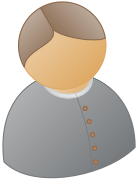
SECURITY MODEL [CKS08]



$b \xleftarrow{\$} \{0, 1\}$



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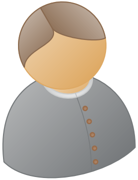

$$\downarrow$$

$$b'$$

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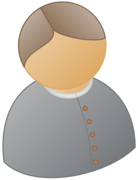


if $b = b'$

return win

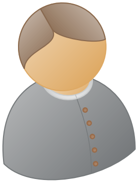
$$\downarrow$$

b'

$$\xleftarrow{\quad\texttt{RegHonUsr(ID)}\quad}$$

$b \xleftarrow{\$} \{0, 1\}$

$$\xrightarrow{\quad pk \quad}$$



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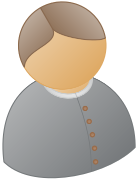

if $b = b'$

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$\xleftarrow{\mathtt{TestQue}(\mathtt{ID}_1, \mathtt{ID}_2)}$

$\downarrow$

b'

$$\xleftarrow{\texttt{RegHonUsr}(\texttt{ID})}$$

$b \xleftarrow{\$} \{0,1\}$

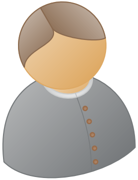
$$\xrightarrow{pk}$$

if $b = 0$

$\quad k := \mathsf{SdK}(sk_1, pk_2)$

if $b = 1$

$\quad k \xleftarrow{\$} \mathcal{SKS}$



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$$\xrightarrow{k}$$

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if $b = b'$

$\quad$ **return** win

$\texttt{RegHonUsr}(\texttt{ID})$ $\longleftarrow$

$b \xleftarrow{\$} \{0,1\}$

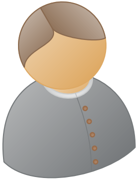
pk $\longrightarrow$

if $b = 0$

$k := \mathsf{SdK}(sk_1, pk_2)$

if $b = 1$

$k \xleftarrow{\$} \mathcal{SKS}$



Only for DKR

if $b = b'$

return win

$\texttt{TestQue}(\texttt{ID}_1, \texttt{ID}_2)$ $\longleftarrow$

$\downarrow$ b'

k $\longrightarrow$

Security model [CKS08]

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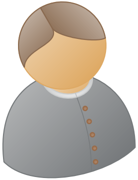

$\xleftarrow{\texttt{RegHonUsr}(\texttt{ID})}$

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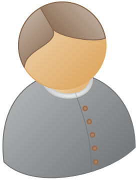

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$\left.\begin{array}{l} \\ \\ \\ \end{array}\right\}$ Only for DKR

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- Diffie-Hellman has active security "almost for free" due to perfect correctness
- Passive-SWOOSH needs:
  - Semi-malicious correctness
  - Non-interactive zero-knowledge (NIZK) proof of knowledge
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PARAMETERS AND IMPLEMENTATION

Parameter	Description	Value
β	upper bound on $\lVert\vec{\boldsymbol{s}}\rVert_\infty = \lVert\vec{\boldsymbol{e}}\rVert_\infty$	1
q	prime modulus	$2^{214} - 255$
d	dim of $\mathcal{R}_q := \mathbb{Z}_q[X]/(X^d + 1)$	256
l	# factors $X^d + 1$ splits into $\mod q$	128
N	height of the $\boldsymbol{A}$ matrix	32
n	lattice dimension	8192
χ	secret / noise distribution (ternary)	$p(-1) = 25\%$ $p(0) = 50\%$ $p(1) = 25\%$

- Passive-SWOOSH (Semi-malicious correctness) implementation in Rust and Jasmin[1]
  - NIZK not included
  - Performance penalty depends on context
- Main optimisation targets
  - Key Generation Gen
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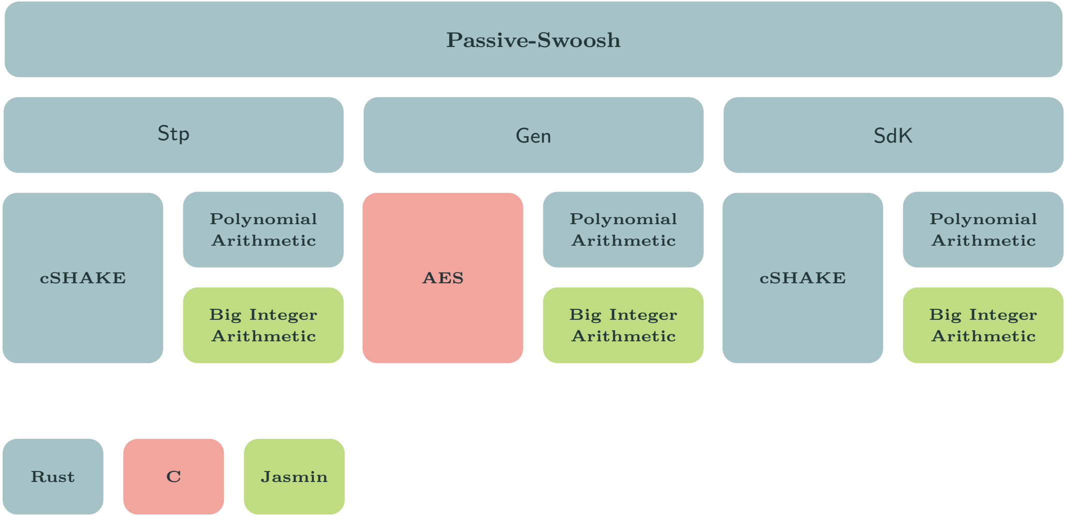
IMPLEMENTATION: OVERVIEW



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Classic McEliece (`mceliece348864`)	Binary Goppa Codes	✓	✗	96	261 120	46 715 060	143 178
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This work (Passive-Swoosh)	M-LWE	✓	✓	—	221 184	146 920 890	10 612 666

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COMPARISON OF SELECT POST-QUANTUM KEMS AND NIKES

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- Diffie-Hellman is most efficient but not PQ secure
- PQC KEMs are faster than Passive-Swoosh but require interaction
- PQ NIKEs: trade-off between key size and speed

[3]Post-quantum
[4]Non-interactive

SUMMARY

Contributions:

- M-LWE based NIKE, with strong correctness and proof in the QROM.
  - Generic transformation from passive to active security using NIZKs.
- Optimised implementation of Passive-SWOOSH, written in Rust and Jasmin.
  - Parameters achieving 120 bits of security against quantum adversaries.
  - Smaller public keys than Classic McEliece KEM and faster than CTIDH NIKE.

ia.cr/2023/271 — github.com/MQuaresma/pswoosh

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