FrodoKEM
practical quantum-secure key encapsulation
from generic lattices

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FrodoKEM

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Concrete Instantiations

1. FrodoKEM-640: targets Level 1 security (≥ AES-128)
2. FrodoKEM-976: targets Level 3 security (≥ AES-192)
3. FrodoKEM-1344 (new, round 2): Level 5 security (≥ AES-256)
### Learning With Errors (LWE) [Regev’05]

- **Lineage of** [Ajtai’96, AjtaiDwork’97]: worst-case/average-case reductions:
Pedigree

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  “[This] assures us that attacks on the cryptographic construction are likely to be effective only for small choices of parameters and not asymptotically. In other words . . . there are no fundamental flaws in the design of our cryptographic construction.” [MicciancioRegev’09]
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Public-Key Encryption/Key Exchange

- Many schemes with tight (CPA-)security from LWE:
  
  [Regev’05, PVW’08, GPV’08, P’09, LP’11, . . . ]
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- FrodoCCS [BCDMNNRS’16] instantiated and implemented [LP’11], using pseudorandom public matrix $A$ to reduce public key size.
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- FrodoPKE/KEM [this work]: wider error, new params, CCA security
## LWE and FrodoPKE

### Learning With Errors

- Dimension $n$, modulus $q$, error distribution $\chi$ on ‘small’ integers.
LWE and FrodoPKE

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Assumption: for uniformly random matrix $A$ over $\mathbb{Z}_q$ and $S$ from $\chi$,

$$[A, B \approx SA] \equiv \text{uniform over } \mathbb{Z}_q.$$
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Bounded-distance decoding on a random ‘$q$-ary’ lattice defined by $A$:
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\[
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\[
\begin{align*}
S &\leftarrow \chi^{k \times n} \\
pk &= \text{seed}_A, \ B \approx SA \\
(A &= \text{expand} (\text{seed}_A) \in \mathbb{Z}_q^{n \times n})
\end{align*}
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$$S \leftarrow \chi^{k \times n} \quad pk = \text{seed}_A, \quad B \approx SA \quad (A = \text{expand}(\text{seed}_A) \in \mathbb{Z}_q^{n \times n})$$

$$C \approx AR \quad C' \approx BR + \frac{q}{2} \cdot M$$

$$M \in \{0, 1\}^{k \times \ell}$$

$$C' - SC \approx \frac{q}{2} \cdot M$$

(Images courtesy xkcd.org)
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Distinctive Features of FrodoPKE/KEM

1. Generic, algebraically unstructured lattices: plain LWE. (No algebraic ring structure for potential exploitation.)

2. ‘Medium-sized’ errors conforming to a worst-case/average-case reduction from a previously studied lattice problem (BDD with DGS).

3. Very simple design and constant-time implementation:
   - power-of-2 modulus $q$ for cheap & easy modular arithmetic
   - straightforward error sampling
   - no ‘reconciliation’ or error-correcting codes for removing noise
   - x64 implementation: 256 lines of plain C code (+ preexisting symmetric primitives)
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Medium-Sized Errors

Choosing an Error Distribution

- **Narrower errors** $\Rightarrow$ **smaller parameters** $q, n$ $\Rightarrow$ **better efficiency.**
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1. LWE with $O(1)$-bounded error is poly($n$)-time solvable [AG’11,ACFP’14]
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New Worst-Case Hardness

- A latent reduction from [R’05,PRS’17] works for our $\sigma \approx \eta(\mathbb{Z})$. 
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New Worst-Case Hardness

- A latent reduction from [R’05,PRS’17] works for our $\sigma \approx \eta(\mathbb{Z})$.
- Works for a bounded poly($n$) number of LWE samples: covers PKEs!
What’s New in Round 2

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4. Detailed, tight ROM proof [HHK’17,LSS’14] of
   
   IND-CPA PKE $\Rightarrow$ OW-PCA PKE $\Rightarrow$ IND-CCA KEM,
   
   with ‘Rényi switch’ at OW-PCA step.
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5. WIP: Cortex M4 implementation with 2x memory improvement
Tight ROM Proof of CCA Security

- Generic, tight transforms following [HHK’17]:

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\begin{align*}
\text{FrodoPKE (IND-CPA)} & \xrightarrow{T} \text{T[FrodoPKE] (OW-PCA)} & \xrightarrow{U^\perp} \text{FrodoKEM (IND-CCA)}
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- Generic, tight transforms following [HHK’17]:
  
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  - **Switch at OW-PCA (search)**, security loss $\approx 0$ by Rényi div [LSS’14]. (Precise, tiny bounds given in spec.)
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Alternative Assumption: OW-PCA of T[FrodoPKE]

- OW-PCA \( \equiv \) OW-CPA, unless attacker queries an \( m \neq \text{Dec(Enc}(m)) \).
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- Costs more than claimed security for our FrodoKEM params [DVV’19].
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- OW-PCA $\equiv$ OW-CPA, unless attacker queries an $m \neq \text{Dec(Enc(m))}$.
- Costs more than claimed security for our FrodoKEM params [DVV’19].
- So, $\approx$ OW-CPA of T[FrodoPKE] also suffices for CCA.
Concrete Parameters and Security

- Use ‘core-SVP’ methodology [ADPS’16] to lower-bound the first-order exponential time (and space) of SVP in appropriate dimension.
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This \textbf{significantly underestimates} the cost of known attacks, but it is prudent to expect better \textit{lower-order terms} with further research.
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\begin{itemize}
  \item \textbf{LWE and classical CCA security} (end-to-end from ROM proof):
\end{itemize}

\begin{table}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
 & $n$ & $q$ & $\sigma$ & LWE Security & CCA (ROM) \\
\hline
FrodoKEM-640 & 640 & $2^{15}$ & 2.75 & 145 & 141 \\
FrodoKEM-976 & 976 & $2^{16}$ & 2.3 & 210 & 206 \\
FrodoKEM-1344 & 1344 & $2^{16}$ & 1.4 & 275 & 268 \\
\hline
\end{tabular}
\end{table}
Performance

- Sizes (in bytes):

<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td>10,272</td>
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- Speed (in kilocycles, 3.4GHz Intel Core i7-6700 Skylake, AES-NI):

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- Cache $\mathbf{A} \leftarrow \text{seed}_A$ for $pk$ lifetime: save $\approx 40\%$ in Encaps/Decaps
Parting Thought

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https://FrodoKEM.org

Thanks!