Online-Extractability in the Quantum Random-Oracle Model

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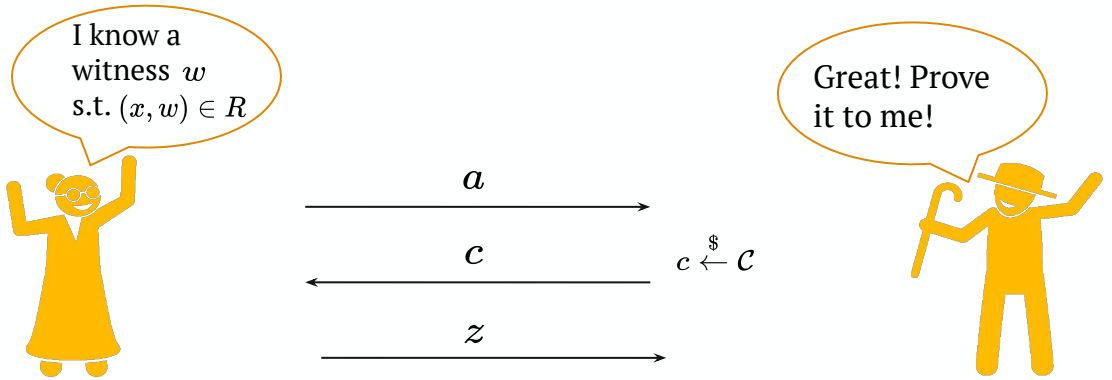
Extraction (in cryptography)

- $\mathcal{A}$ sends messages depending on some secret s
- In an honest execution, s remains secret
- An extractor algorithm with ‘enhanced access’ to $\mathcal{A}$ can obtain s

Examples of extraction

- (Zero-knowledge) proofs of knowledge



- Extractable commitments
- CCA-security of encryption or KEM's

Straight-line and on-the-fly

- Straight-line
  - Single run vs. rewinding
  - Better loss factor/runtime

- On-the-fly
  - Extraction happens during execution vs. afterwards
  - Necessary for CCA-security extraction

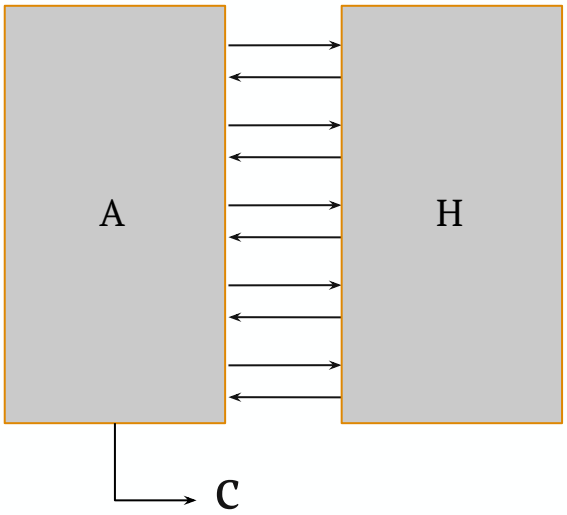
- Straight-line + On-the-fly = online extractability

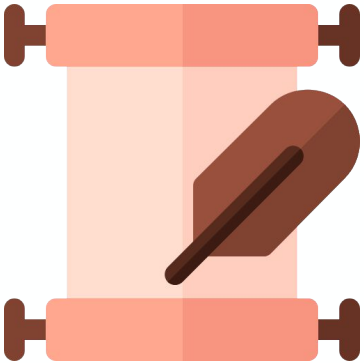
Enhanced access

- Rewinding
  - Proofs of knowledge, zero-knowledge proofs
- Trapdoor
  - Extractable commitments
- Random-Oracle Model (ROM)
  - Hash-based commitments, commit-and-open protocols, CCA security
- Quantum Random-Oracle Model?

Example: Hash-based commitment (ROM)

- A commits to s with c = H(x) for x = s||r, where r is random
- The extractor searches for x' s.t. H(x')=c in the transcript





Example: Hash-based commitment (QROM)

- A commits to s with c = H(x) for x = s||r, where r is random
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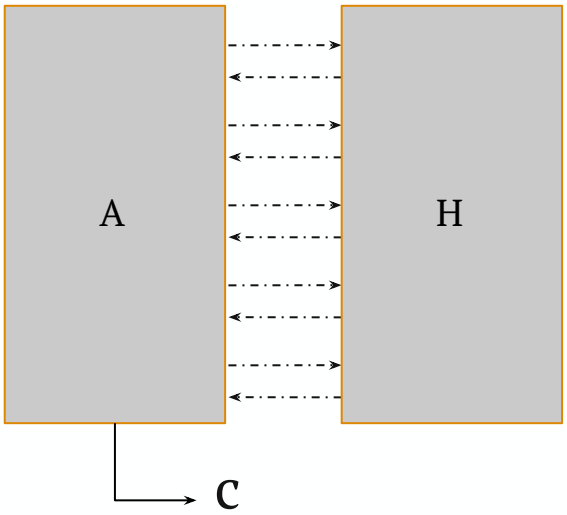
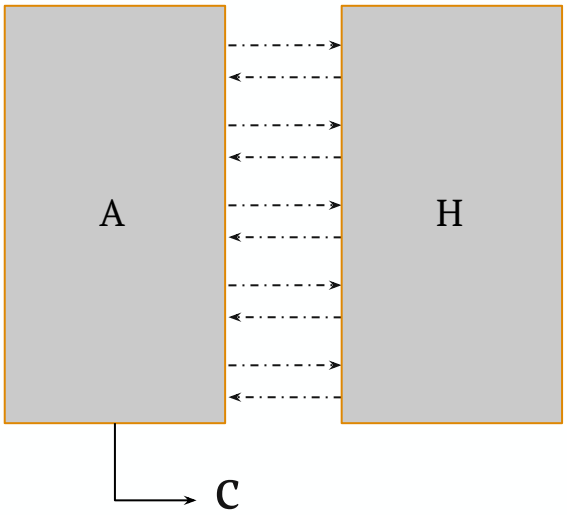
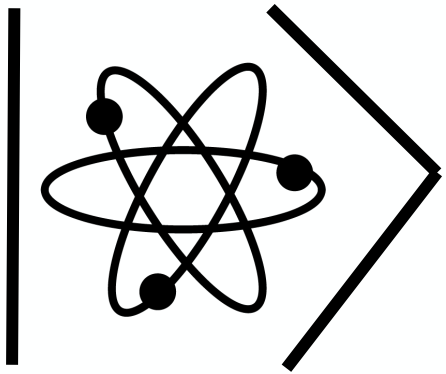


Example: Hash-based commitment (QROM)

- A commits to s with c = H(x) for x = s||r, where r is random
- The extractor performs a measurement on the oracle state?





[Zha19]

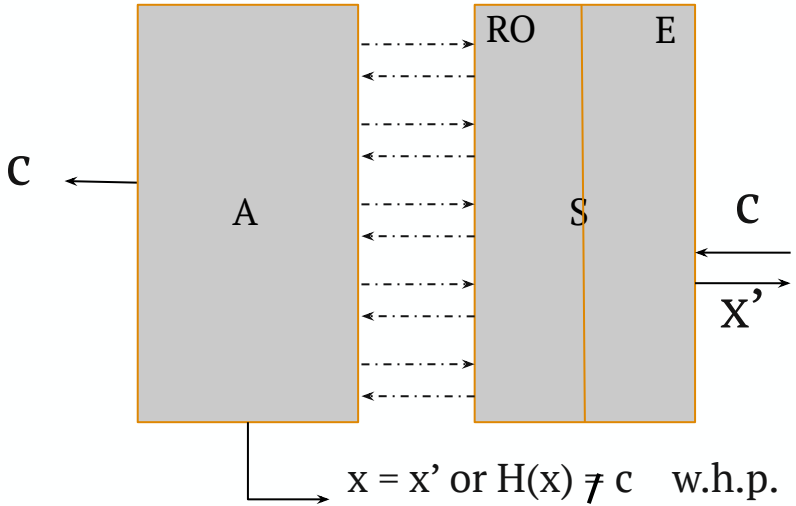
Technical core of our result

- We bound the norm of the commutator [M,O] of a suitable extraction measurement and the compressed oracle unitary

- The bound is negligible in the output size of the oracle, hence
  - We can move the measurement to the end of the run
  - Introducing a measurement at the end does not affect the view of the adversary
  - The adversary does not notice the measurement

Our main result

- There exists a simulator S with RO interface and Extraction interface s.t. for every bounded query algorithm A we have:



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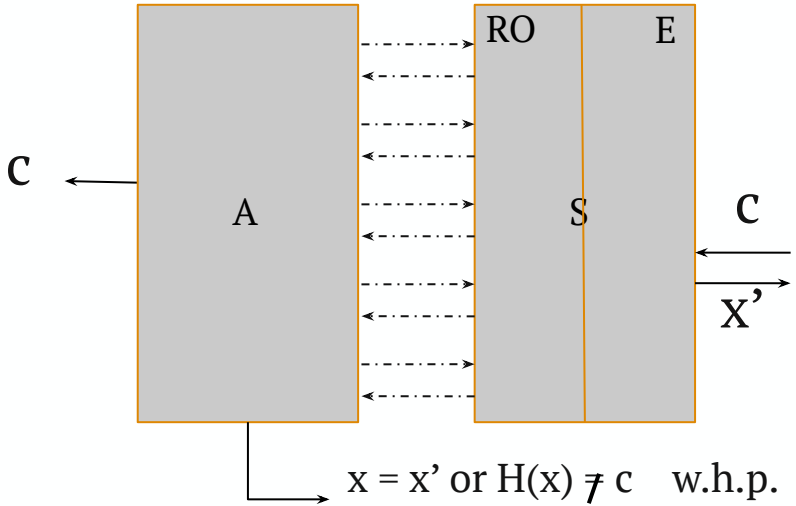
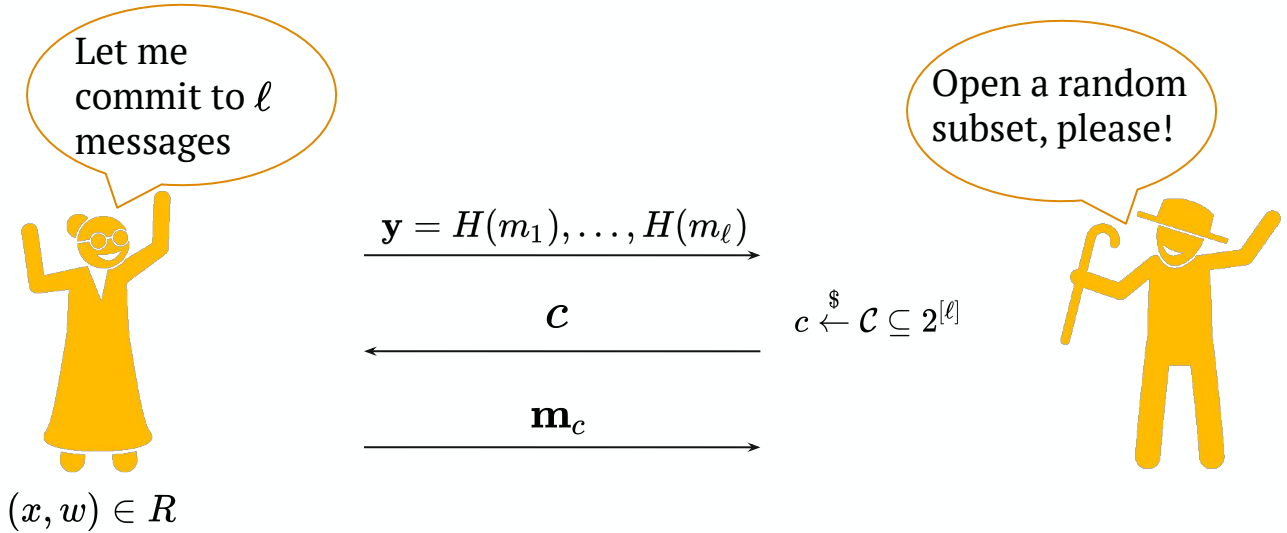


This example: c = H(x)

More general: t = f(x,H(x))

for f(x,y) with the property that there are not too many y's s.t. f(x,y)=t

Application: Commit-and-Open Protocols



Application: Commit-and-Open Protocols

- We show tight online-extractability of generic C&O protocols
  - Without ‘collapsingness’ or ‘unique responses’
  - Previous techniques incurred a cubic loss
- Used in the popular MPC-in-the-head paradigm
- Underlying the NIST post-quantum signature candidate PICNIC
  - PICNIC uses a *Fiat-Shamir-transformed* C&O protocol
  - Proven tightly secure in follow-up work [DFMS22]

Application: Fujisaki-Okamoto transform

- We give the first complete post-quantum security proof of the textbook FO-transform
  - Session key derived as H(m) instead of H(m,c)
  - No “key confirmation hash”
  - Works for FO with “explicit rejection”
- Used in many of the NIST KEM candidates

Summary

- We lift a powerful extraction method from the ROM to the QROM
  - That works straight-line and on-the-fly
- We give the first tight reduction of commit-and-open protocols
- We give the first post-quantum analysis of textbook FO
- If the adversary outputs t and promises an x s.t. f(x,H(x)) = t
  - We can extract it online

Thank you for listening

Questions?