Quantum Symmetric-key Cryptanalysis: An Overview

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Outline

Symmetric-key (SK) Cryptography

Examples:

- Block ciphers (e.g., AES)
- Hash functions (e.g., SHA-2, SHA-3, Whirlpool)
- Modes of operation (e.g., GCM)

These primitives can be further composed to build other SK constructions, for instance OWFs, MACs, AEADs, PRFs, PRGs, etc.

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These primitives can be further composed to build other SK constructions, for instance OWFs, MACs, AEADs, PRFs, PRGs, etc.

- Core building blocks of cryptographic protocols and systems
- Security relies on *cryptanalysis*, rather than reduction to hardness assumptions

Generic v.s. Dedicated Attacks

Generic attack (or generic bound)

- defines the ideal security of a SK primitive
- e.g. for hash function with n-bit output, in the classical setting, generic preimage attack costs $O(2^n)$, generic collision attack costs $O(2^{n/2})$

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Security margin

$$1 - \frac{\text{Number of rounds attacked}}{\text{Number of full rounds}}$$

Quantum Implications on SK Cryptanalysis

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In this talk, we will briefly introduce:

- Commonly used adversary modes in quantum SK cryptanalysis
- Simon's algorithm and its applications on Modes of Operations
- Grover's algorithm and its application on Hash Functions

Outline

Quantum Adversary Models

In quantum SK cryptanalysis, we usually consider two axes of assumptions:

Query access to cryptographic oracles: (keyed oracles are more concerned)

- **Model Q0**: classical queries to oracle, classical computation
- **Model Q1**: classical queries to oracle, access to a quantum computer
- **Model Q2**: superposition queries to oracle
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Existence of qRAM:

- **Model QA**: No qRAM, consider quantum time-space trade-offs
- **Model QB**: No qRAM, consider quantum time complexity, with only polynomial-sized quantum computer, may use classical memory for storage
- **Model QC**: Arbitrary qRAM, consider quantum time complexity

Outline

Simon's Algorithm

Simon's Problem

Given oracle access to a function $f : \{0,1\}^n \to \{0,1\}^m$ such that

$$f(x) = f(x \oplus s)$$

for a secret $s \neq 0$, recover s.

- Classical query complexity: $O(2^{n/2})$
- Quantum query complexity [Sim94]: $O(n)$
- Requires **Q2 model**: superposition oracle access
- Core idea: Each query of the Simon's algorithm recovers one linear relation on s. $O(n)$ queries to recover full s.

Impact on SK Modes and Constructions

Simon's algorithm enables **polynomial-time** key-recovery attacks on many modes and constructions in the Q2 model:

- On Modes of Operation [KLLN16, Bon17]:
  - MACs: CBC–MAC, PMAC, GMAC
  - AEAD: GCM, OCB
  - Many CAESAR candidates (e.g., AEZ, CLOC, COPA, OTR)
- On Constructions:
  - 3–round Feistel [KM10]
  - Even–Mansour [KM12]
  - FX construction [LM17]

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Remarks:

- Q2 attacks assumes the adversary has quantum access to the keyed primitives.
- Need to be extra careful when implementing those primitives on quantum computers.

Outline

Grover's Algorithm

Unstructured Search

Given oracle access to $f : \{0,1\}^n \to \{0,1\}$, find x such that $f(x) = 1$.

- Classical complexity: $O(2^n)$
- Quantum complexity: $O(2^{n/2})$ [Gro96]
- Key generalization: Quantum Amplitude Amplification (QAA) [BHMT02]
- Quadratic speed-up for brute-force key recovery for block ciphers and preimage search for hash functions, i.e., from $O(2^n)$ to $O(2^{n/2})$.
- How about collision search?

Application to Quantum Collision Search

Collision Search

Given a random function $H : \{0,1\}^n \to \{0,1\}^n$, find $x \neq y$ such that $H(x) = H(y)$.

- Best classical attack: Parallel Collision Search (PCS) [OW99]
  - Time complexity: $O(2^{n/2}/S)$ with S processors;
  - Time-space complexity: $O(2^{n/2})$
- Quantum Parallel Collision Search (QPCS) [Ber09]
  - Quantum time-space complexity $O(2^{n/2})$
  - Current best attack in terms of quantum time-space trade-offs
- How about in terms of time complexity?

Comparison of Quantum Generic Collision Attacks

	Time	Queries	Qubits	cMem	qRAM
QPCS	$2^{n/2}$	$2^{n/2}$	$\mathrm{poly}(n)$	/	/
BHT	$2^{n/3}$	$2^{n/3}$	/	/	$2^{n/3}$
CNS	$2^{2n/5}$	$2^{2n/5}$	$\mathrm{poly}(n)$	$2^{n/5}$	/

Generic bounds under different quantum adversary models:

- BHT algorithm achieve the lowest time complexity, but with exponential qRAM
- CNS algorithm is the best attack under the (*realistic*) assumption of polynomial qubits and no qRAM

Application 1: Differential-based Attacks

Differential Probability

Let $F : \{0,1\}^n \to \{0,1\}^n$ be a function. The **differential probability** of a pair of input/output differences $(\Delta_{in}, \Delta_{out})$ is

$$\Pr_{x \leftarrow \{0,1\}^n}\left[F(x) \oplus F(x \oplus \Delta_{in}) = \Delta_{out}\right].$$

A differential trail with probability p defines the cost of finding a valid pair

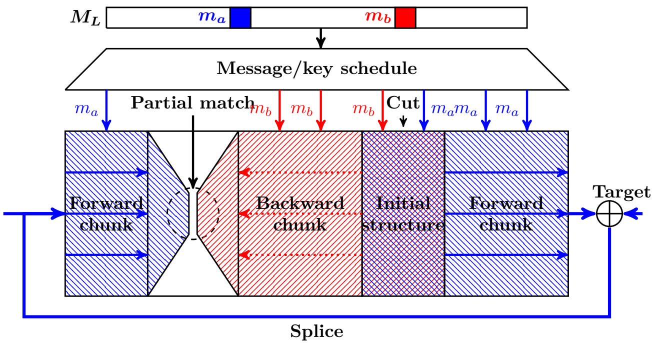
- **Classical setting:** Requires $\approx 1/p$ evaluations
- **Quantum setting:** QAA finds a valid pair in time $\approx \sqrt{1/p}$
  $\Rightarrow$ able to exploit differentials that are unusable in the classical setting!
- Enable quantum attacks on higher rounds than classical attacks!

Results on Classical/Quantum Collision Attacks

Attack	Rounds	Time	cMem	qRAM	Setting	Technique	Source
AES-128-MMO							
Collision	6	2^{56}	2^{32}	–	C	Rebound	[LMRRS09; GP10]
Collision	7	2^{60}	2^{60}	–	C	MITM	**Asiacrypt'25***
Chosen-prefix	5	2^{52}	2^{32}	–	C	Rebound, CPC	**FSE'25***
Collision	7	$2^{59.5}$	–	–	QA	Rebound, Grover	[HS20]
Collision	8	$2^{55.53}$	–	–	QA	Rebound, Grover, TA	**Crypto'22***
Chosen-prefix	6	$2^{61.5}$	–	–	QA	Rebound, Grover, CPC	**FSE'25***
Whirlpool							
Collision	5	2^{120}	2^{64}	–	C	Rebound	[GP10; LMRRS09]
Collision	6	2^{240}	2^{240}	–	C	MITM	**Eurocrypt'24***
Collision	6	2^{228}	–	–	QA	Rebound, QAA	[HS20]
Collision	6	$2^{201.4}$	–	–	QA/QB	Rebound, QAA	**FSE'25***
Chosen-prefix	6	$2^{205.4}$	–	–	QA	Rebound, QAA, CPC	**FSE'25***

* Results from CATF

Application 2: Quantum MITM Preimage Attacks



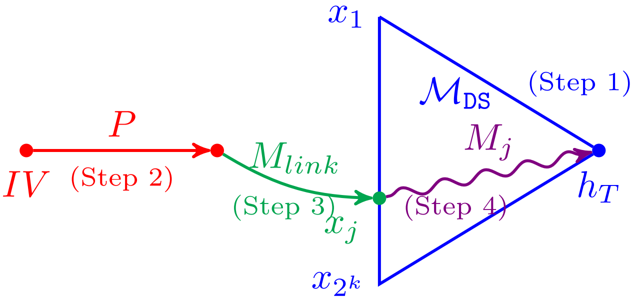
- Classical MITM Attacks: partition the function to two independently computable chunks, which meet in the middle and filtered by partial-match
- Quantum Variant: Nested Grover's search [SS22], storing one chunk into qRAM, and search for partial-matched candidates
- Need stronger conditions than classical attack!

Results on Classical/Quantum Preimage Attacks

Attack	Rounds	Time	cMem	qRAM	Setting	Technique	Source
AES-128-MMO							
Preimage	8/10	2^{120}	2^{32}	–	C	MITM	**Eurocrypt'21***
Preimage	7/10	2^{60}	–	2^{8}	QC	MITM, QAA	[SS23]
Preimage	7/10	2^{56}	–	2^{16}	QC	MITM, QAA	[DDS25]
AES-192-MMO							
Preimage	9/12	2^{112}	–	–	C	MITM	**Crypto'22***
Preimage	10/12	2^{124}	2^{124}	–	C	MITM	**Eurocrypt'24***
Preimage	9/12	2^{60}	–	2^{24}	QC	MITM, QAA	[DDS25]
AES-256-MMO							
Preimage	10/14	2^{120}	2^{56}	–	C	MITM	[DHS+21]
Preimage	9/14	2^{60}	–	2^{8}	QC	MITM, QAA	[DDS25]
Whirlpool							
Preimage	7/10	2^{480}	2^{128}	–	C	MITM	**Crypto'22***
Preimage	7.75/10	2^{480}	2^{256}	–	C	MITM	**Eurocrypt'24***
Preimage	6/10	2^{232}	–	2^{128}	QC	MITM, QAA	[DDS25]

* Results from CATF

Application 3: Quantum Nostradamus Attacks



- Nostradamus attack [KK06]: commit a hash value, then for any message given by the user, append a suffix to force the resulted message hash to the commitment
- Offline phase: builds a diamond structure
- Online phase: finds a link from initial hash value to any leaf of the diamond structure
- Both phases can be accelerated by quantum algorithms (offline: CNS/BHT, online: quantum MITM)

Results on Classical/Quantum Nostradamus Attacks

Attack	Rounds	Time	cMem	qRAM	Setting	Technique	Source
AES-128-MMO							
Nostradamus	6	$2^{82.7}$	$2^{82.2}$	–	C	MITM, Diamond	[ZSWH23]
Nostradamus	7	2^{83}	2^{82}	–	C	MITM, Diamond	**FSE'24***
Nostradamus	7	2^{58}	2^{30}	2^{8}	QC	MITM, Diamond, QAA	**FSE'24***
Whirlpool							
Nostradamus	4	2^{320}	2^{192}	–	C	MITM, Diamond	[ZSWH23]
Nostradamus	6	2^{334}	2^{333}	–	C	MITM, Diamond	**FSE'24***
Nostradamus	6	2^{230}	2^{117}	2^{24}	QC	MITM, Diamond, QAA	**FSE'24***

* Results from CATF

Thank You For Listening!

Questions?