Quantum-secure message authentication via blind-unforgeability

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Eurocrypt 2020, in Cyberspace
Introduction
Integrity and authenticity
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‣ “It says X on the bottom, but is this letter really from them?”
Integrity and authenticity

‣ “It says X on the bottom, but is this letter really from them?”

‣ “The letter probably took 5 days to get here, offering plenty of opportunities for somebody to change it.”
Integrity and authenticity

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Nowadays: digital signature schemes, message authentication codes (MACs).
Message authentication
Message authentication
Message authentication

Alice

\[ m \quad k \]

\[ \text{Mac} \]

\[ t \]

Bob

\[ k \]
Message authentication

...the Internet is a scary place...
Message authentication

...the Internet is a scary place...

Alice

\[ m \quad k \]

[Mac]

\[ t \]

Bob

\[ m' \quad k \]

[Mac]

\[ m' \quad t' \]

\[ \text{Il?} \]

acc/rej
Security: UF-CMA

Definition: Unforgeability under chosen message attacks (UF-CMA)

A message authentication code is secure, if no successful forger exists:

\[ m^* \neq m_i \text{ for all } i = 1, \ldots, q \]

\[ \text{Success:} \]

\[ i) \quad m^* \neq m_i \text{ for all } i = 1, \ldots, q \]

\[ ii) \quad \text{Mac}_k(m^*) = t^* \]
Quantum Access Security

Stronger security model: quantum oracle access to $\text{Mac}_k$:

$$|m\rangle |t\rangle \mapsto |m\rangle |t \oplus \text{Mac}_k(m)\rangle$$
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- As-strong-as-possible security
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- Physics?
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Let’s try **UF-“QCMA”**
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Let’s try UF-“QCMA”

Example:

i) Query $|m_1\rangle = \sum_{m \in \{0,1\}^n} |m\rangle |0\rangle$ to obtain $\sum_{m \in \{0,1\}^n} |m\rangle |\text{Mac}_k(m)\rangle$

ii) Measure in the computational basis to obtain $(m, \text{Mac}_k(m))$ for random $m$

iii) Output $(m, \text{Mac}_k(m))$
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UF-CMA doesn’t make sense anymore…
Quantum chosen message attacks

What does it mean for a function to be unpredictable against quantum?

What is a successful forging adversary?
Quantum chosen message attacks

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What is a successful forging adversary?

We shouldn’t be worried about:

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We should be worried about:

key $k$ specifies a random periodic function $f_k$ with period $p_k$

$\text{Mac}_k(p_k) = 0$, and $\text{Mac}_k(x) = f_k(x)$ $\forall x \neq p_k$

i) run period finding (a subroutine of Shor’s algorithm) to find $p_k$

ii) output $(p_k, 0)$
Quantum problems

Success:

i) $m^* \neq m_i$ for all $i = 1, \ldots, q$

ii) $\text{Mac}_k(m^*) = t^*$
Quantum problems

\[ m_1 \rightarrow t_1 \rightarrow m_1 \] \[ m_2 \rightarrow t_2 \rightarrow m_2 \] \[ \ldots \] \[ m_q \rightarrow t_q \rightarrow m_q \] \[ \text{Success:} \]  
\[ i) \ m^* \neq m_i \text{ for all } i = 1, \ldots, q \]  
\[ ii) \text{Mac}_k(m^*) = t^* \]

- No-cloning principle: can’t keep a transcript
- Measurement causes disturbance!
Results
Our results

- We study unforgeability under quantum chosen message attacks
- We propose a new security definition: blind unforgeability (BU)
- We exhibit a MAC that is secure under a previous definition by Boneh and Zhandry (Eurocrypt 2013) but clearly broken, and BU-insecure
- We characterize BU
  - It implies the previous definition
  - Random functions, Lamport signatures are BU secure
  - Hash-and-Mac/Hash-and-Sign preserves BU security for appropriate hash functions
Boneh and Zhandry (Eurocrypt 2013) propose:

Ask $q + 1$ forgeries for $q$ queries!

Success:

$$\text{Mac}_k(m_i^*) = t_i^* \quad \forall i = 1, \ldots, q + 1$$
Boneh Zhandry unforgeability

Boneh and Zhandry (Eurocrypt 2013) propose:

Ask $q + 1$ forgeries for $q$ queries!

Success:

\[ \text{Mac}_k(m^*_i) = t^*_i \quad \forall i = 1, \ldots, q + 1 \]

Has some nice properties:

- Equivalent to UF-CMA for classical oracle
- A random oracle is BZ-unforgeable (BZ ’13)
The right definition?

\[
\text{Success:} \quad \text{Mac}_k(m_i^*) = t_i^* \quad \forall i = 1, \ldots, q + 1
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What if…

- an adversary has to fully measure many queries to generate one forgery? (no-cloning)
The right definition?

\[ \text{Mac}_k \]

\[ \begin{align*}
  \uparrow t_1 & \quad \uparrow t_2 & \quad \uparrow t_q \\
  m_1 & \quad \downarrow m_2 & \quad \downarrow m_q \\
  \ldots & & \\
 \end{align*} \]

\[ \rightarrow (m^*_1, t^*_1), (m^*_2, t^*_2), \ldots, (m^*_{q+1}, t^*_{q+1}) \]

Success:
\[ \text{Mac}_k(m^*_i) = t^*_i \; \forall i = 1, \ldots, q+1 \]

What if…

- an adversary has to fully measure many queries to generate one forgery? (no-cloning)
- an adversary “queries here, forges there”?

all queries supported here
(msg prefix “from Alice”)

space of all messages

forgery comes from here
(msg prefix “from the White Rabbit”)
The right definition?

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\text{Mac}_k(m_i^*) = t_i^* \quad \forall i = 1, \ldots, q+1
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Success:

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In fact, it seems like it should be easy to find examples like this!
The right definition?

Mac_k

\[ Mac_k(m_i) = t_i \quad \forall i = 1, \ldots, q+1 \]

Success:

\[ (m_1, t_1), (m_2, t_2), \ldots, (m_{q+1}, t_{q+1}) \]

What if…

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all queries supported here (msg prefix “from Alice”)

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is not

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One obstacle: “property finding” cannot be used.
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One obstacle: “property finding” cannot be used.

One-time Mac that’s BZ secure, GYZ (Garg, Yuen&Zhandry, Crypto ’17) insecure, assuming iO (Zhandry, Eurocrypt ’19)
A MAC that unconditionally "breaks" Boneh-Zhandry:
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\[ m = \begin{cases} b \rightarrow & f^0_b(x) \\ x \rightarrow & f^1_b(x) \end{cases} \]

\[ \begin{align*} f^0_0(x) &= \hat{f}^0_0(x \mod p) \text{ for random } p, f^0_1 = \hat{f}^1_0 \\ f^0_i &= \begin{cases} 0^n & x = p \\ \hat{f}^0_i(x) & \text{else} \end{cases}, f^1_1 \equiv 0^n \\ f^i_b : \{0,1\}^n \rightarrow \{0,1\}^n \text{ random functions} \end{align*} \]
A MAC that unconditionally “breaks” Boneh-Zhandry:

A concrete example

Message space

$\{\text{Random periodic function shielded by a random function}\}$

$b = 0$

$\{\text{Random function punctured at the period}\}$

$b = 1$
A MAC that unconditionally "breaks" Boneh-Zhandry:

A concrete example

Simple one-query attack:
i) Use period finding to find $p$, "ignoring" $f_0^1$

ii) output $(1p, 0^{2n})$
A concrete example

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Simple one-query attack:

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A MAC that unconditionally "breaks" Boneh-Zhandry:

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Theorem (AMRS17). There is no efficient quantum algorithm which query \( \text{Mac}_k \) once but output two distinct input-output pairs of \( \text{Mac}_k \).
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Simple one-query attack:

i) Use period finding to find $p$, "ignoring" $f_0^1$

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Key step: ignorance is necessary
New approach: Blind Unforgeability (BU)

**Problem:** how do we define unforgeability vs quantum?
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**A new approach:** “blind unforgeability.”

**Idea:** to test a forger…

- give it the oracle for the MAC, but “blind” it on some inputs;
- ask the adversary to forge on a blinded spot.
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More formally: for $\text{Mac}_k$

1. Select $B_\varepsilon \subset \{0,1\}^n$ by putting every $m \in B_\varepsilon$ independently with probability $\varepsilon$;

2. Define “blinded” oracle: $B_\varepsilon \text{Mac}_k : m \mapsto \begin{cases} \text{Mac}_k(m) & m \notin B_\varepsilon \\ \bot & m \in B_\varepsilon \end{cases}$
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**Definition (Blind-Unforgeability):**

A MAC $Mac_k$ is blind-unforgeable if for every adversary $\mathcal{A}$ with a quantum oracle for $B_\varepsilon Mac_k$,

$$\mathbb{P} \left[ (m, Mac_k(m) \leftarrow \mathcal{A}^{B_\varepsilon Mac_k} \text{ and } m \in B_\varepsilon \right) = \text{negl}(n) \right]$$
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Does this work?

- equivalent to UF-CMA in classical setting;
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- Implies previous definition by Boneh and Zhandry;
- classifies the examples we have seen thus far correctly.

1. prepare: $m_1 = \sum_{m \in \{0,1\}^n} |m\rangle |0\rangle$;
2. query
3. measure
Output: $(m, B_\epsilon \text{Mac}_k(m))$ for random $m$. 

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Check, e.g., for random functions:

- if oracle is blinded…
- … $\text{Mac}_k(m)$ for blinded $m$ is independent of post-query state,
- this adversary fails.
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One-query attack: Find period in orange part, forge in olive part.
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Check, say for $\varepsilon = 0.0001$,

- oracle is blinded only on few random inputs…
- …post-query state won’t change too much;
- $(1p, 0)$ is blinded with \textit{independent} probability $\varepsilon$;
- so this adversary succeeds!
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Additional results:
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**Tools:**
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Tools:
- A simulation lemma that relates an adversary’s performance in the blinded and unblinded cases
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Tools:
- A simulation lemma that relates an adversary’s performance in the blinded and unblinded cases
- Zhandry’s superposition representation of quantum random oracles
Summary, open questions

Summary:

‣ We exhibit a MAC that is secure according to a definition by Boneh and Zhandry but allows for an intuitive forgery attack.

‣ We propose a replacement definition: Blind Unforgeability

‣ Blind unforgeability has a lot of nice properties and classifies all known examples correctly.

Open questions:

‣ The security game for blind unforgeability is not natural. Can this be fixed?

‣ Are popular schemes (MACs and DSS) blind-unforgeable? We only have NMAC, HMAC and Lamport in the QROM for now…