On Best-Possible One-Time Programs

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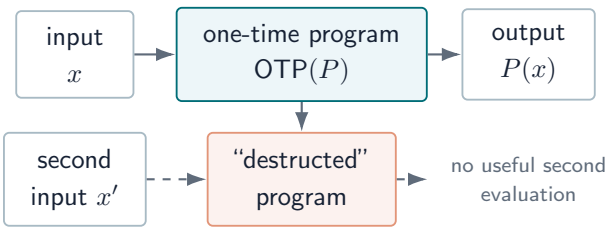
One-Time Programs (OTPs) [Goldwasser–Kalai–Rothblum'08]

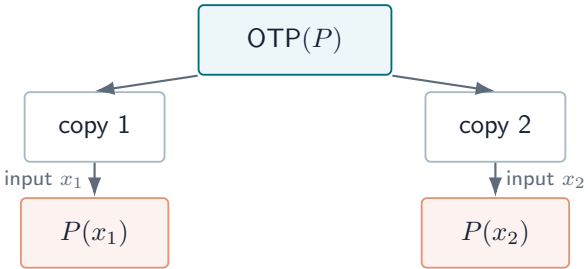
Ideal goal

A one-time program for P lets a user evaluate P on one input of their choice, while preventing them from learning anything else useful about P.



Classical OTPs are impossible

Suppose OTP outputs classical bitstrings.



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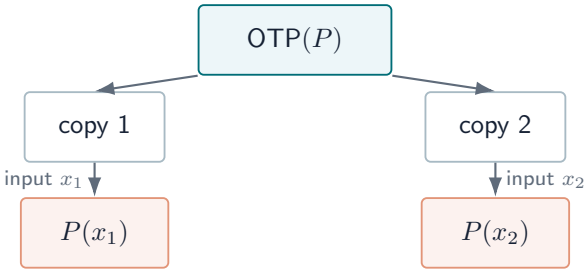
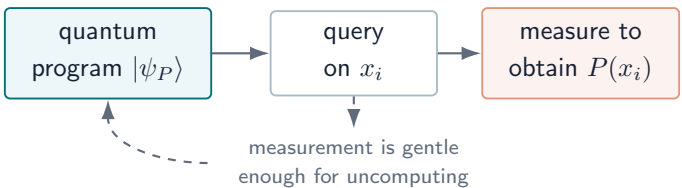


No cloning please rescue 🙏🙏🙏

Quantum OTPs are also impossible

Broadbent–Gutoski–Stebila'13 impossibility

Correctness for deterministic classical $P \Rightarrow$ measurement of output is gentle

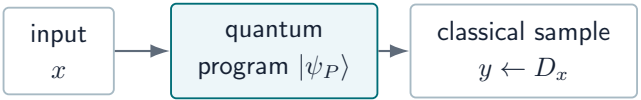


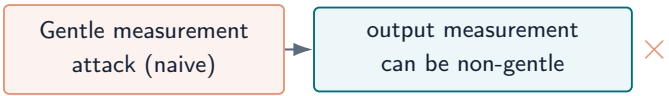
Even worse: coherent access for free

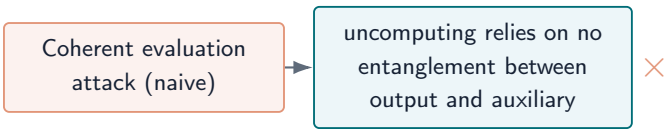
Coherent computation is always possible even if implemented by a quantum state:

$$|x\rangle|\psi_P\rangle \longmapsto |x\rangle|P(x)\rangle|\psi_P\rangle.$$

A way out? Quantum program + randomized outputs



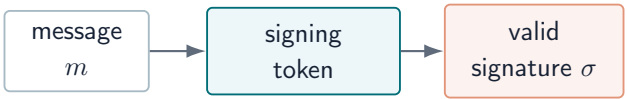




Signature tokens [Ben-David–Sattath'19]

A signature token is a (quantum) one-time program for the signing functionality:

$$\mathsf{Sign}_{\mathsf{sk}}(m; r) \to \sigma \quad \text{with} \quad \mathsf{Ver}_{\mathsf{vk}}(m, \sigma) = 1.$$



Security: an adversary should not produce valid signatures on two different messages.

Prior work: randomized OTPs

Functionalities	Prior work	Security achieved	Gap
Signing	Ben-David–Sattath'19	Signature tokens	Only signing

For simplicity, we use ideal classical obfuscation / classical oracles as assumptions.

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PRF/NIZK		Two-time indistinguishability/unprovability	Application-specialized security
Contrived high-entropy randomized $P(x;r)$		Ideal one-time interface $x \mapsto y \leftarrow D_x$ is impossible	(negative result)

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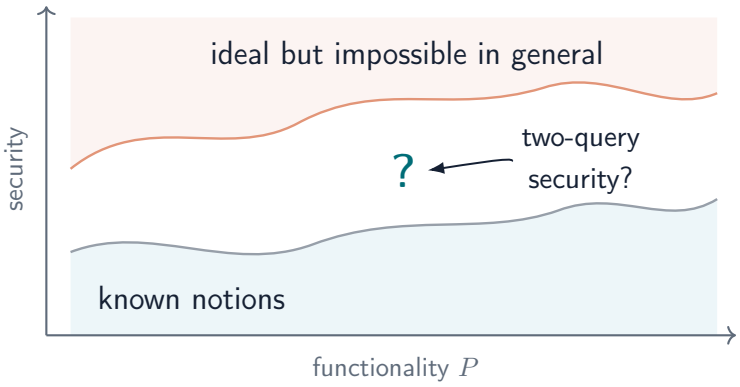
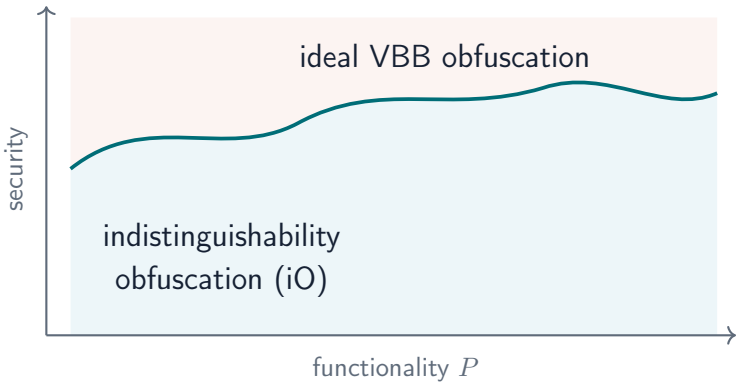
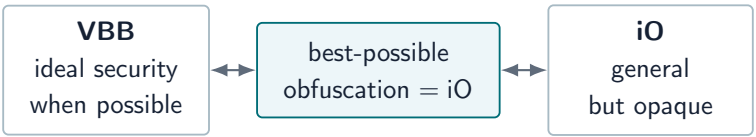
What is the strongest achievable security?



Many-time analogy: obfuscation



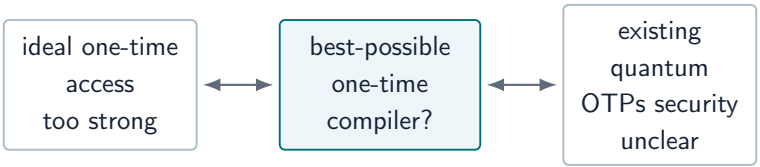
Best-Possible Obfuscation [Goldwasser–Rothblum'07]



If a functionality can be VBB-obfuscated, then iO achieves VBB.
(Also applies to other obfuscation security notions.)
It suffices to focus on constructing iO!

Best-Possible One-Time Programs?

Can quantum OTPs have the same "best-possible" story?



Is there a generic one-time compiler that achieves the best-possible security for any functionality?

Talk outline

- Background and motivation
  (you are here)
- Best-possible one-time programs are impossible
  - Proof sketch
- Getting around the impossibility
  - More new one-time security notions
  - Generalizing to quantum functionalities
  - New OTP constructions

Theorem 1: no best-possible OTP

Assuming lossy encryptions exist, no best-possible one-time compiler exists.

- Lossy encryptions can be constructed from Learning with Errors (LWE) or from weak pseudorandom group actions.
- Also relativizes to all oracles.

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Insight: Whether a program samples from the same distribution for every input should not be efficiently learnable. (Use crypto to formalize this.)

Formalizing the contradiction

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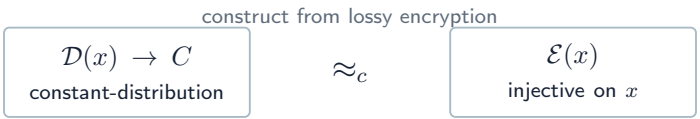

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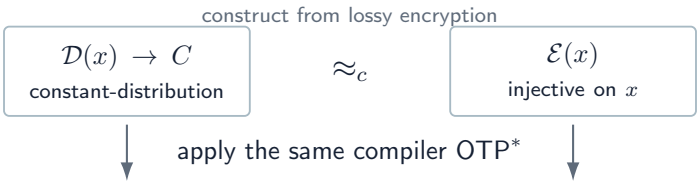

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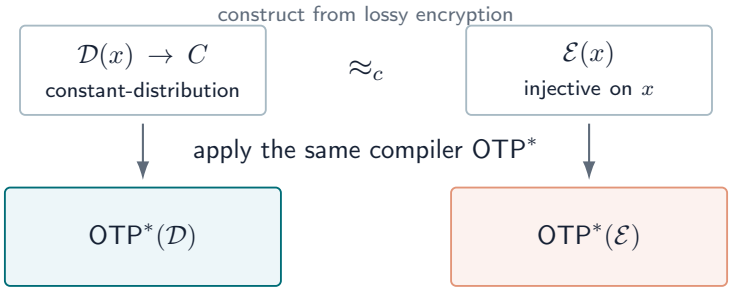

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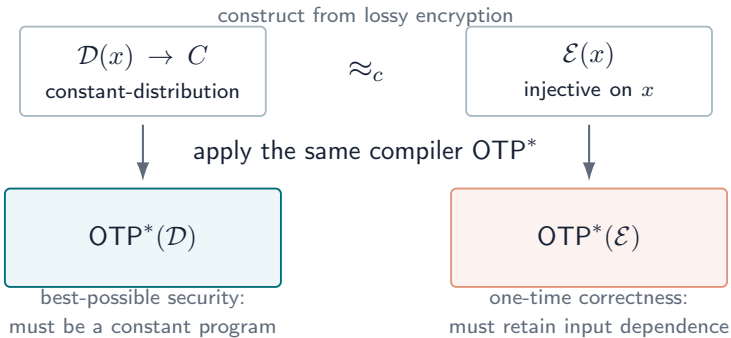

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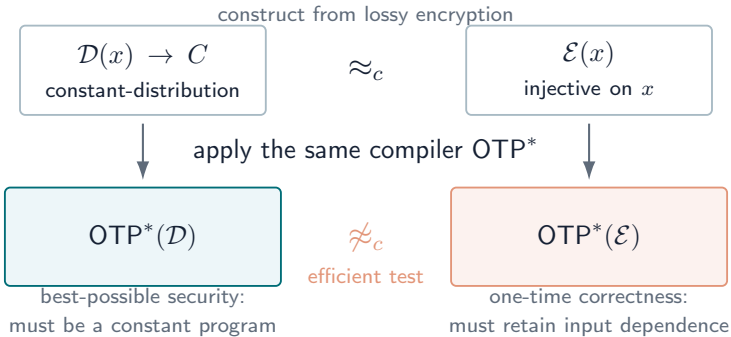

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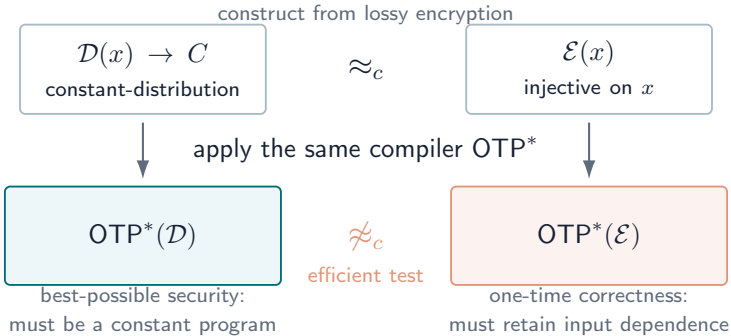

Contradiction: OTP^* must be inefficient.

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- By best-possible security, $\mathsf{OTP}^*(D)$ must be simulatable from one sample of C_y.
- By correctness, given only one sample of C_y, the simulator must output a constant program.

Getting around the best-possible impossibility

Two approaches:

- Restrict the class of protected functionalities from all randomized/quantum functionalities.
- Restrict the class of one-time compilers from all efficient implementations.

Getting around the best-possible impossibility, approach 2

Our definition (and proof) compares the given OTP to *any* implementation, including mixed implementations:

$$\rho = \sum_i p_i |\phi_i\rangle\langle\phi_i|.$$

We allow a program to be one-time correct only after averaging over p_i.

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Question: What if we only focus on best possible within a restricted subclass of one-time compilers that output "pure programs"?

Naive pure BPOTP still allows random purification

The counterexample above

$$\rho = \sum_y p_y |C_y\rangle\langle C_y|$$

can be purified as

$$\rho = \mathbb{E}_r \left[|\psi_r\rangle\langle\psi_r| \right] \text{ where } |\psi_r\rangle = \sum_y \sqrt{p_y} e^{i r_y} |C_y\rangle.$$

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A pure-state OTP class needs a more careful definition.

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Definition: A *testable one-time compiler* is a one-time compiler that outputs mixtures over $(|\psi\rangle, R_\psi)$ where every $|\psi\rangle$ is a pure one-time correct implementation.

Testability of known OTP constructions

OTP construction	**Testable?**
Classical program	✅ Reflecting for computational basis is trivial
Uncloneable $\|\text{token}\rangle$ + obfuscated program that only computes P only with a valid $\|\text{token}\rangle$	✅ Use the obfuscated program
Mixures of constant programs for constant distributions	🟥 Mixed implementation: intentionally excluded

Testable OTPs capture all known OTP constructions in prior works.

Theorem 2: best-possible testable OTP

Best-possible *testable* one-time compiler exists for all randomized functionalities relative to a classical oracle.

- Also extends to all quantum functionalities $\downarrow$

A SEQ detour

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- **Known:** CSEQ-secure OTPs for all randomized classical functionalities in the classical oracle model.

The CSEQ interface

Definition (The Classical Single Effective Query Oracle). For a randomized function $f : \mathcal{X} \times \mathcal{R} \to \mathcal{Y}$, we define the classical single effective query oracle O_f^{CSEQ} as implementing the following algorithm:

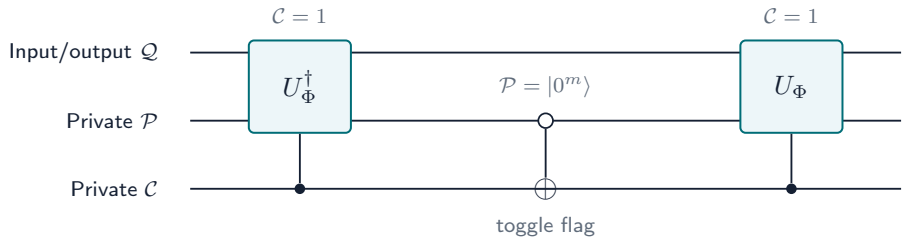
- We assume it has oracle access to O_f, which maps
$$|x, r, u\rangle \mapsto |x, r, u \oplus f(x; r)\rangle.$$
- The oracle maintains two internal registers: a workspace register $\mathcal{W}$ to perform intermediate computations, and a database register $\mathcal{D}$ to implement the database for the compressed random oracle. These registers are initialized to $|0\rangle_{\mathcal{W}} \otimes |\emptyset\rangle_{\mathcal{D}}$.
- To describe its behavior on queries, all we need to do is describe its behavior on basis states. We will maintain the invariant that the workspace register is always $|0\rangle_{\mathcal{W}}$.
- On query $|x, u, b\rangle_{\mathcal{Q}}$ on query register $\mathcal{Q}$, the oracle implements an isometry specified by the following steps on each basis state
$$|x, u, b\rangle_{\mathcal{Q}} \otimes |D\rangle_{\mathcal{D}} \otimes |0\rangle_{\mathcal{W}}.$$

1. If there exists some $x' \neq x$ such that $(x', r) \in D$ for some $r \in \mathcal{R}$, skip the following steps.
2. Copy x into the workspace register
$$|x, u, b\rangle_{\mathcal{Q}}|D\rangle_{\mathcal{D}}|0\rangle_{\mathcal{W}} \mapsto |x, u, b\rangle_{\mathcal{Q}}|D\rangle_{\mathcal{D}}|x, 0\rangle_{\mathcal{W}}.$$
3. Apply a compressed random oracle query isometry with query register $\mathcal{W}$ and database register $\mathcal{D}$.
4. On the basis states apply the following unitary map that acts on registers $\mathcal{Q}, \mathcal{W}$:
$$|x, u, b\rangle_{\mathcal{Q}}|D\rangle_{\mathcal{D}}|x, r\rangle_{\mathcal{W}} \mapsto |x, u \oplus f(x; r), b \oplus 1\rangle_{\mathcal{Q}}|D\rangle_{\mathcal{D}}|x, r\rangle_{\mathcal{W}}.$$
5. Uncompute the workspace register: first, query the compressed oracle again with the query register being $\mathcal{W}$ and the database register being $\mathcal{D}$, and then copy the input x.

(Generalized) SEQ interface for quantum functionalities

Definition (The Single Effective Query Oracle). Let Φ be a channel with any Stinespring unitary $U_\Phi : \mathcal{H}_\mathcal{Q} \otimes \mathcal{H}_\mathcal{P} \to \mathcal{H}_\mathcal{Q} \otimes \mathcal{H}_\mathcal{P}$, with $\mathcal{P}$ initialized to $|0^m\rangle_\mathcal{P}$. The oracle O_Φ^{SEQ} acts on the query register $\mathcal{Q}$ and maintains hidden registers $\mathcal{P}$ and $\mathcal{C}$, initialized to $|0^m\rangle_\mathcal{P}|0\rangle_\mathcal{C}$:

$$|\varphi\rangle_\mathcal{Q}|0^m\rangle_\mathcal{P}|0\rangle_\mathcal{C} \;\longleftrightarrow\; U_\Phi(|\varphi\rangle_\mathcal{Q}|0^m\rangle_\mathcal{P})\,|1\rangle_\mathcal{C}.$$



Example: SEQ on random-coin channel

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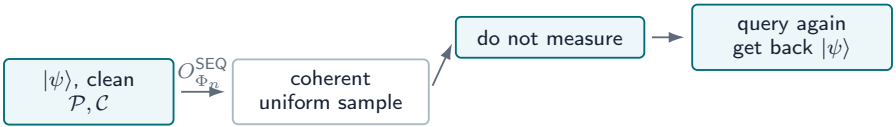
Then $O^{\text{SEQ}}_{\Phi_n}$ hides $\mathcal{P},\mathcal{C}$ and swaps

$$|\psi\rangle_{\mathcal{Q}}|0^n\rangle_{\mathcal{P}_R}|0^n\rangle_{\mathcal{P}_{\text{in}}}|0\rangle_{\mathcal{C}} \longleftrightarrow 2^{-n/2}\sum_r |r\rangle_{\mathcal{Q}}|r\rangle_{\mathcal{P}_R}|\psi\rangle_{\mathcal{P}_{\text{in}}}|1\rangle_{\mathcal{C}}.$$



Example: SEQ on random-coin channel

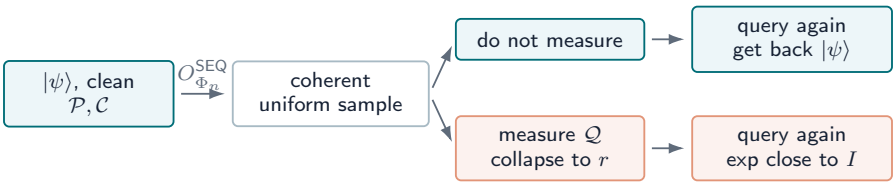
Channel: $\Phi_n(\rho_{\mathcal{Q}}) = 2^{-n} \sum_{r\in\{0,1\}^n} |r\rangle\langle r|_{\mathcal{Q}}$ discards the input.

Consider Stinespring unitary

$$U_{\Phi_n} : |\psi\rangle_{\mathcal{Q}}|0^n\rangle_{\mathcal{P}_R}|0^n\rangle_{\mathcal{P}_{\text{in}}} \longmapsto 2^{-n/2}\sum_r |r\rangle_{\mathcal{Q}}|r\rangle_{\mathcal{P}_R}|\psi\rangle_{\mathcal{P}_{\text{in}}}.$$

Then $O^{\text{SEQ}}_{\Phi_n}$ hides $\mathcal{P},\mathcal{C}$ and swaps

$$|\psi\rangle_{\mathcal{Q}}|0^n\rangle_{\mathcal{P}_R}|0^n\rangle_{\mathcal{P}_{\text{in}}}|0\rangle_{\mathcal{C}} \longleftrightarrow 2^{-n/2}\sum_r |r\rangle_{\mathcal{Q}}|r\rangle_{\mathcal{P}_R}|\psi\rangle_{\mathcal{P}_{\text{in}}}|1\rangle_{\mathcal{C}}.$$



Theorem 3: SEQ subsumes CSEQ

For every non-trivial randomized classical $f : \mathcal{X} \times \mathcal{R} \to \mathcal{Y}$ with $|\mathcal{X}| > 1$, there is a channel Φ_f such that O_f^{CSEQ} and $O_{\Phi_f}^{\mathsf{SEQ}}$ are efficiently inter-simulatable.

Thus SEQ generalizes and simplifies CSEQ.

CSEQ = SEQ using channel wrapper Φ_f.

The proof is involved because CSEQ is involved.

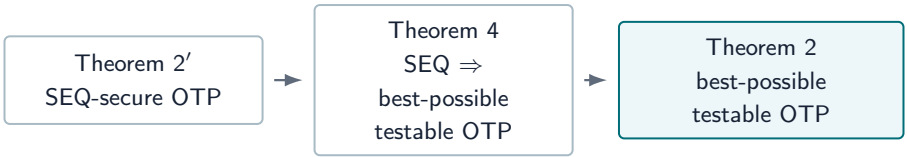
Theorem 4: SEQ $\Rightarrow$ best-possible testable OTPs

Any SEQ-secure one-time compiler is best-possible among testable one-time compilers.
Moreover, this implication relativizes to all unitary oracles.

SEQ plays for testable OTPs the role that VBB plays for obfuscation.

Theorem 2′: SEQ-secure OTP

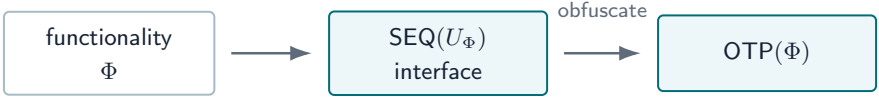
There exists an SEQ-secure one-time compiler for all quantum functionalities in the classical oracle model.



Combining Theorem 2′ with Theorem 4 gives the original Theorem 2.

Construction overview

Idea: it suffices to obfuscate the SEQ interface.



The catch: SEQ has private states

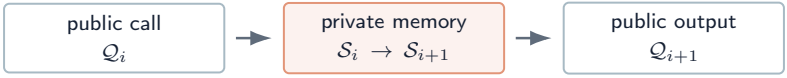
Not a stateless unitary $\mathcal{Q} \to \mathcal{Q}$

New primitive: stateful iO

A stateful program is a unitary plus an initial private state.

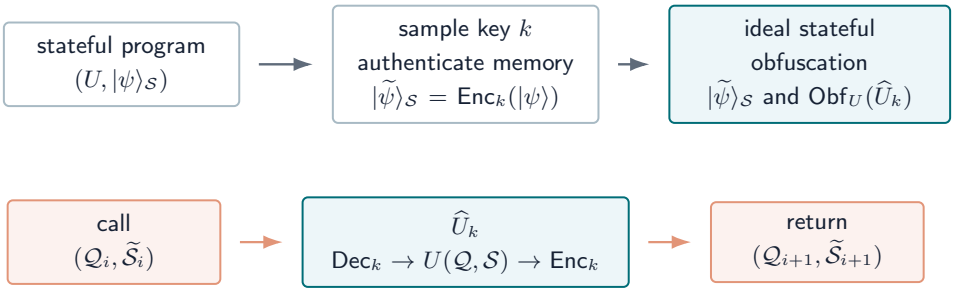
indistinguishable behavior for every polynomial sequence of calls

$\Longrightarrow$ indistinguishable obfuscations



Constructing ideal stateful obfuscation

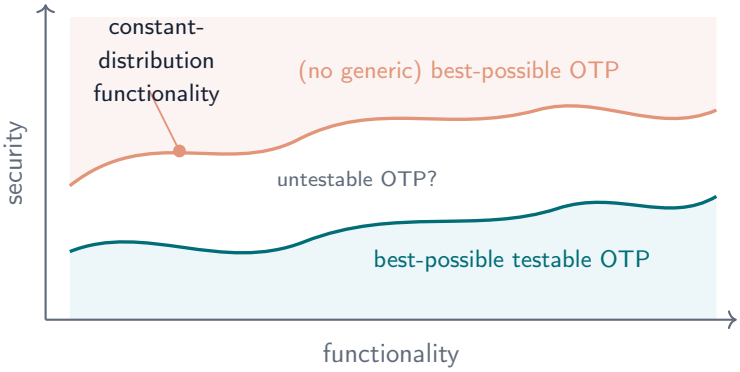
Protect the private memory, then obfuscate the memory-update unitary.



Ideal unitary obfuscation can be instantiated in the classical oracle model [Huang–Tang'25].

Open: replace ideal obfuscation with (quantum) iO

Conclusions



See paper for a generic multi-observable attack against testable OTPs.