Non-Observable Quantum Random Oracle Model

Varun Maram
Applied Cryptography Group
ETH Zurich

APPLIED CRYPTO GROUP

Joint work with Navid Alamati and Daniel Masny

[Full version of paper: https://eprint.iacr.org/2023/1126.pdf]

NO QROM(!)

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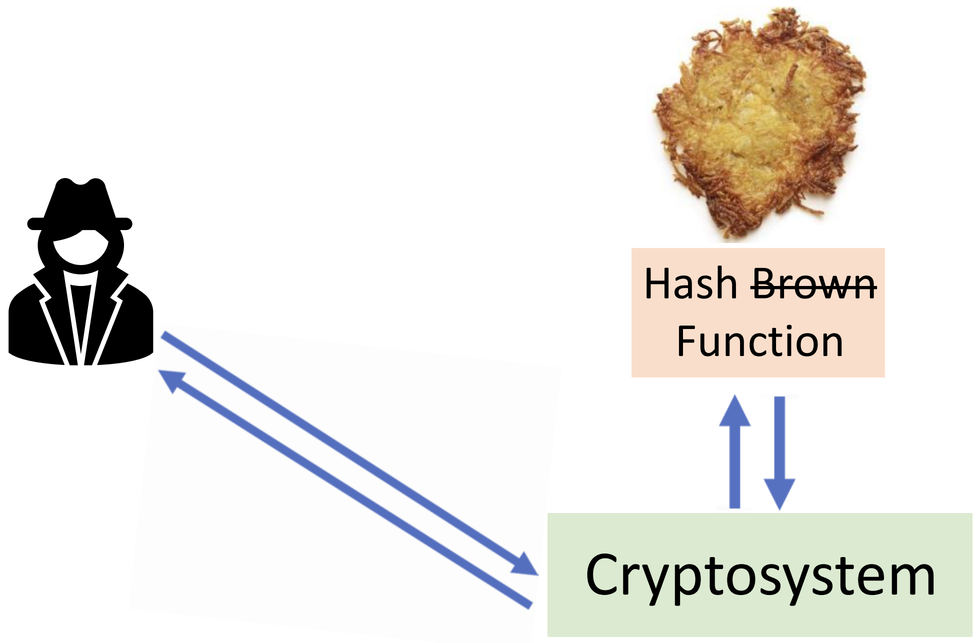

- Formalized by [Bellare-Rogaway'93].

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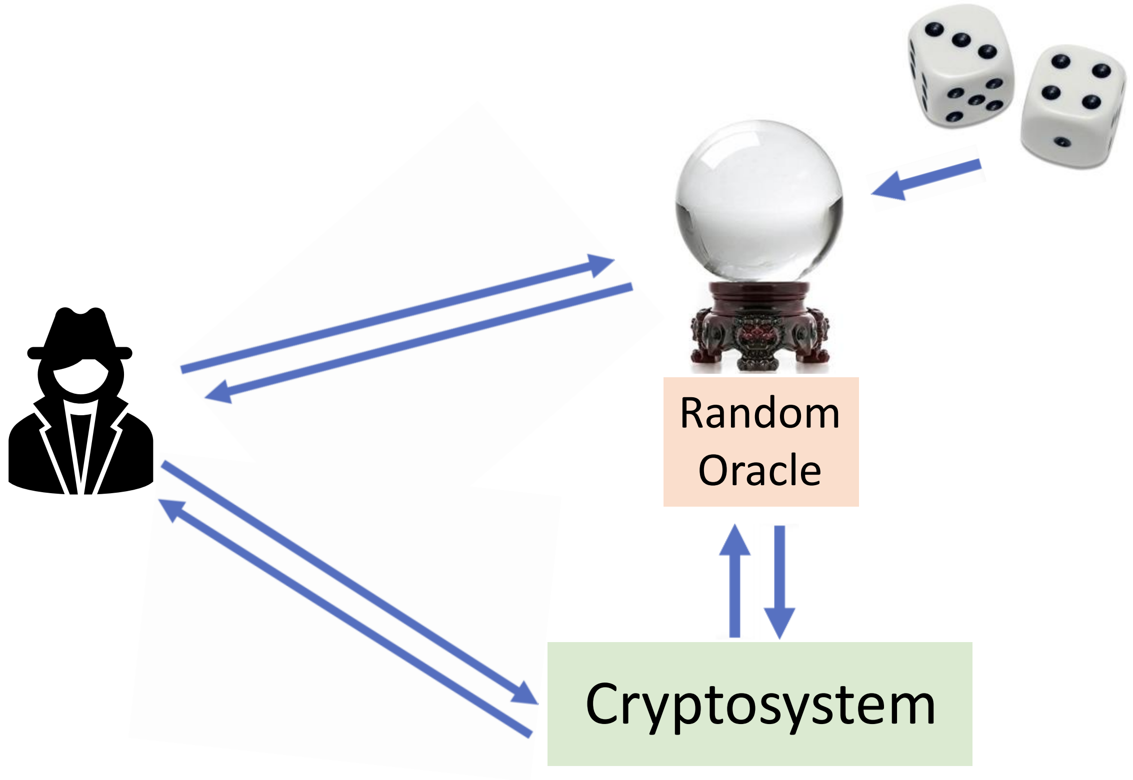

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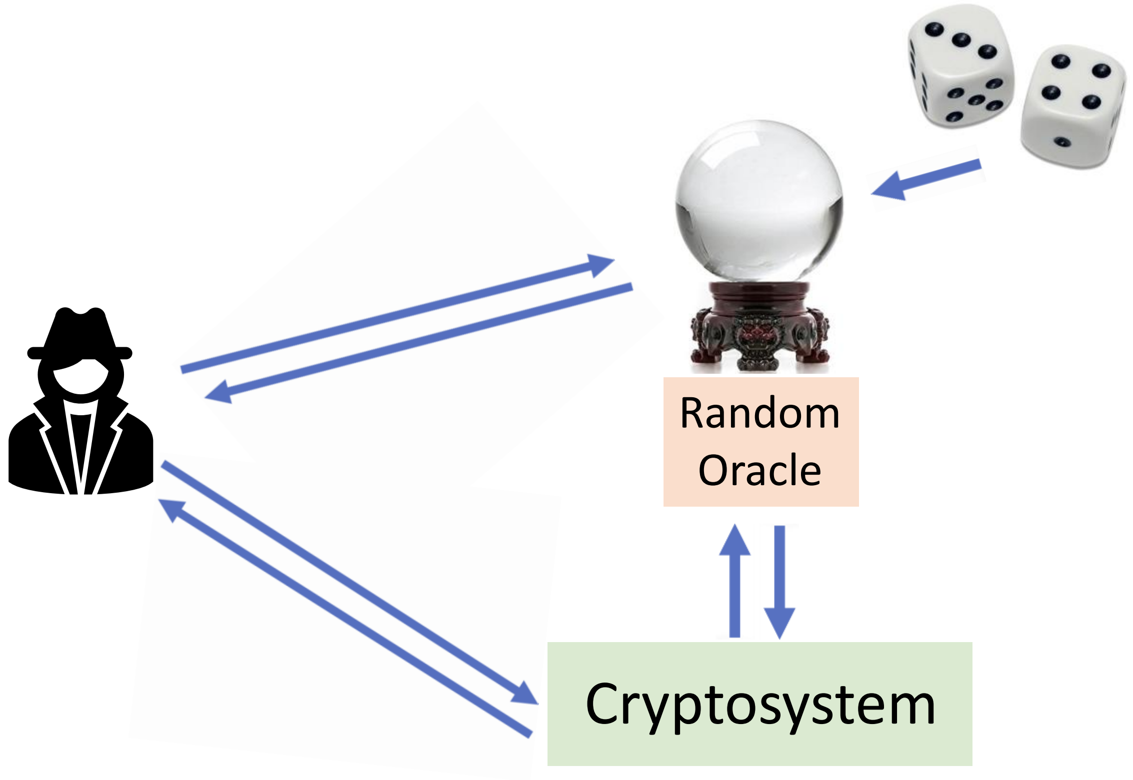

- Formalized by [Bellare-Rogaway'93].
- Highly influential model to argue <u>heuristic</u> security of efficient and practical cryptosystems.

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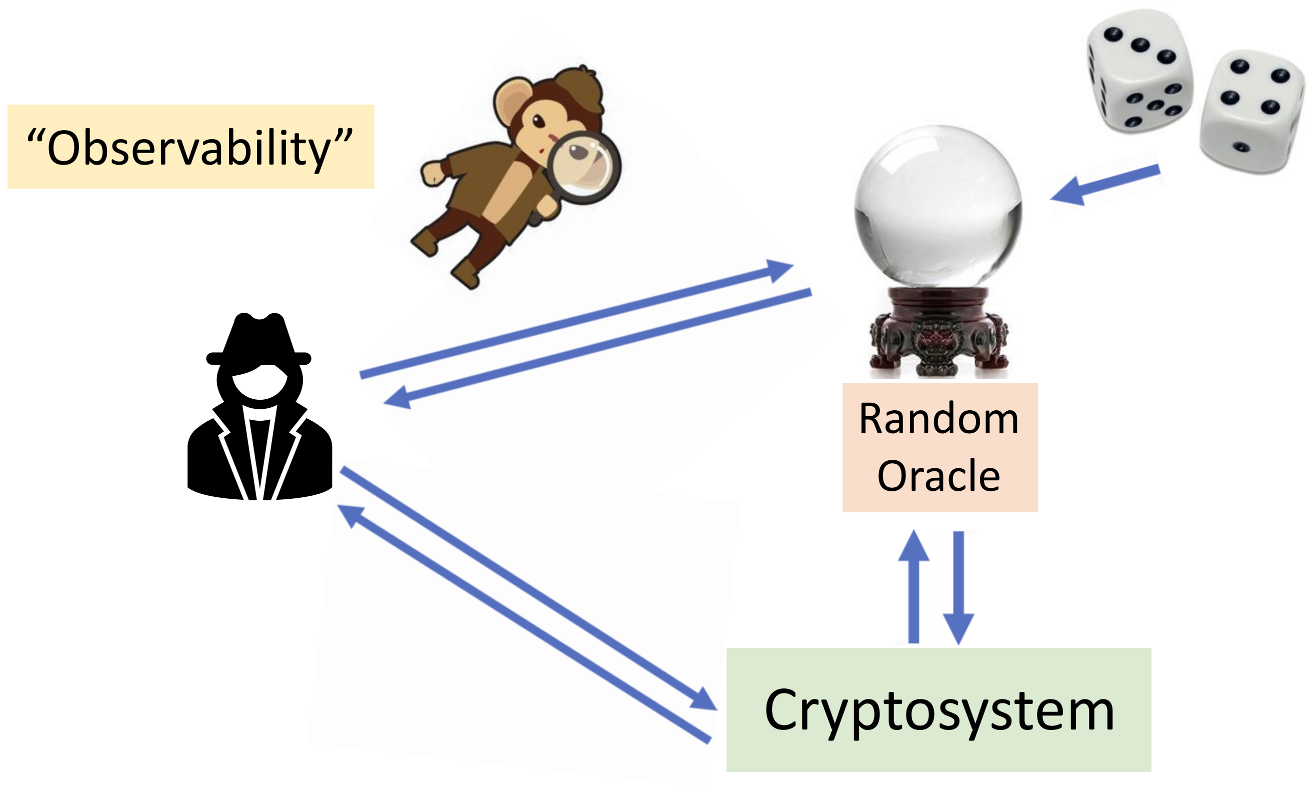

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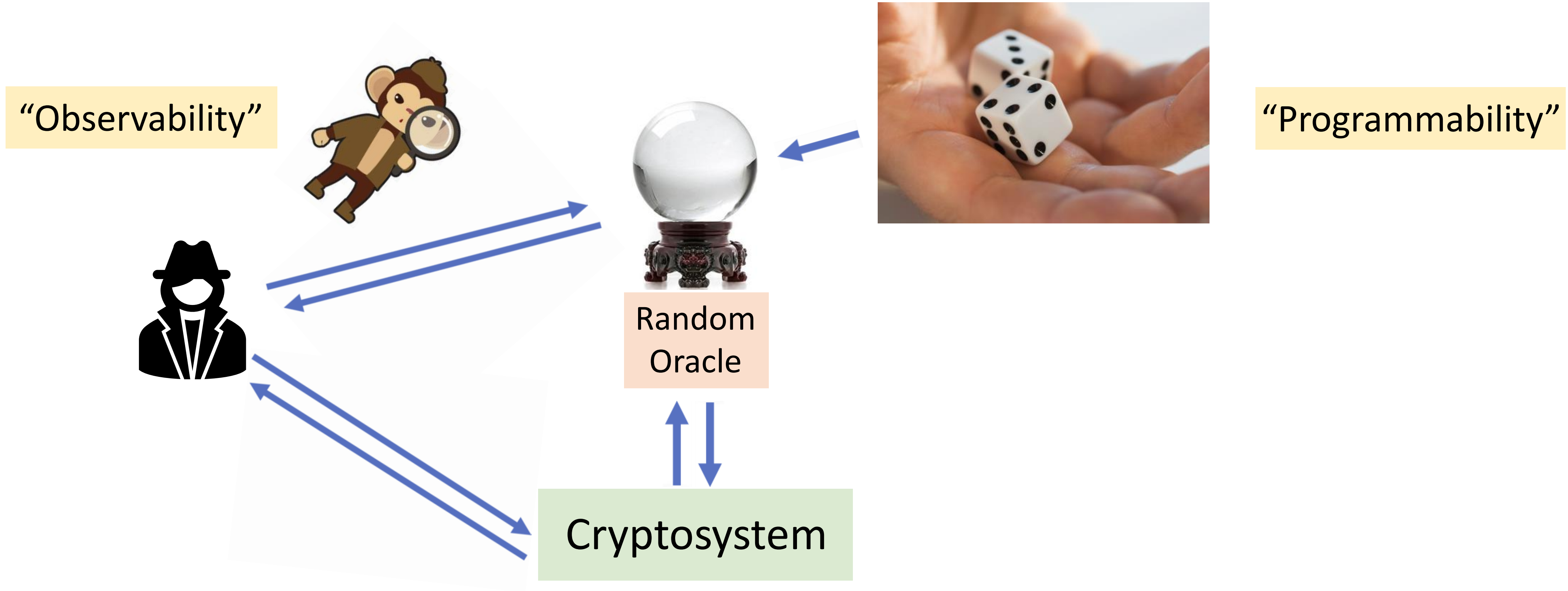

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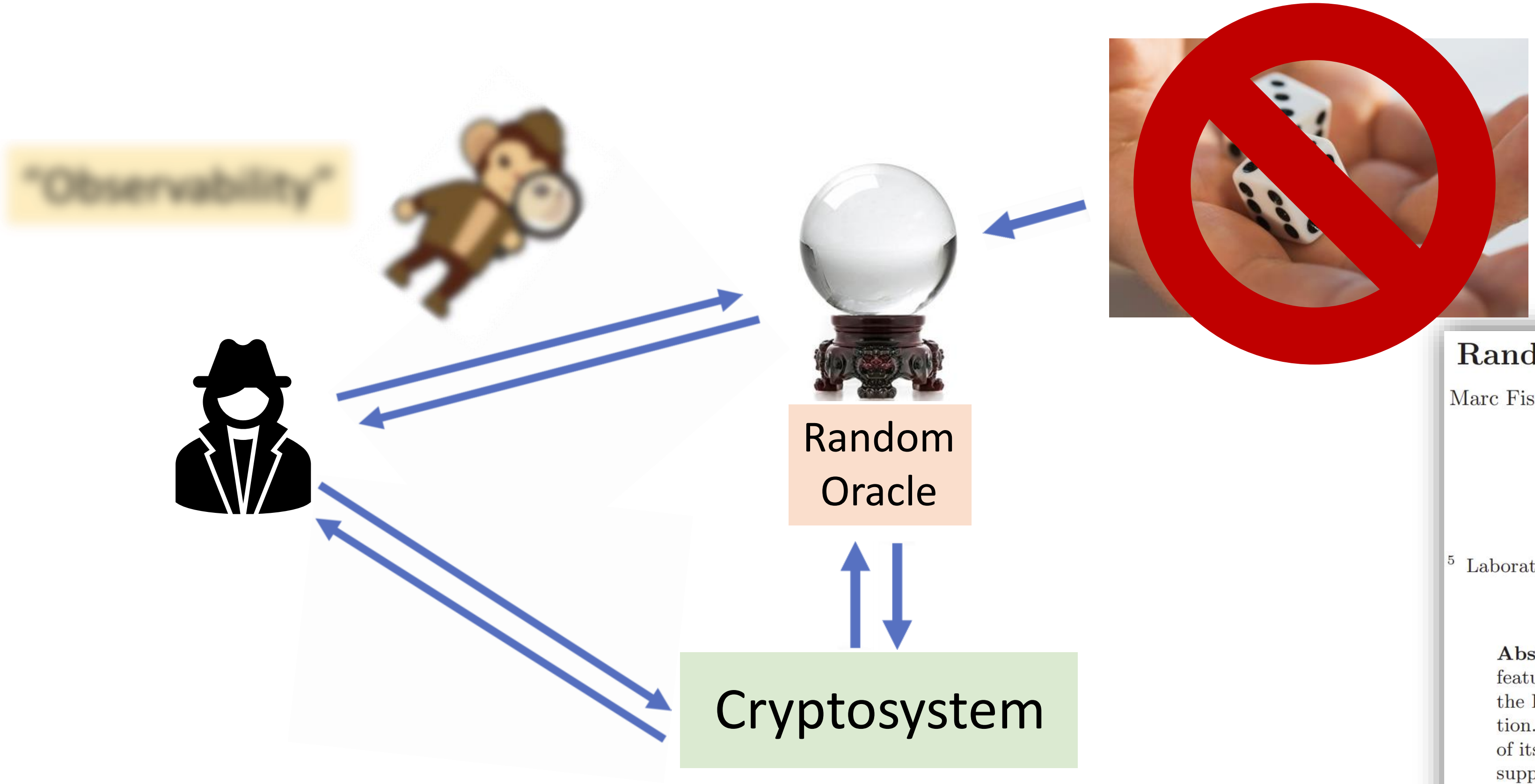
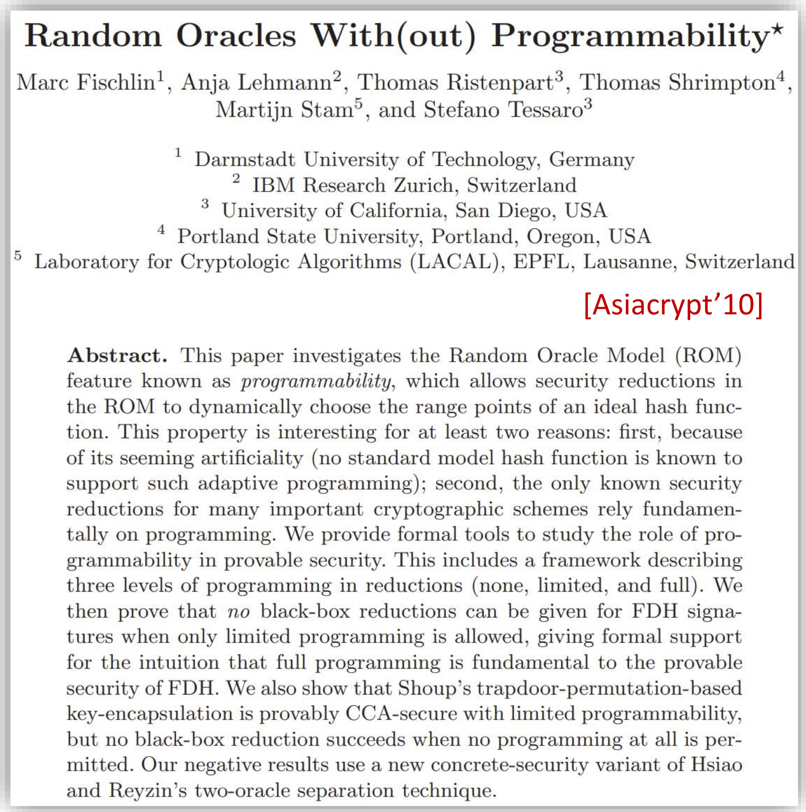


"Non-Programmability"



Random Oracles With(out) Programmability*

Marc Fischlin[1], Anja Lehmann[2], Thomas Ristenpart[3], Thomas Shrimpton[4], Martijn Stam[5], and Stefano Tessaro[3]

[1] Darmstadt University of Technology, Germany
[2] IBM Research Zurich, Switzerland
[3] University of California, San Diego, USA
[4] Portland State University, Portland, Oregon, USA
[5] Laboratory for Cryptologic Algorithms (LACAL), EPFL, Lausanne, Switzerland

[Asiacrypt'10]

Abstract. This paper investigates the Random Oracle Model (ROM) feature known as *programmability*, which allows security reductions in the ROM to dynamically choose the range points of an ideal hash function. This property is interesting for at least two reasons: first, because of its seeming artificiality (no standard model hash function is known to support such adaptive programming); second, the only known security reductions for many important cryptographic schemes rely fundamentally on programming. We provide formal tools to study the role of programmability in provable security. This includes a framework describing three levels of programming in reductions (none, limited, and full). We then prove that *no* black-box reductions can be given for FDH signatures when only limited programming is allowed, giving formal support for the intuition that full programming is fundamental to the provable security of FDH. We also show that Shoup's trapdoor-permutation-based key-encapsulation is provably CCA-secure with limited programmability, but no black-box reduction succeeds when no programming at all is permitted. Our negative results use a new concrete-security variant of Hsiao and Reyzin's two-oracle separation technique.

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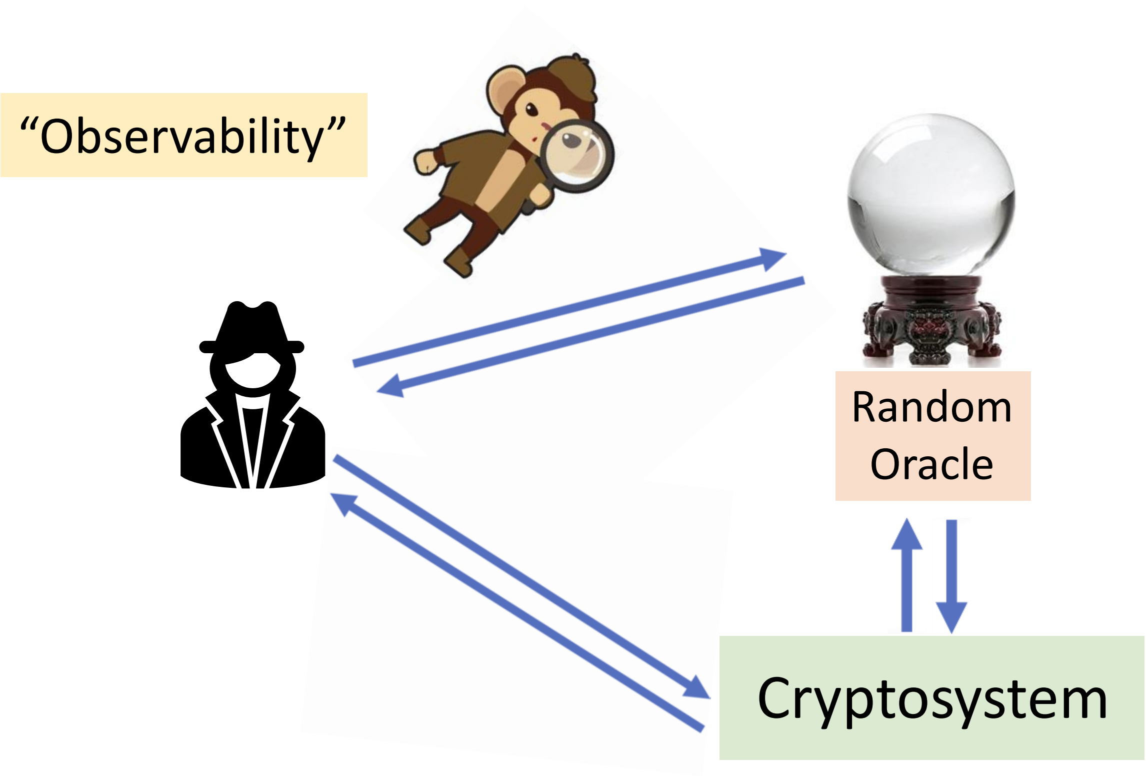

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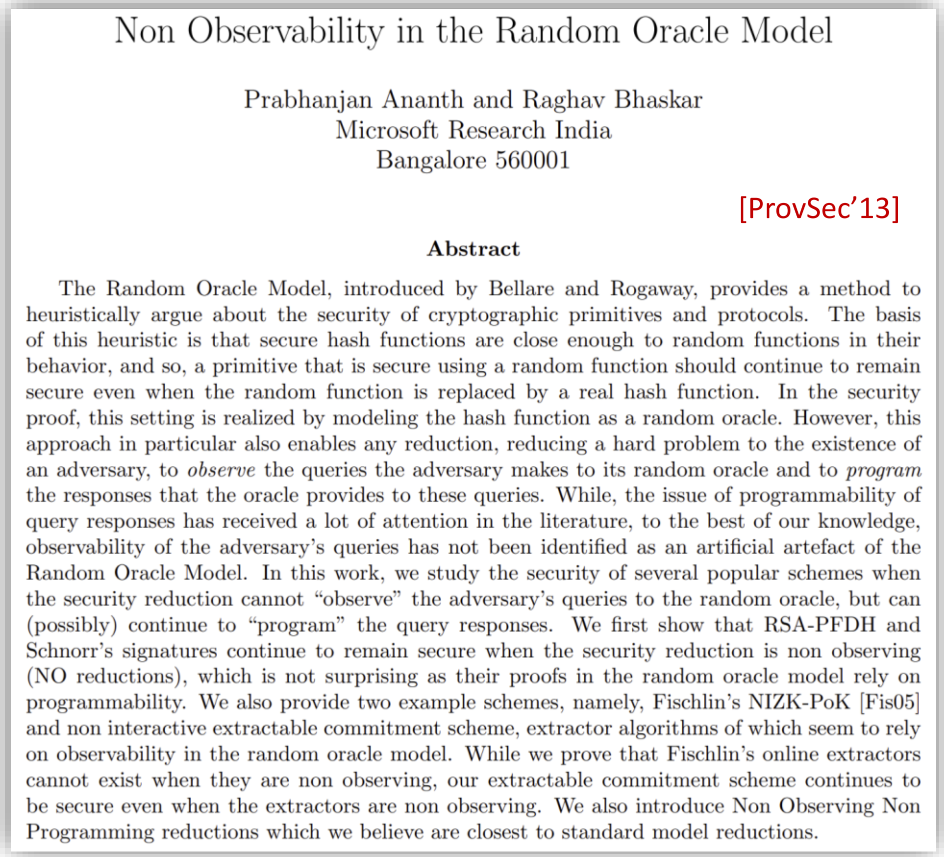

Non Observability in the Random Oracle Model

Prabhanjan Ananth and Raghav Bhaskar
Microsoft Research India
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[ProvSec'13]

Abstract

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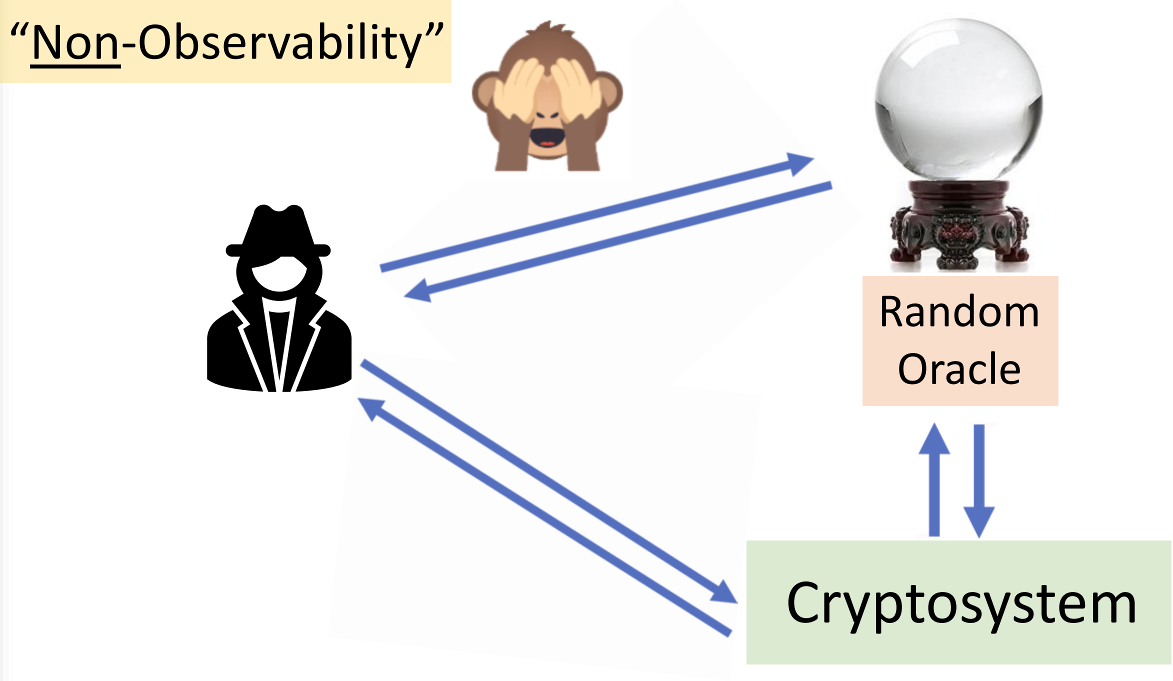

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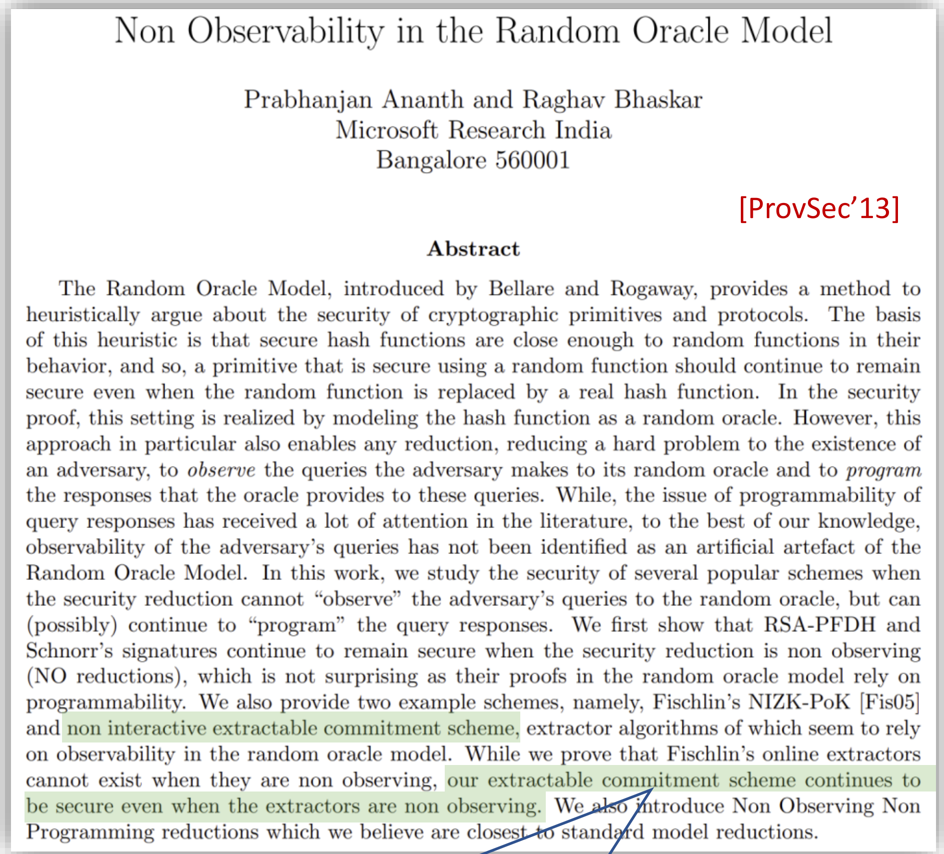

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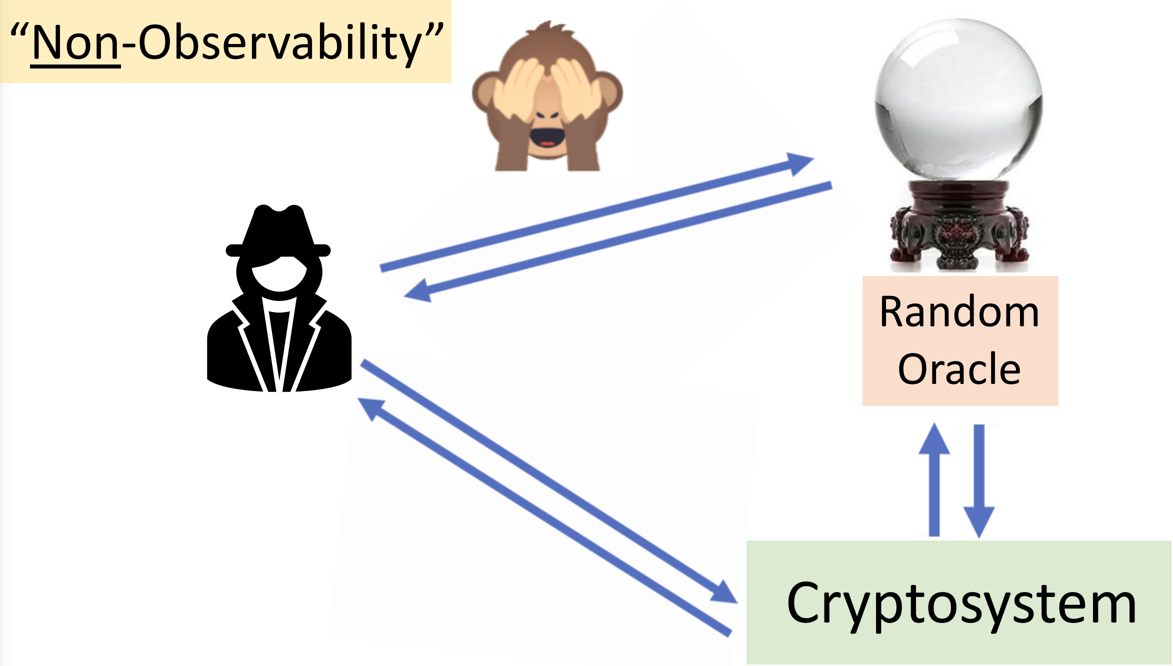

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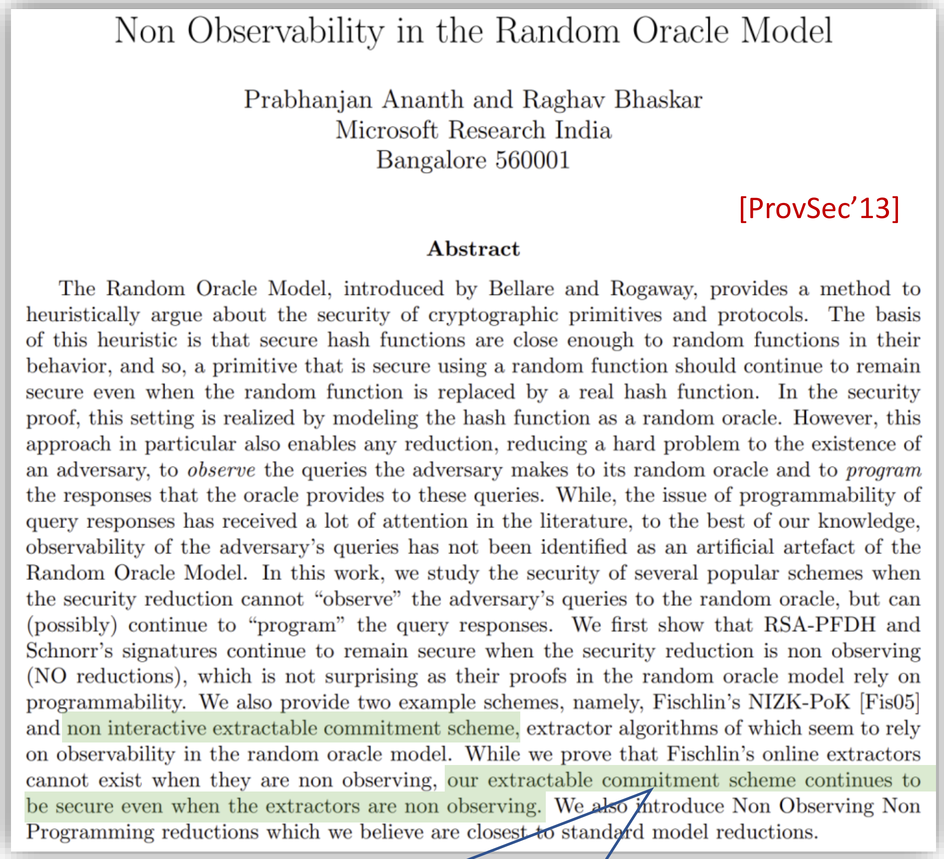

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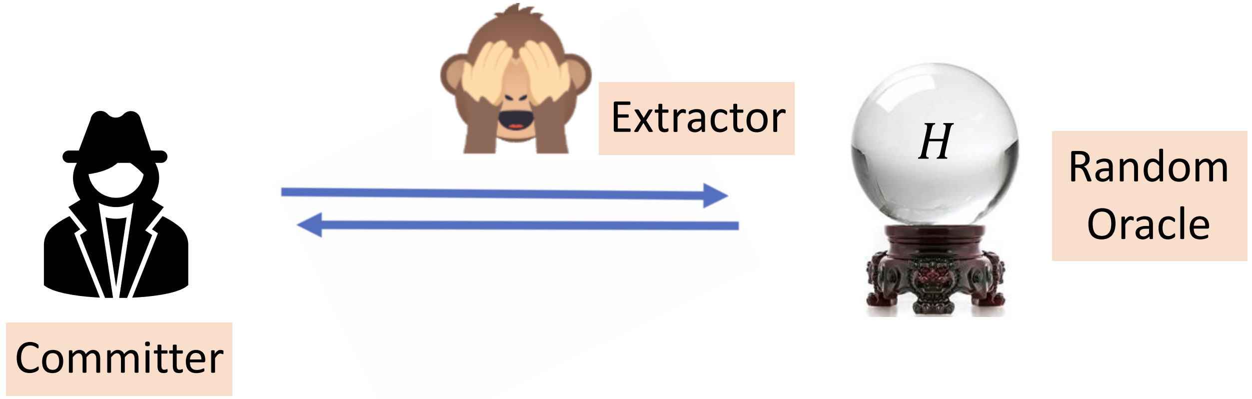

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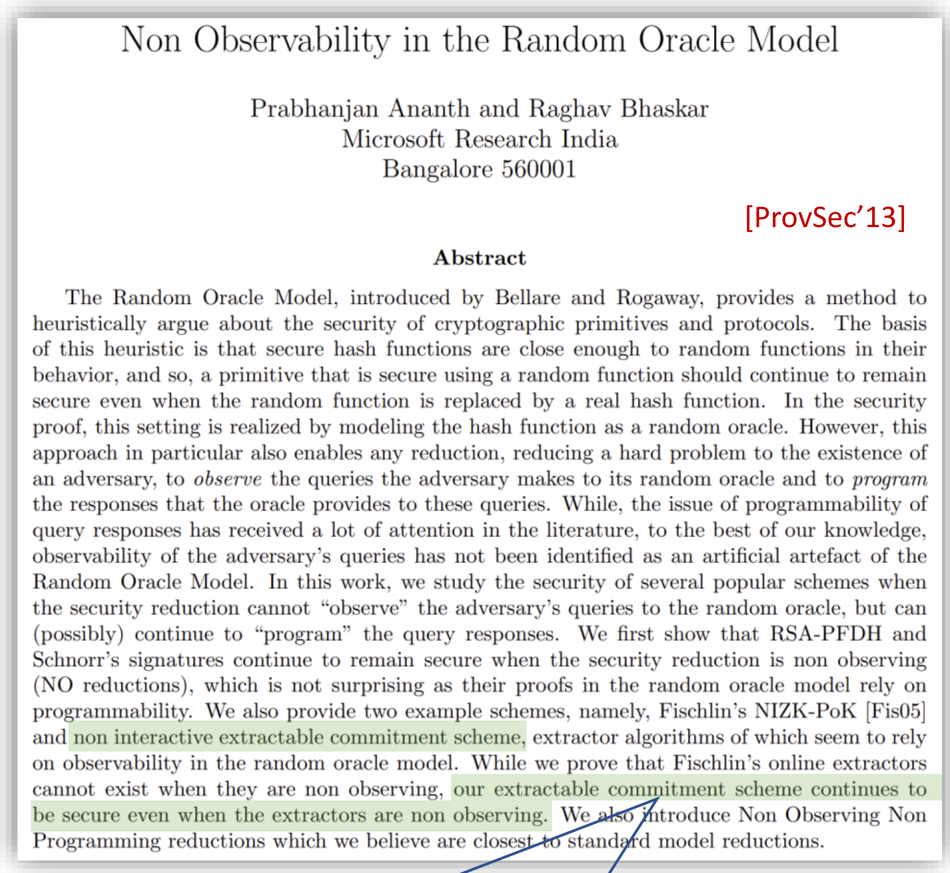

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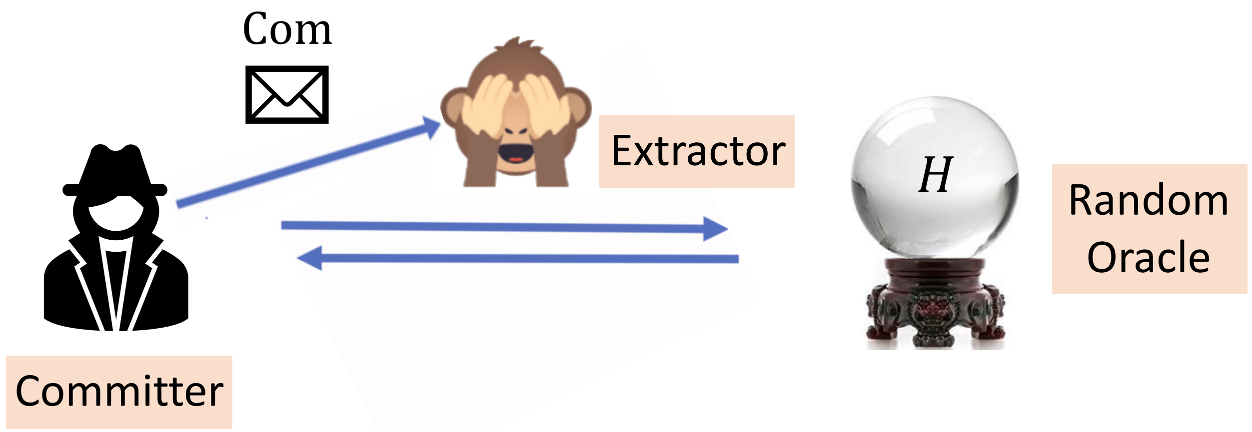

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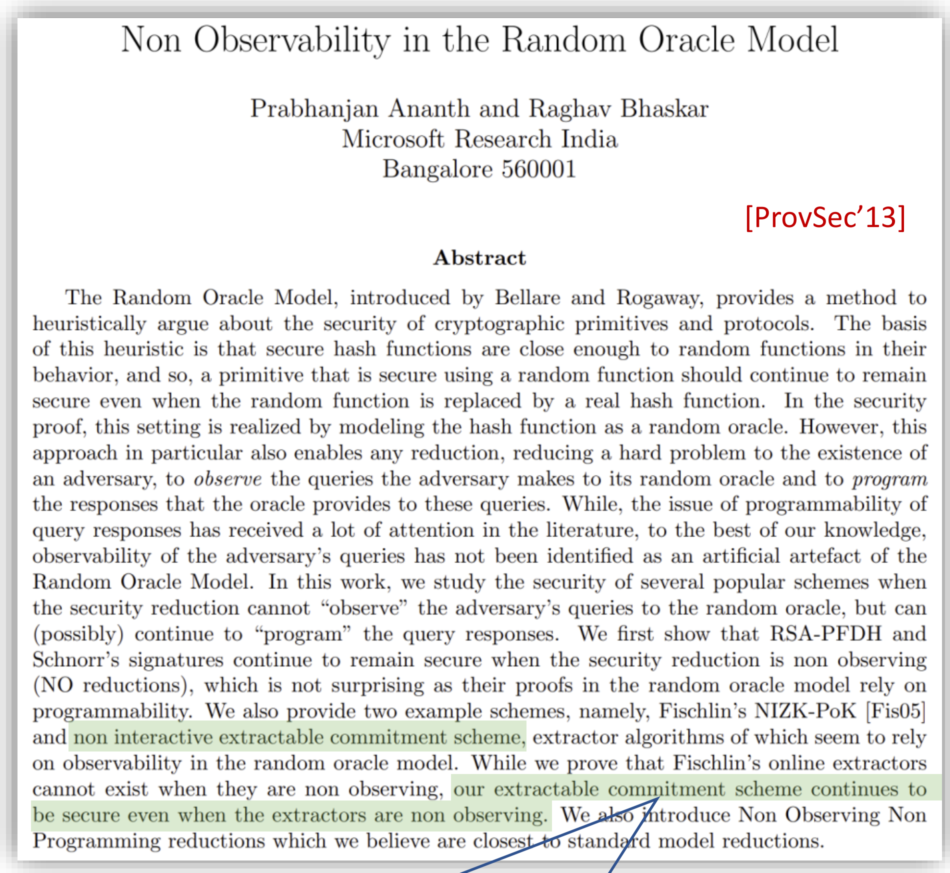
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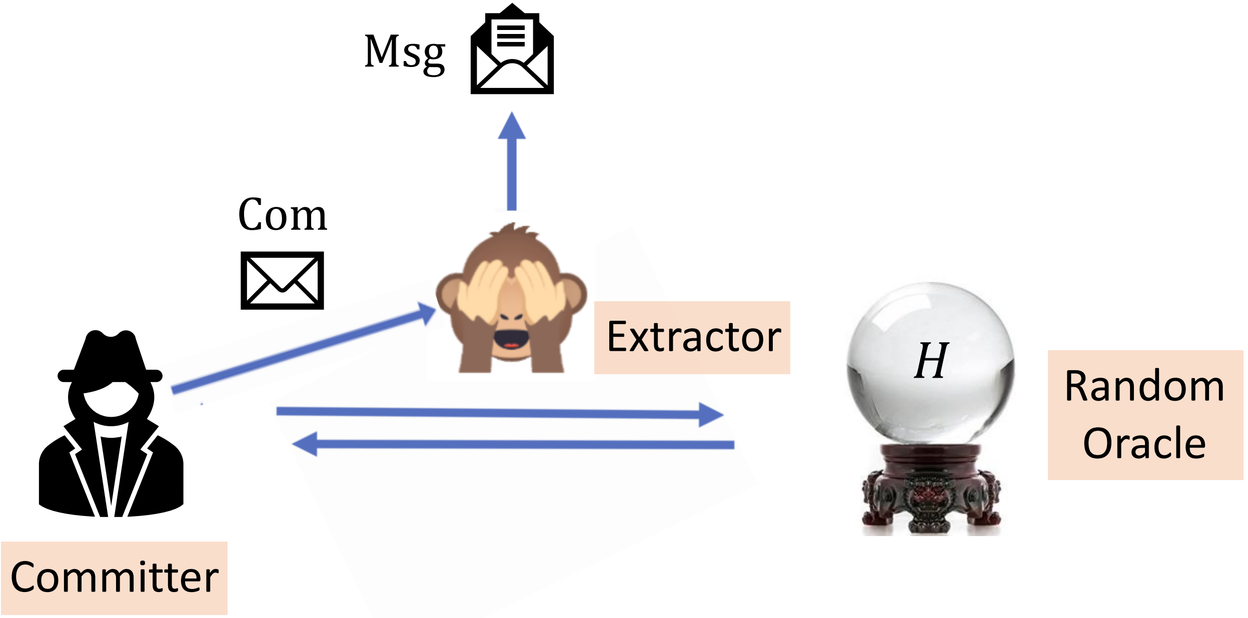

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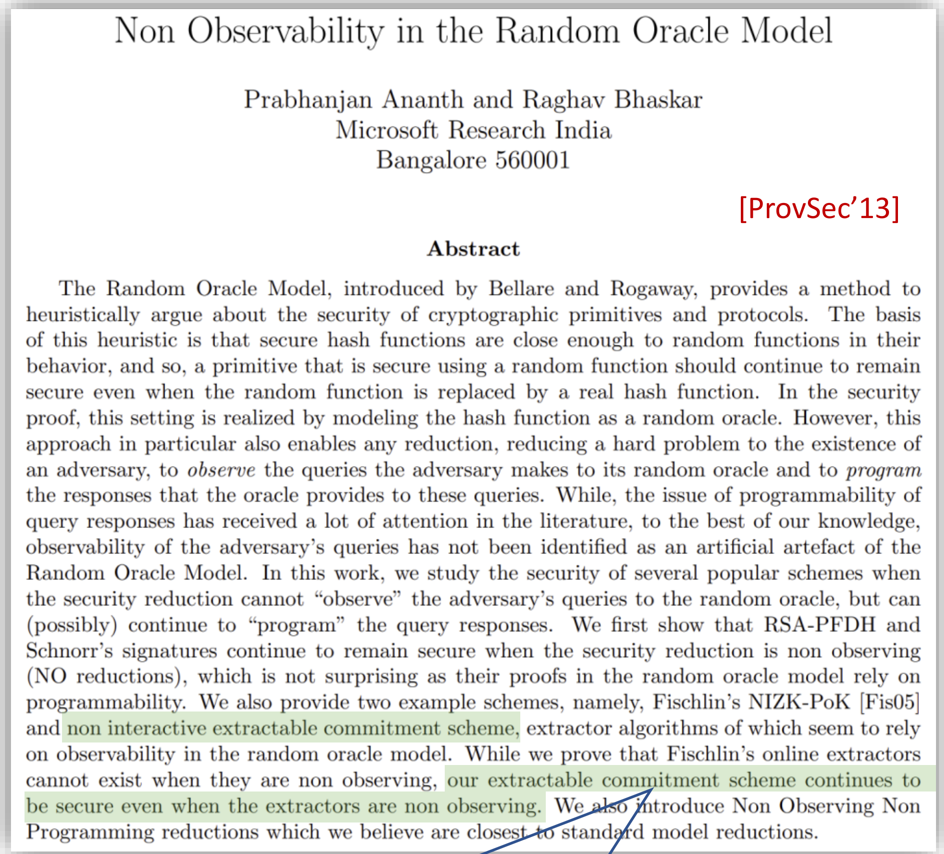

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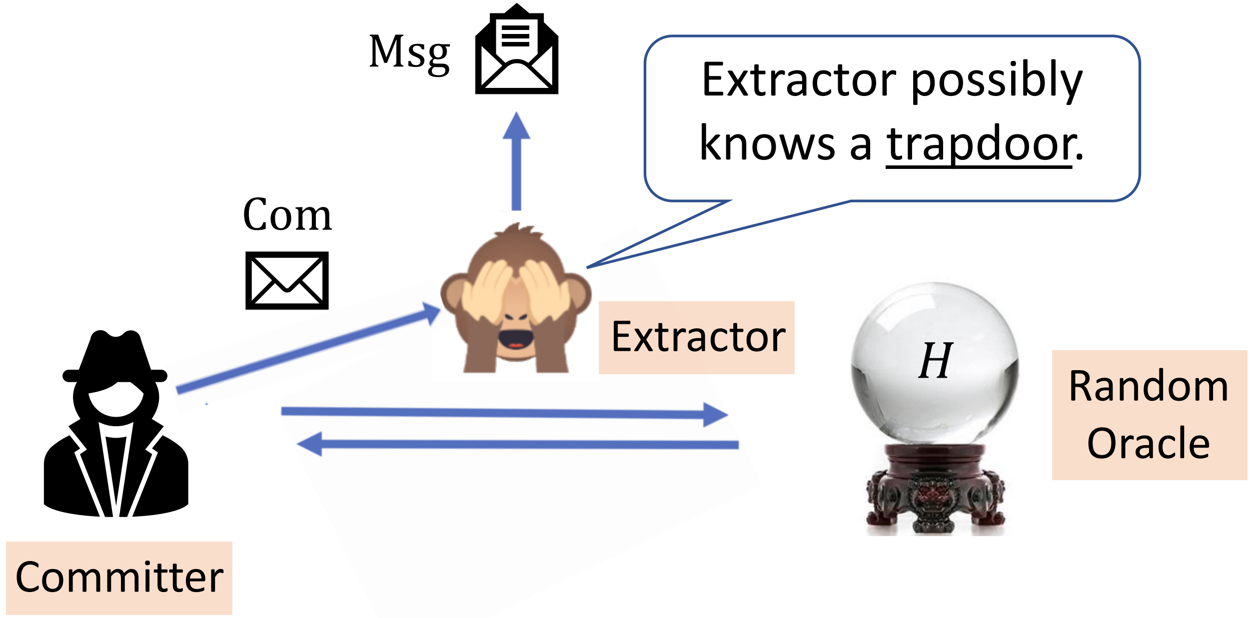

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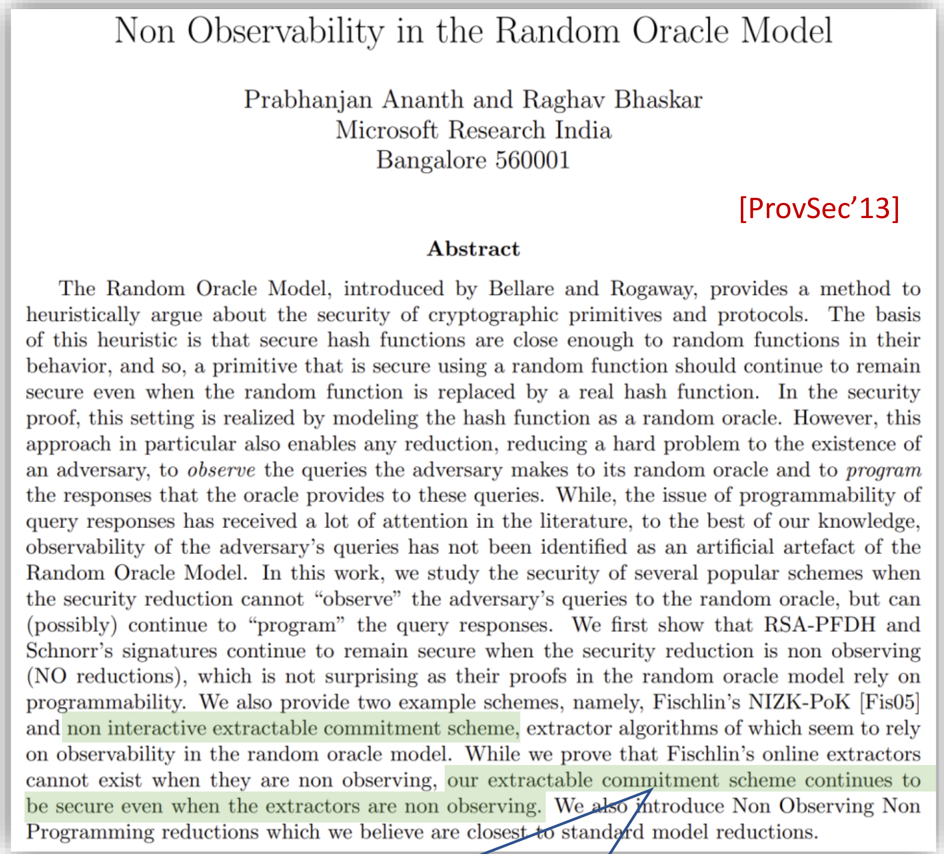

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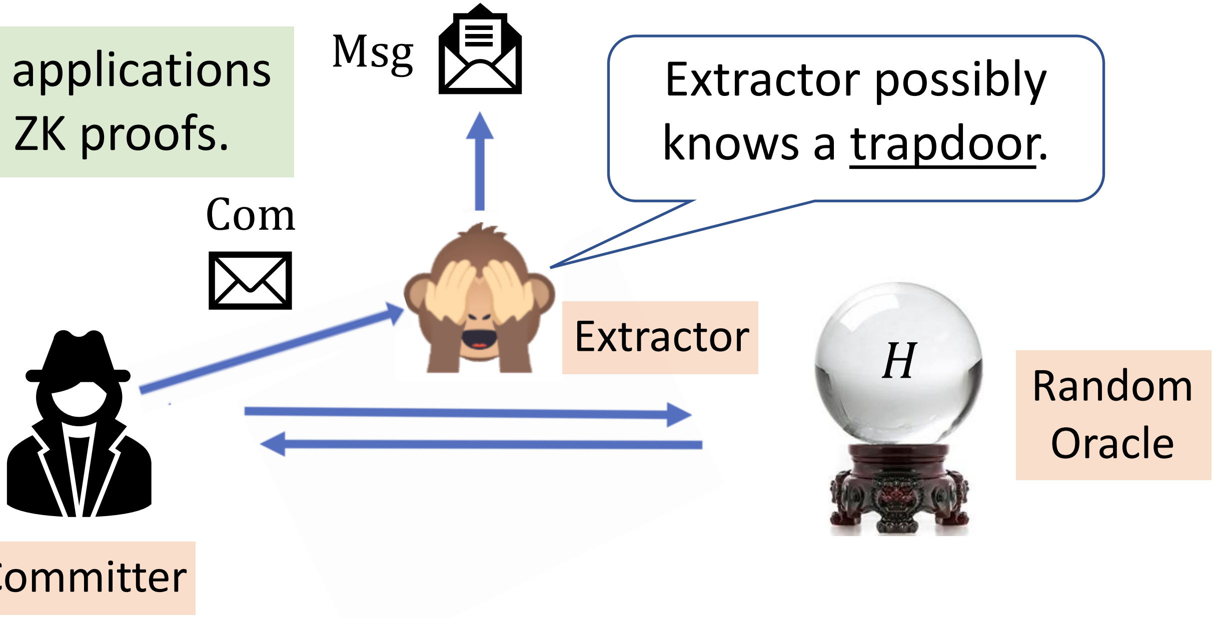

Extractor possibly knows a trapdoor.

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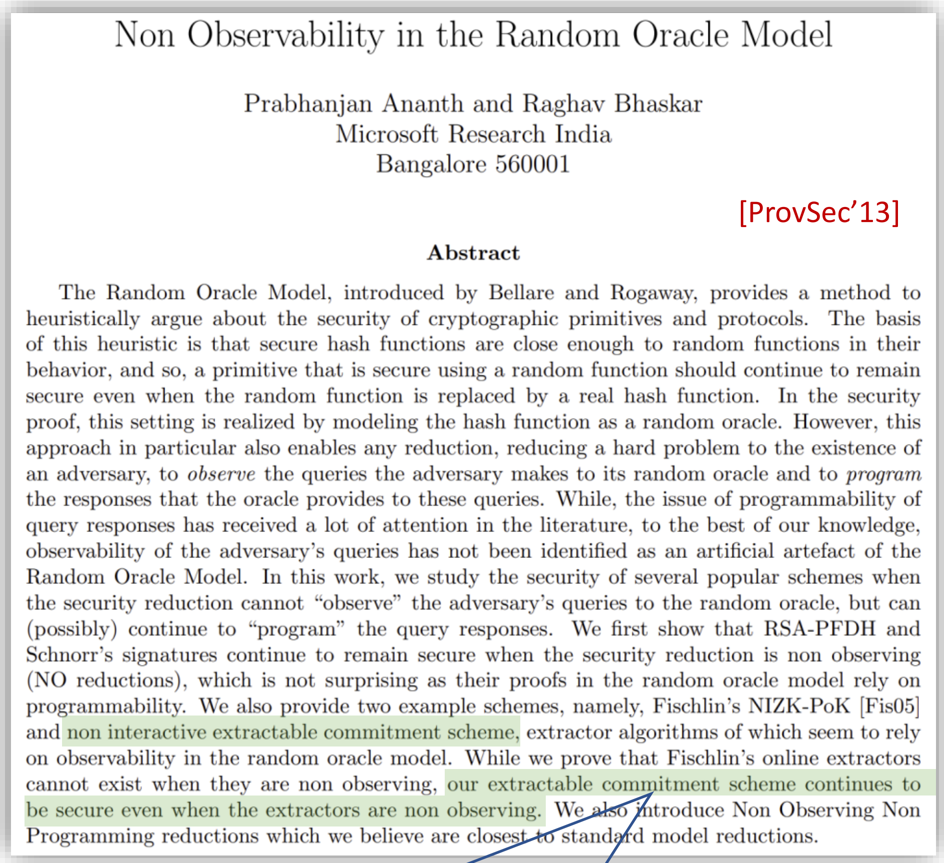

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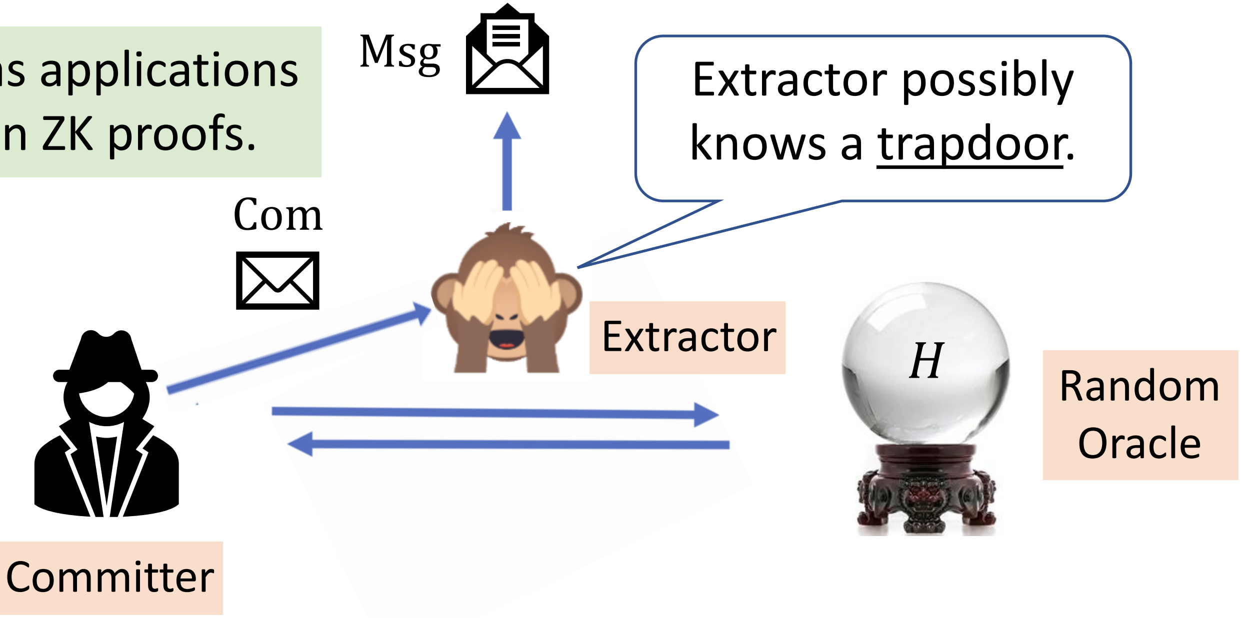

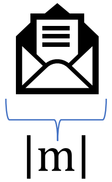

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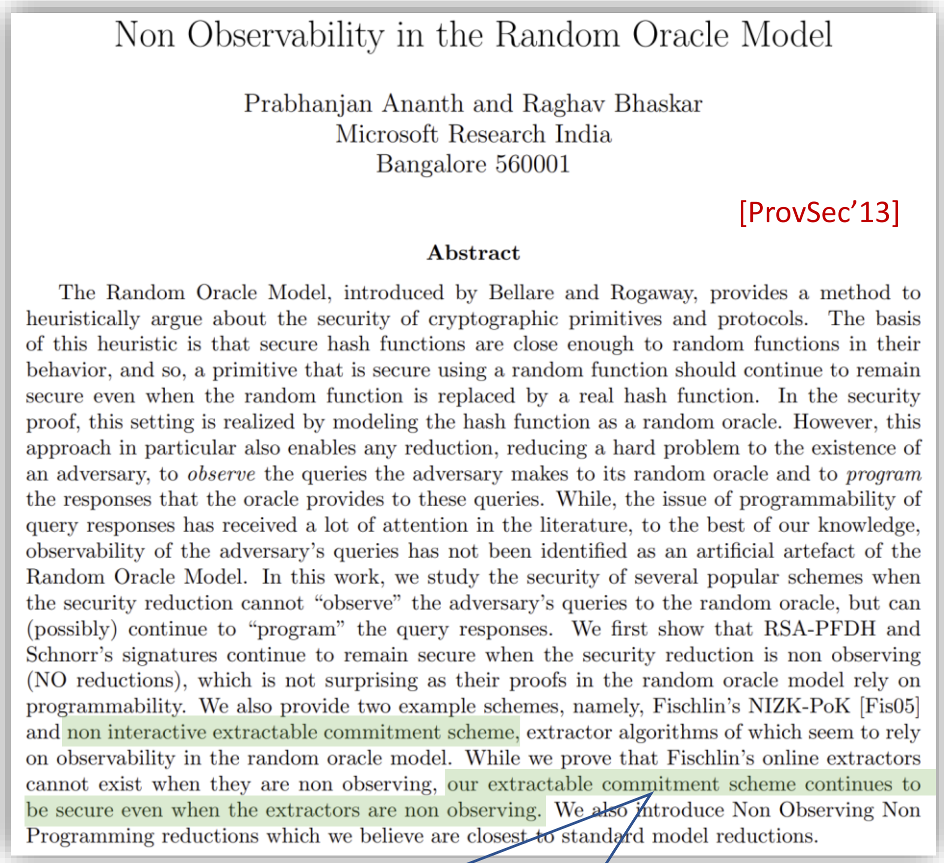

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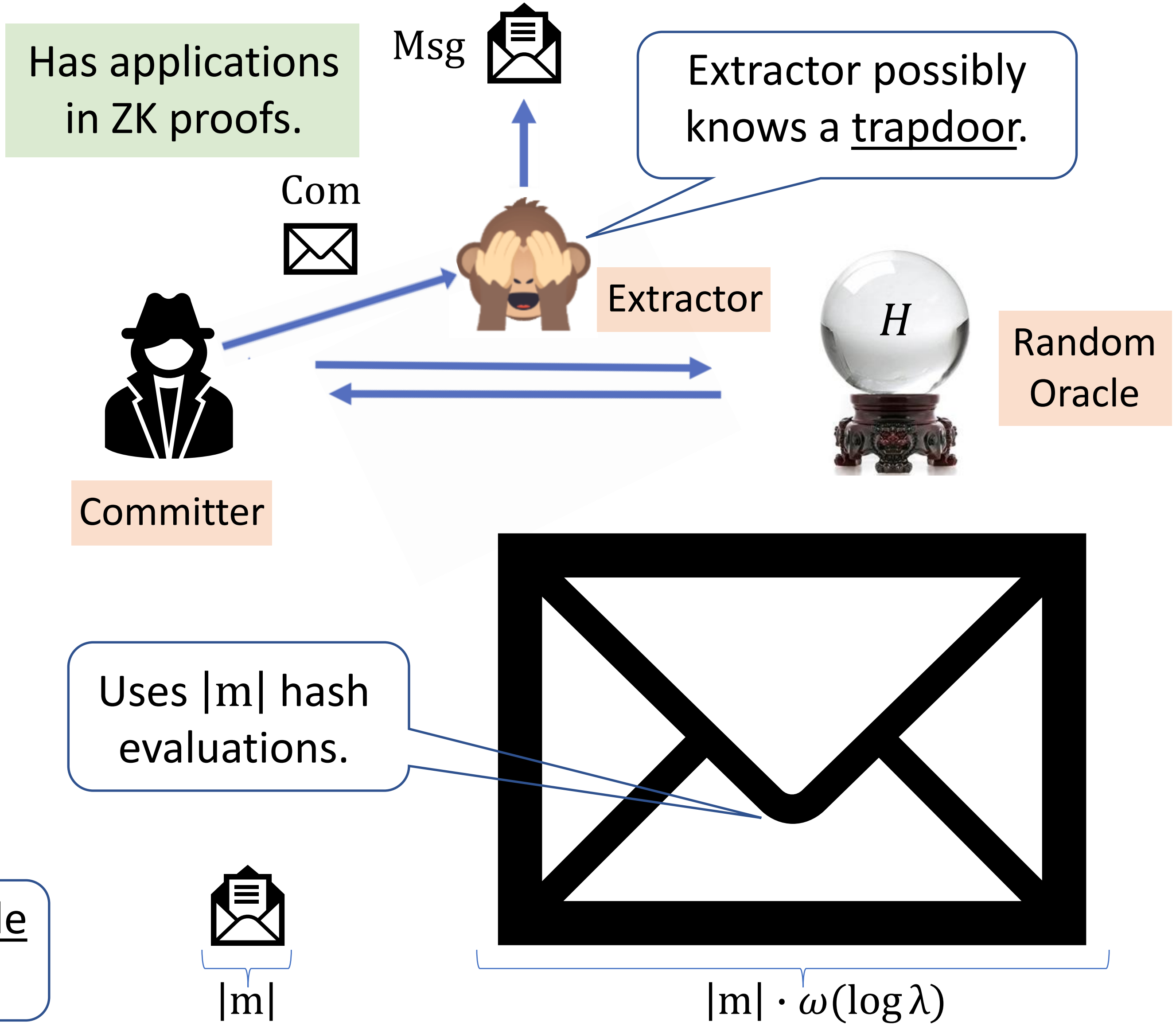

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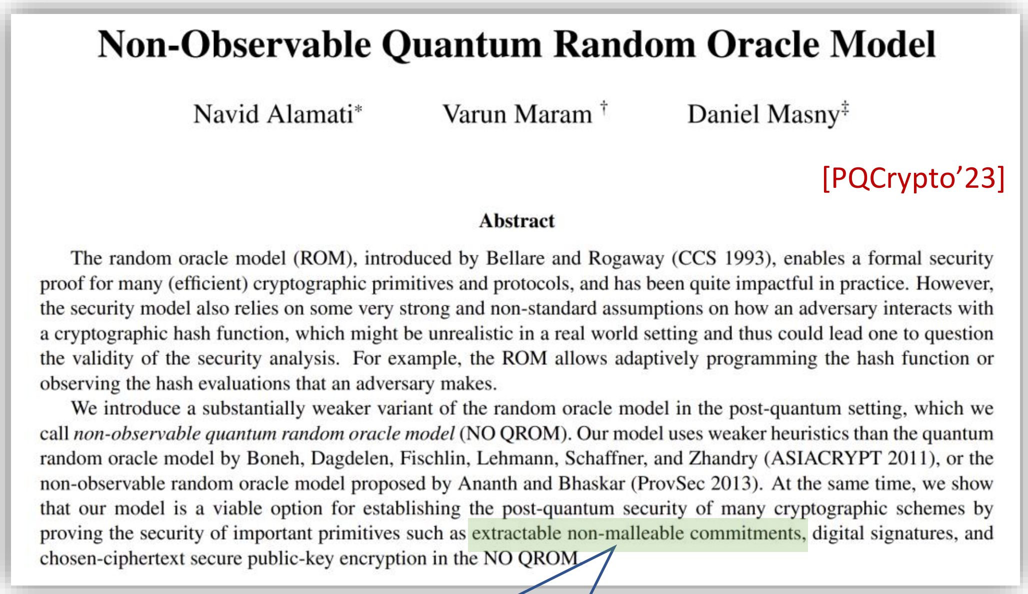

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Navid Alamati* Varun Maram † Daniel Masny‡

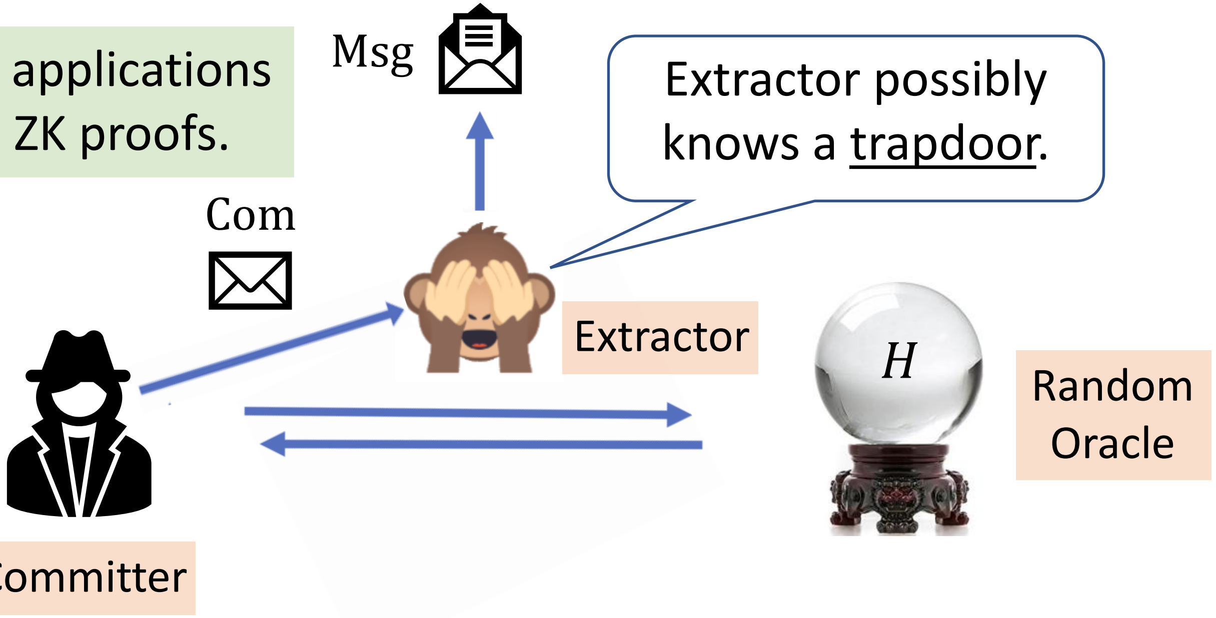
[PQCrypto'23]

Abstract

The random oracle model (ROM), introduced by Bellare and Rogaway (CCS 1993), enables a formal security proof for many (efficient) cryptographic primitives and protocols, and has been quite impactful in practice. However, the security model also relies on some very strong and non-standard assumptions on how an adversary interacts with a cryptographic hash function, which might be unrealistic in a real world setting and thus could lead one to question the validity of the security analysis. For example, the ROM allows adaptively programming the hash function or observing the hash evaluations that an adversary makes.

We introduce a substantially weaker variant of the random oracle model in the post-quantum setting, which we call *non-observable quantum random oracle model* (NO QROM). Our model uses weaker heuristics than the quantum random oracle model by Boneh, Dagdelen, Fischlin, Lehmann, Schaffner, and Zhandry (ASIACRYPT 2011), or the non-observable random oracle model proposed by Ananth and Bhaskar (ProvSec 2013). At the same time, we show that our model is a viable option for establishing the post-quantum security of many cryptographic schemes by proving the security of important primitives such as extractable non-malleable commitments, digital signatures, and chosen-ciphertext secure public-key encryption in the NO QROM.

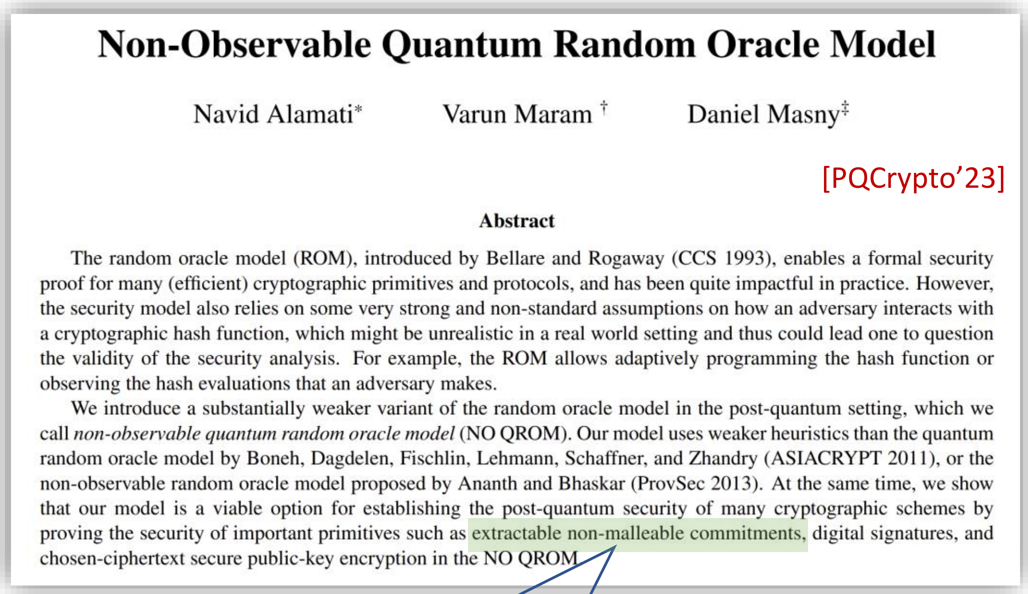
Construct a hash-based <u>extractable commitment</u> in the NO ROM.



Extractor possibly knows a <u>trapdoor</u>.

Uses $O(1)$ hash evaluations.

Non-Observable ROM (NO ROM)



Non-Observable Quantum Random Oracle Model

Navid Alamati* Varun Maram † Daniel Masny‡

[PQCrypto'23]

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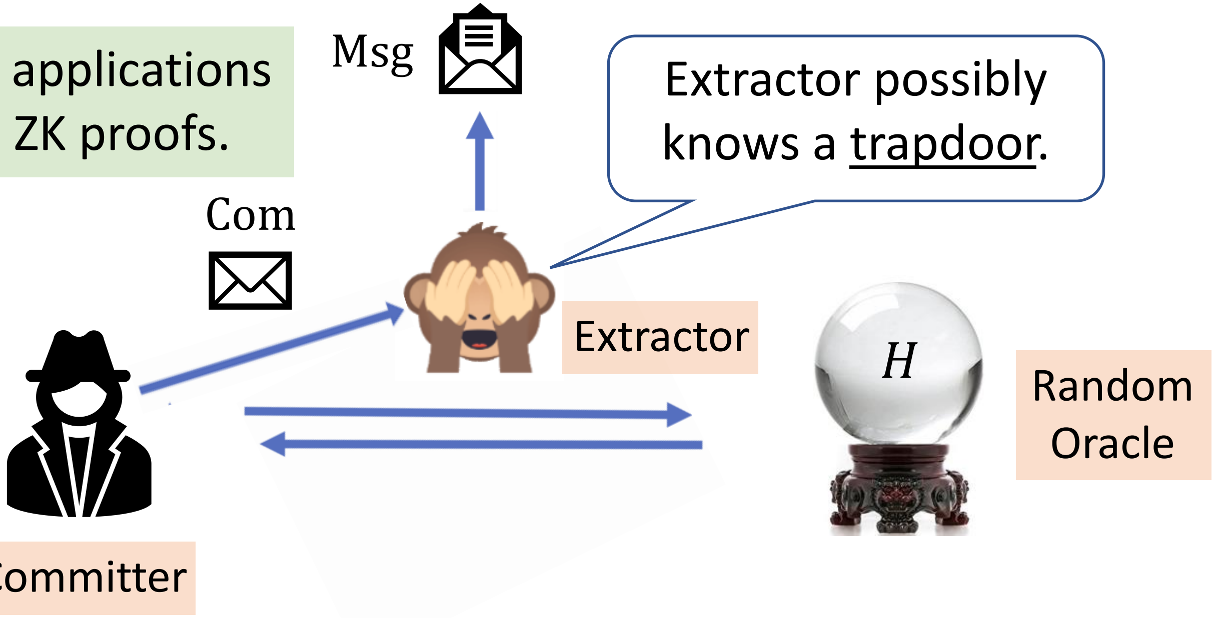
Has applications in ZK proofs.



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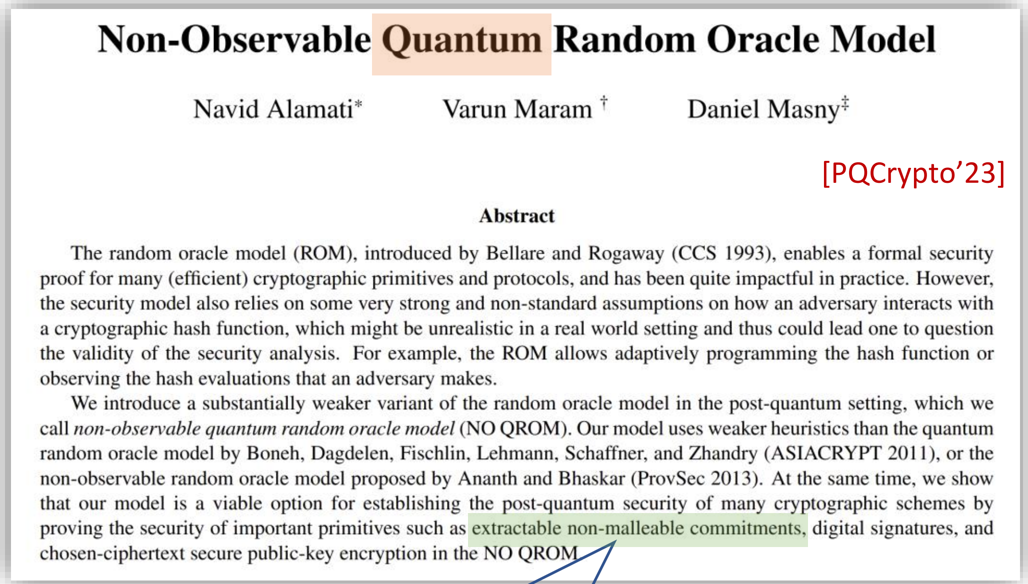
Non-Observable QROM (NO QROM)



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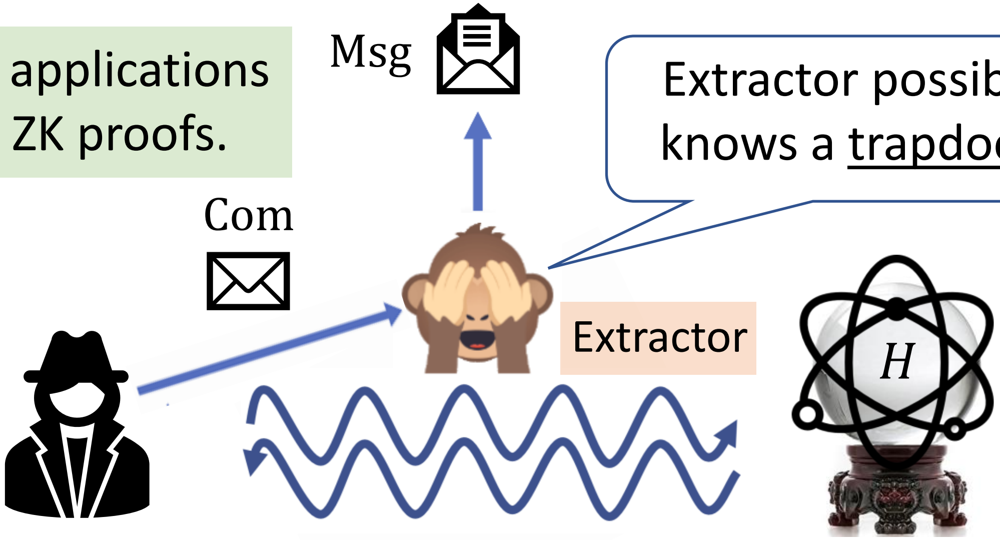

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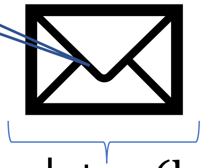
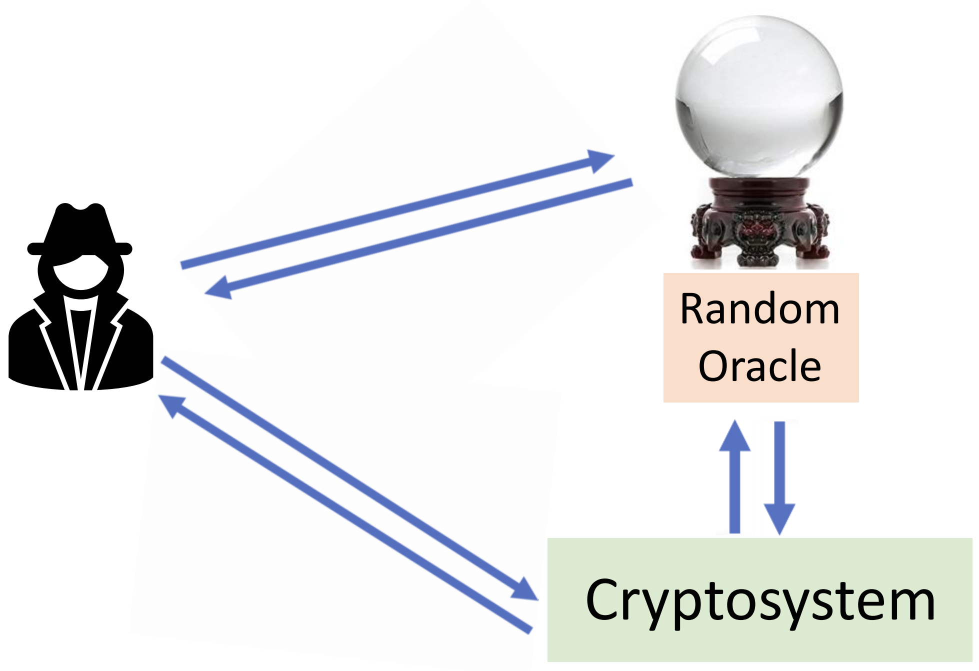
"Textbook" hash-based commitment: $\mathrm{Com} = H(\mathrm{Msg}, r)$

$|\mathrm{m}|$



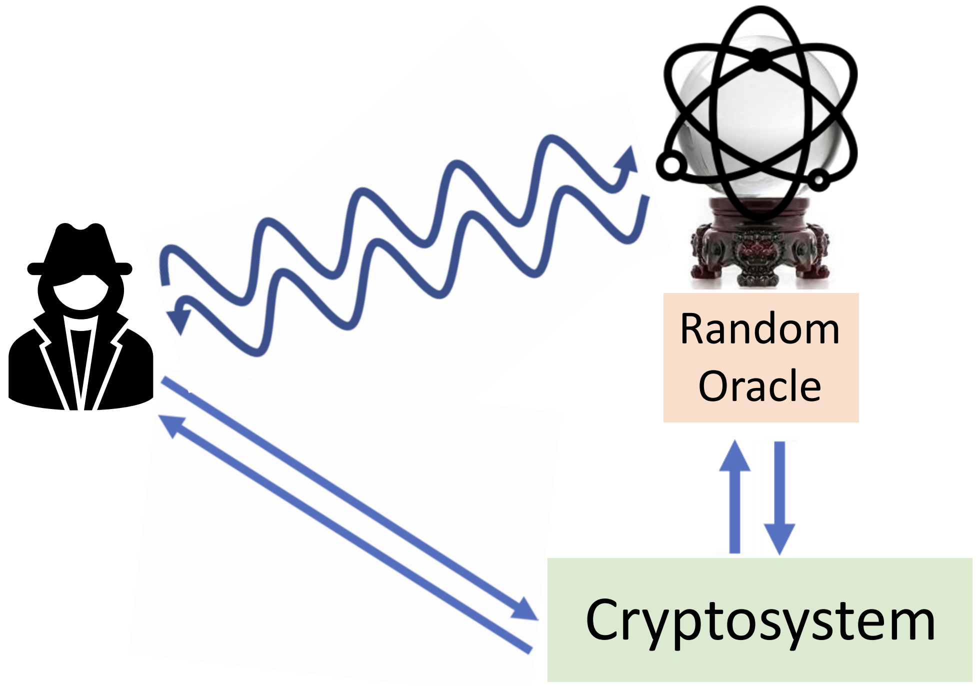
$|\mathrm{m}| + \omega(\log \lambda)$

(Classical) Random Oracle Model (ROM)



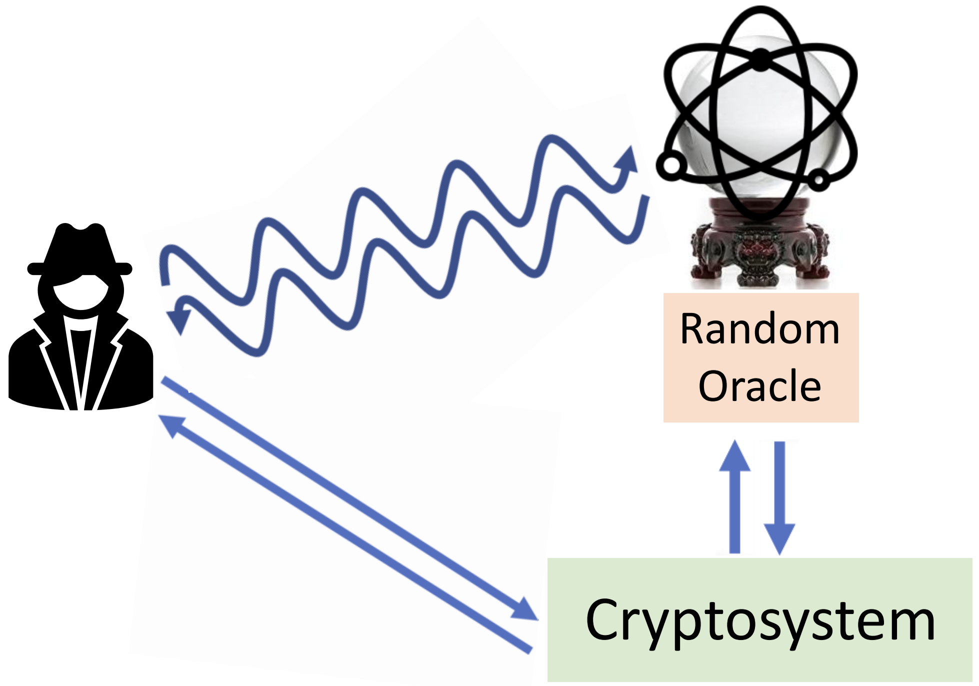
Formalized by [Bellare-Rogaway’93].

Quantum Random Oracle Model (QROM)



Formalized by [Boneh-Dagdelen-Fischlin-Lehmann-Schaffner-Zhandry'11].

Quantum Random Oracle Model (QROM)



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- Tremendous progress has been made to adapt ROM security proofs to the QROM setting.

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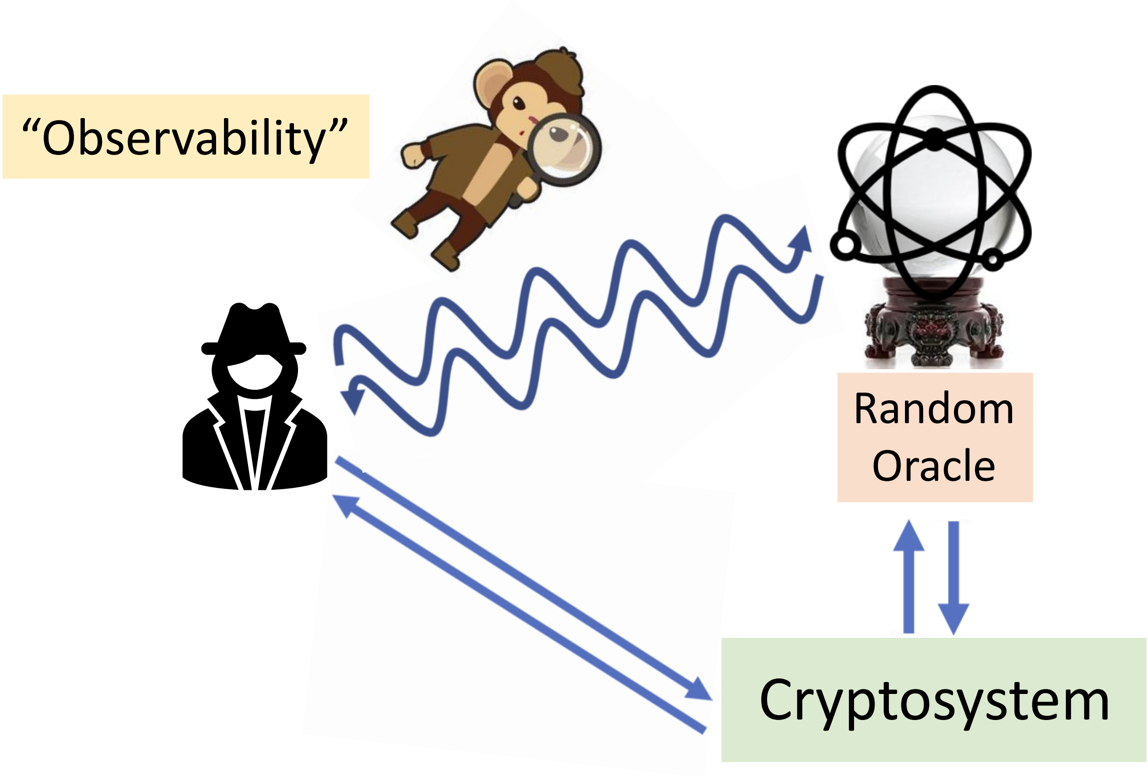

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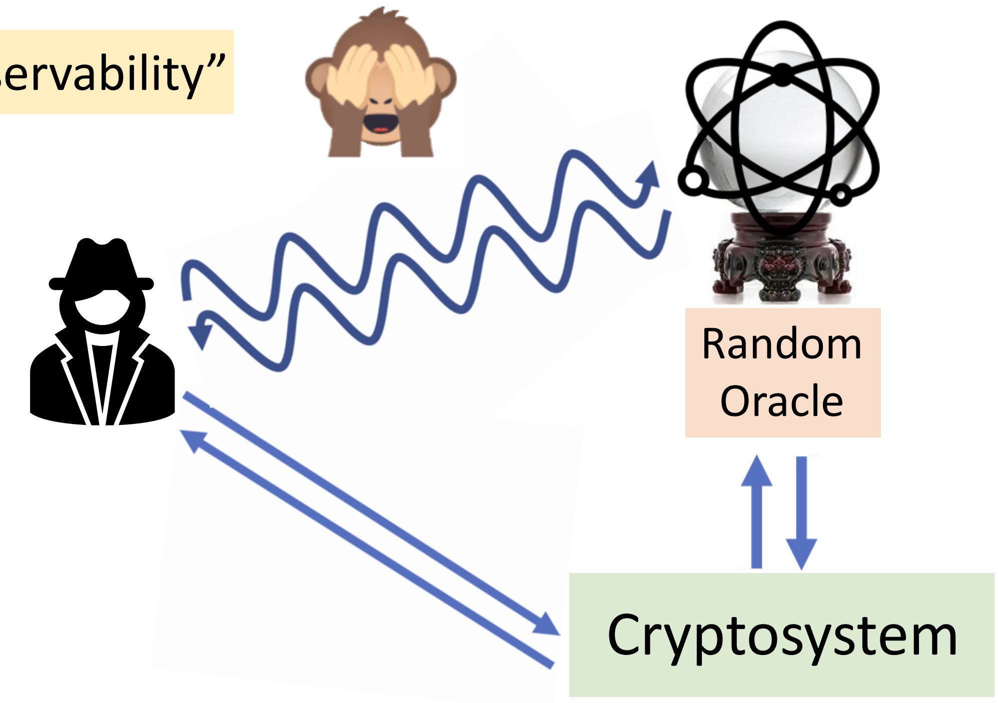
- Captures ability of an adversary to evaluate a <u>public</u> hash function in superposition in a PQ setting.
- Tremendous progress has been made to adapt ROM security proofs to the QROM setting.
- However, most proofs rely on <u>observing/measuring</u> an adversary's quantum queries to random oracle.

Non-Observable QROM (NO QROM)

“Non-Observability”



Formalized by [Alamati-Maram-Masny’23].

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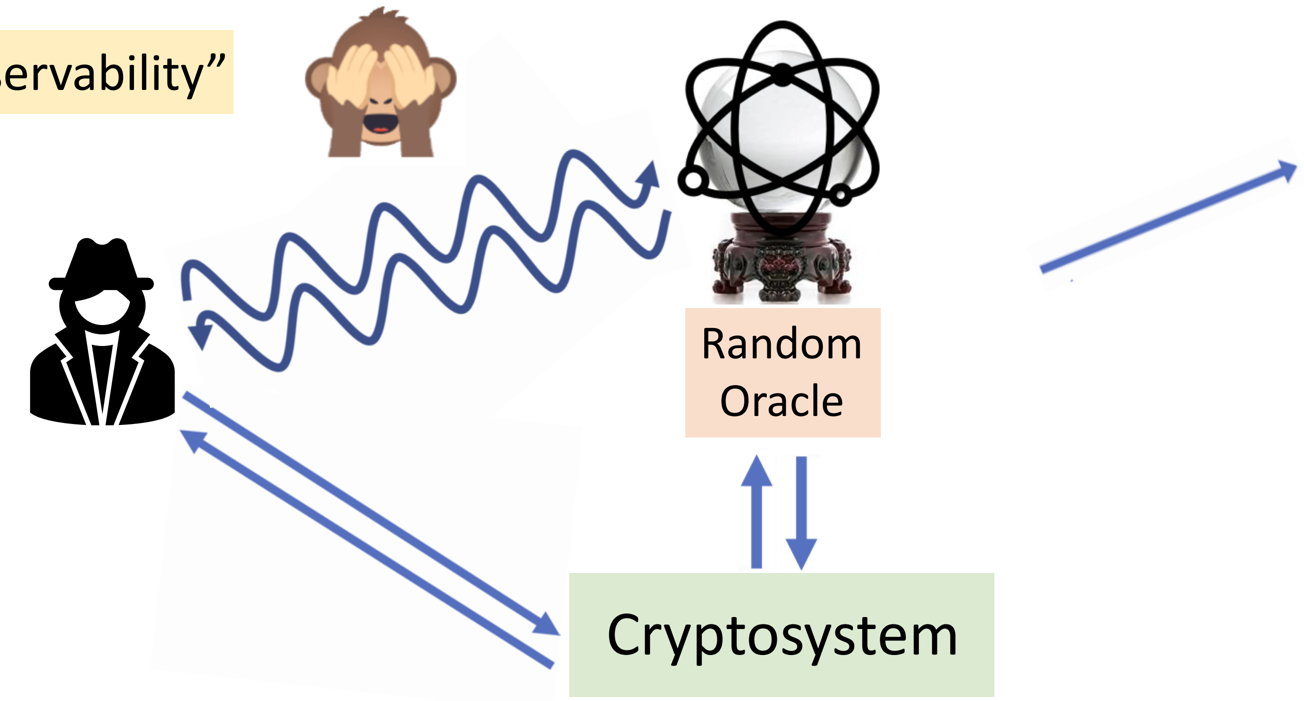

Extractable commitments

Formalized by [Alamati-Maram-Masny'23].

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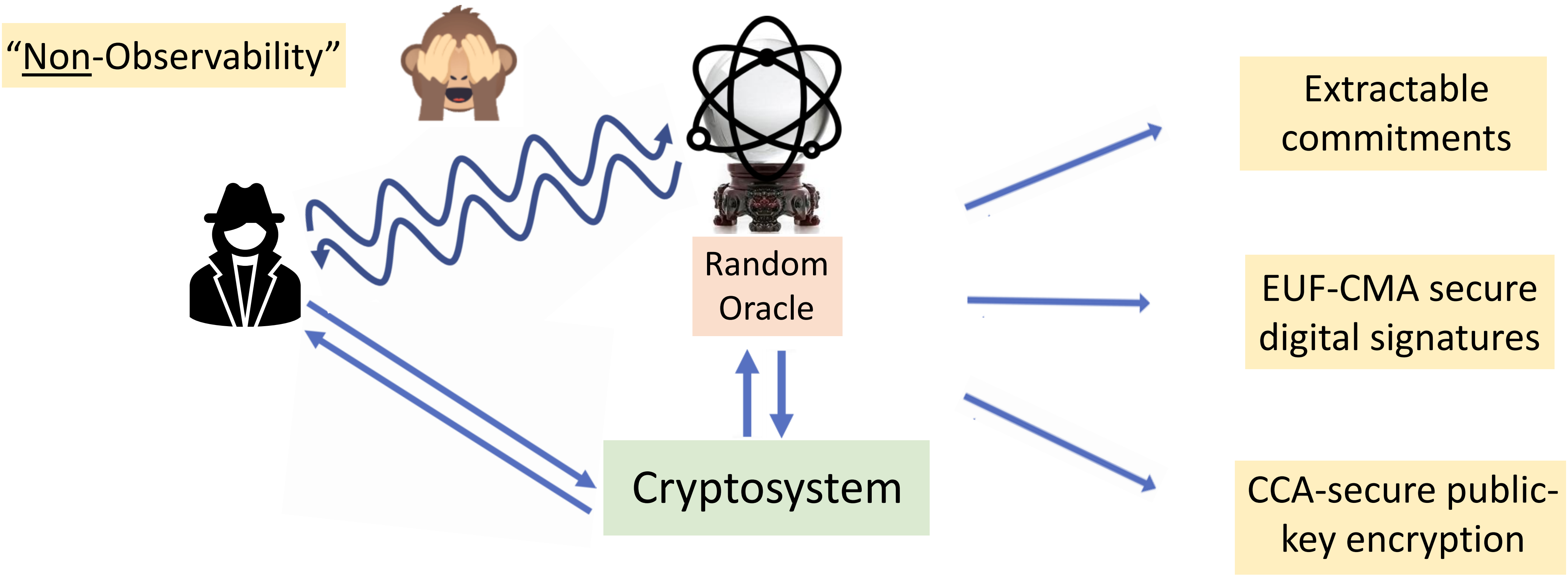

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Non-Observable QROM (NO QROM)

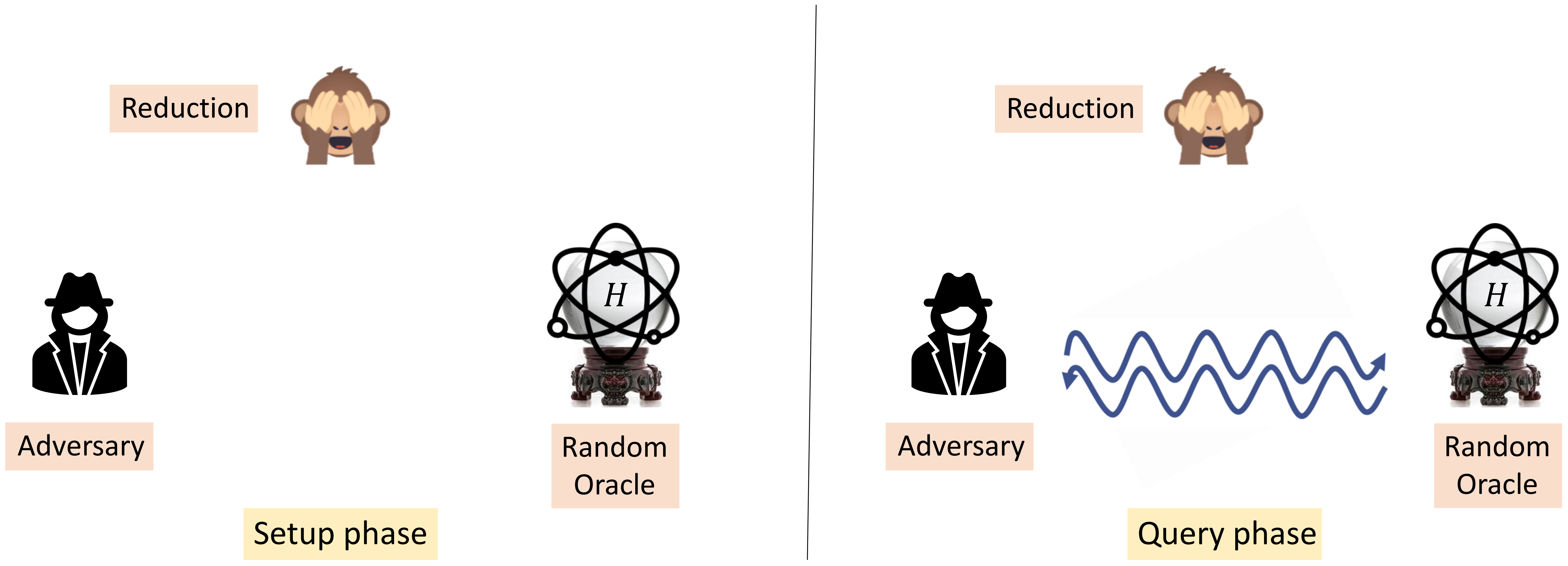
Reduction

Adversary

Random Oracle

Setup phase

Non-Observable QROM (NO QROM)



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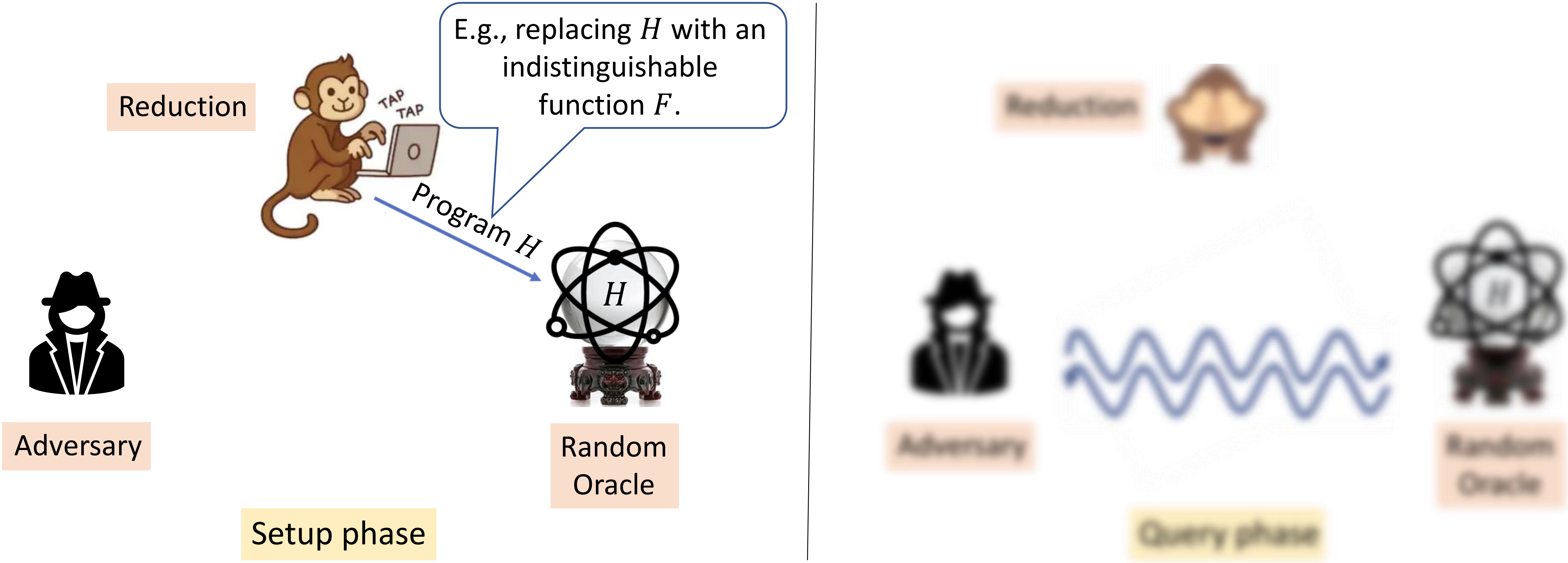

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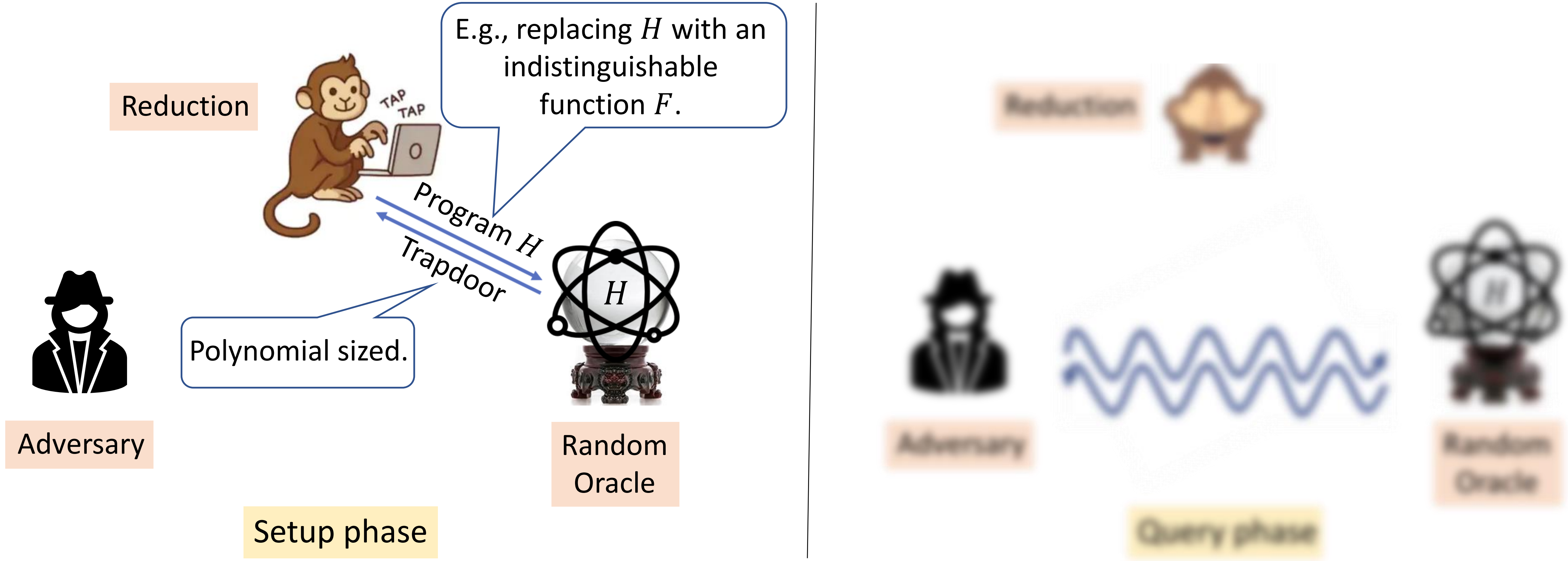

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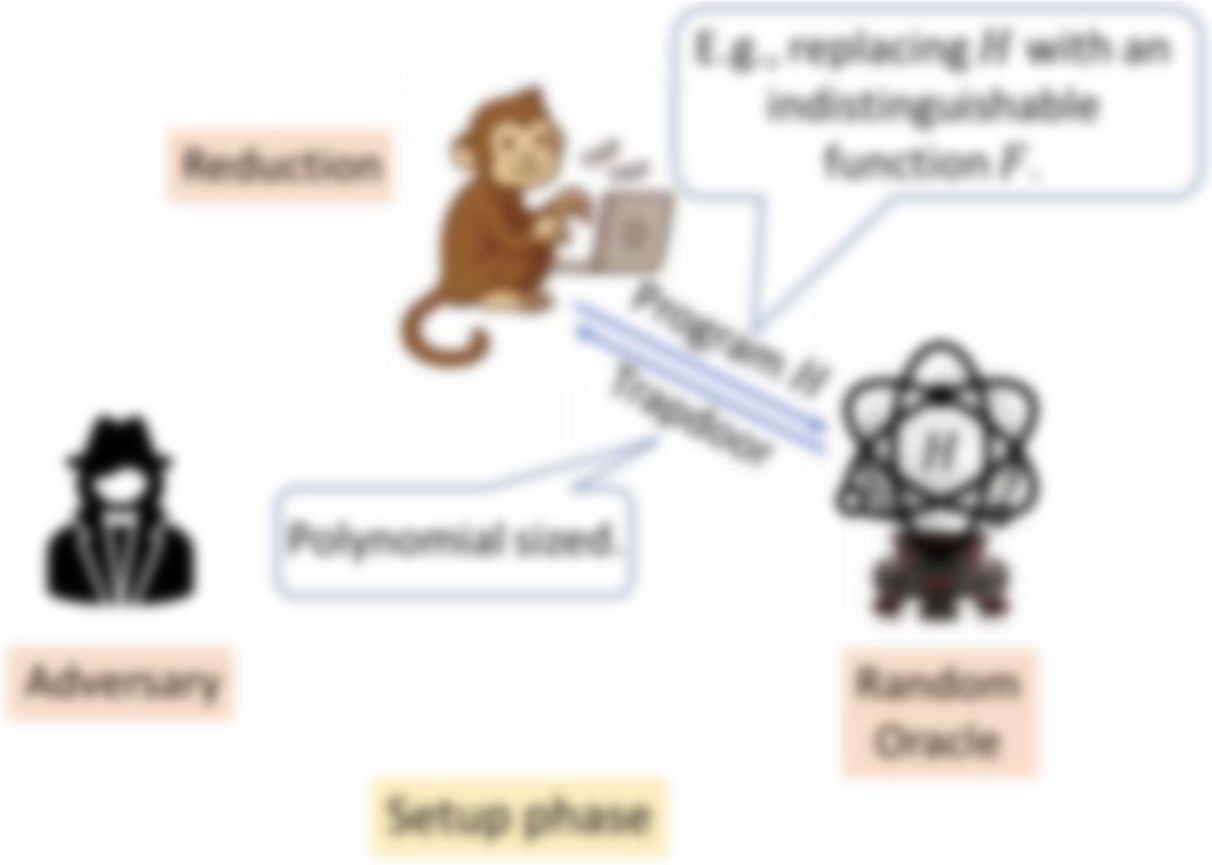

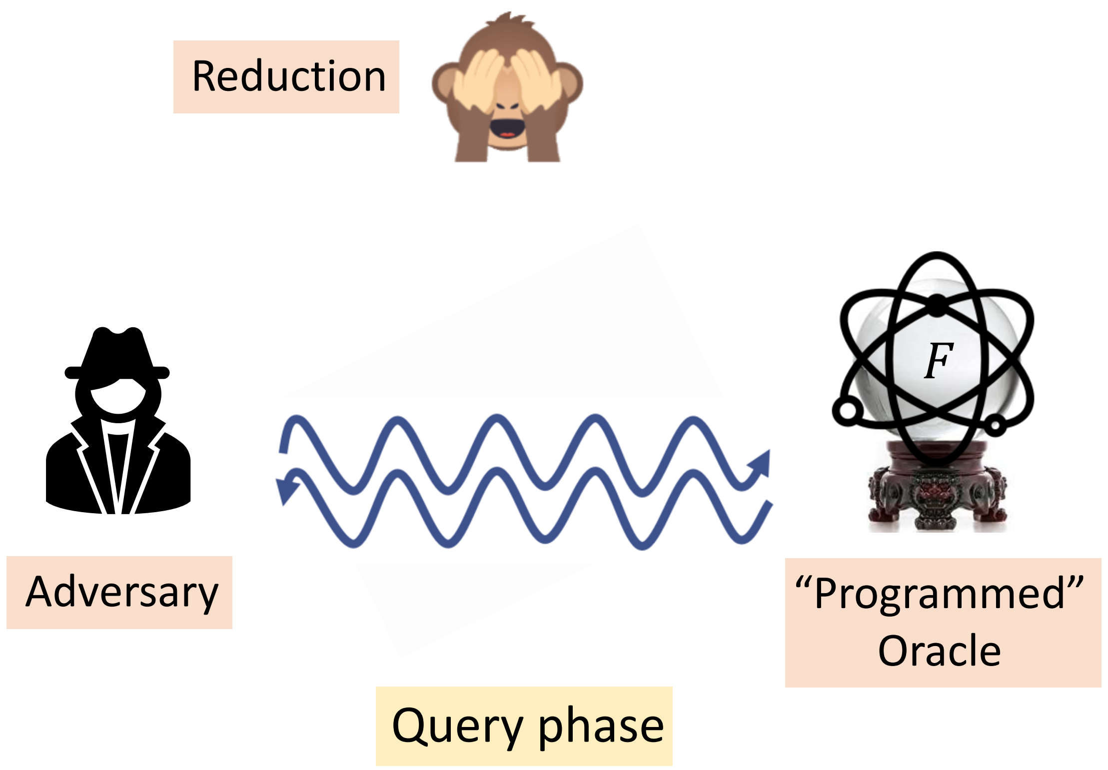

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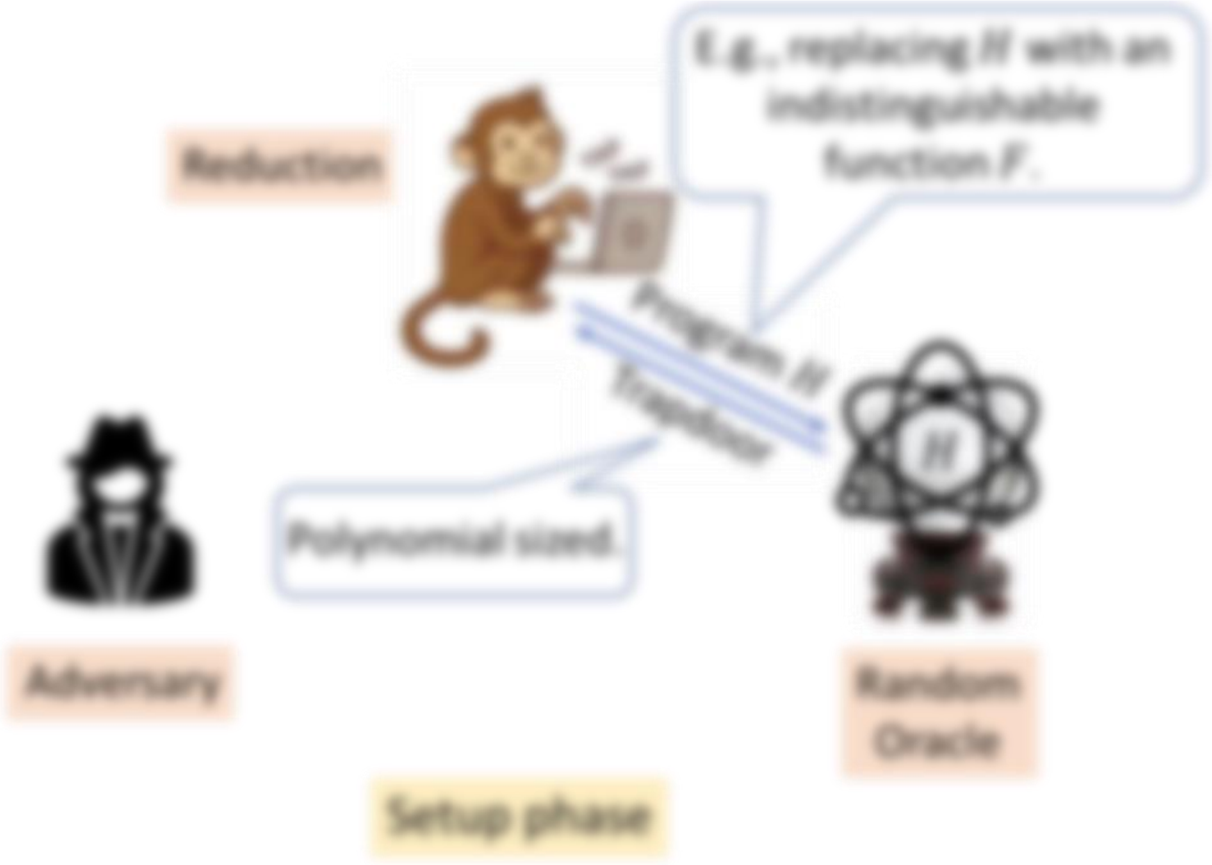

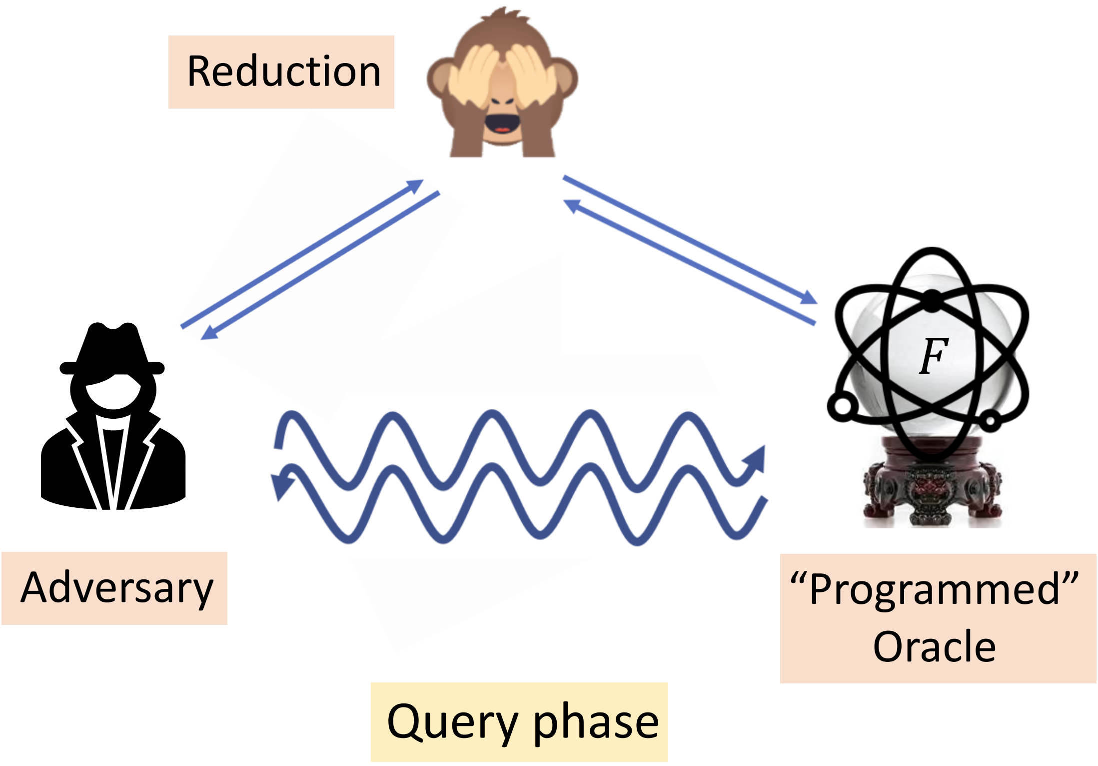

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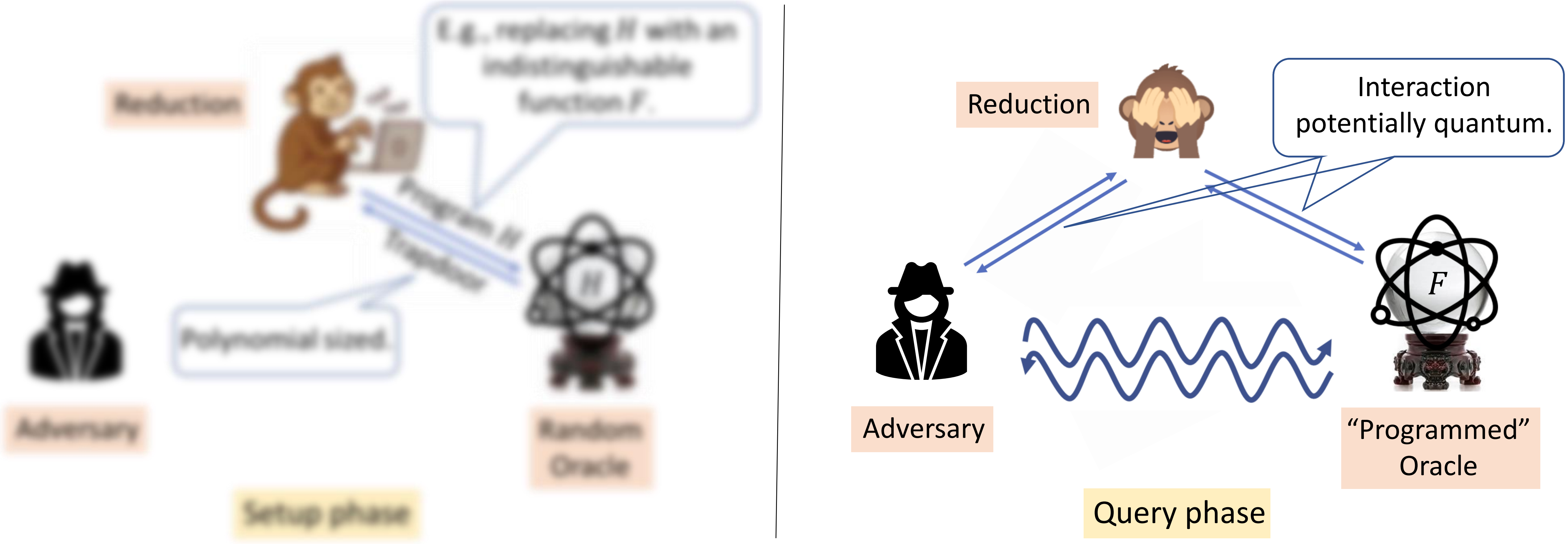

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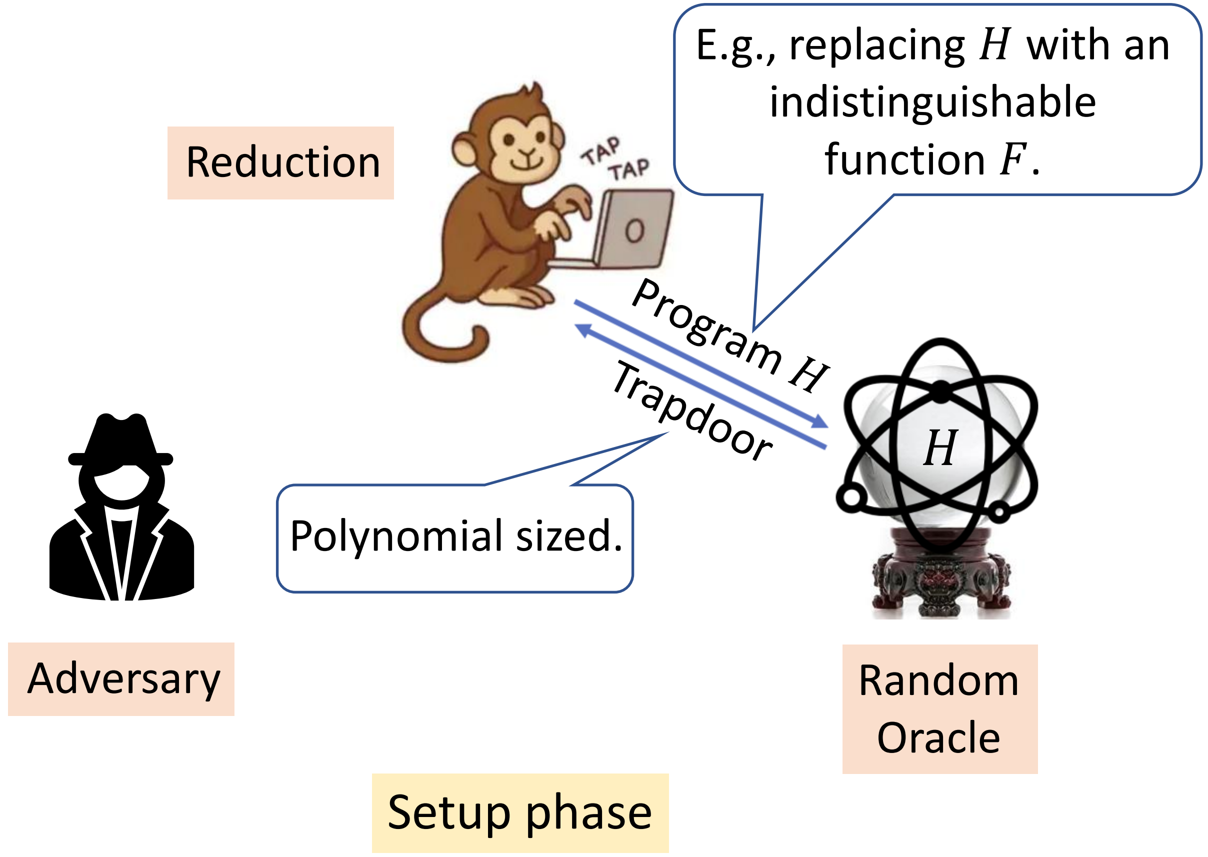
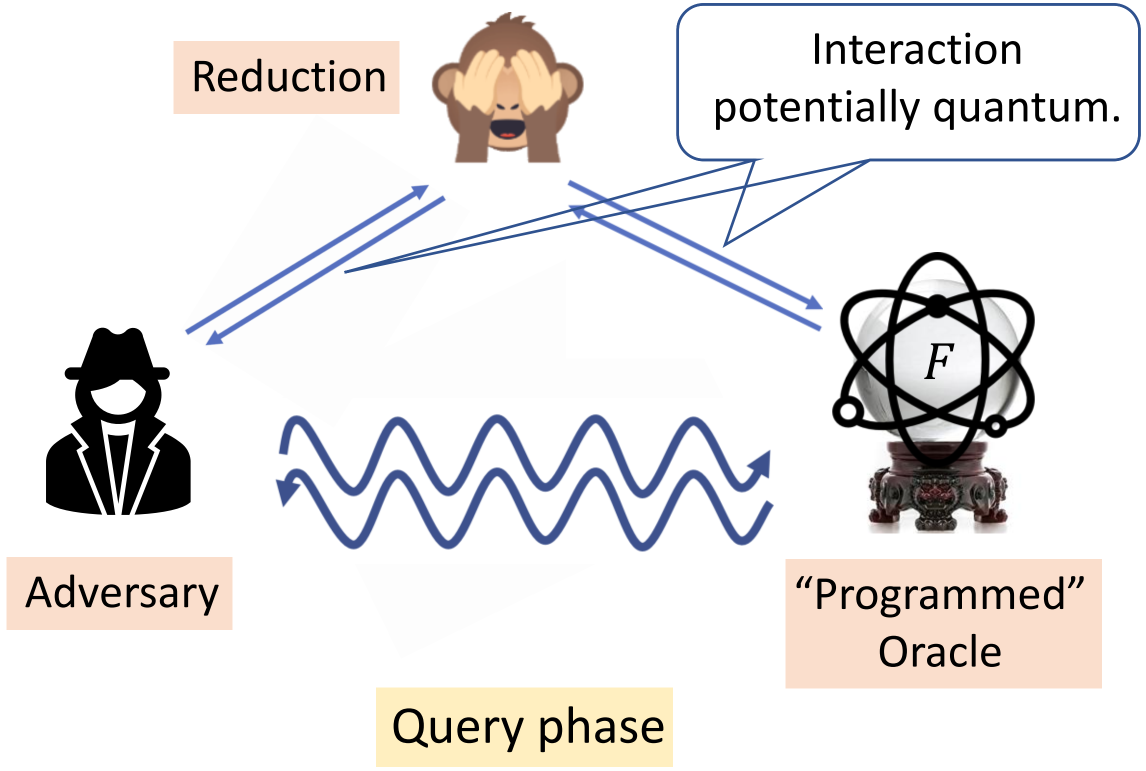
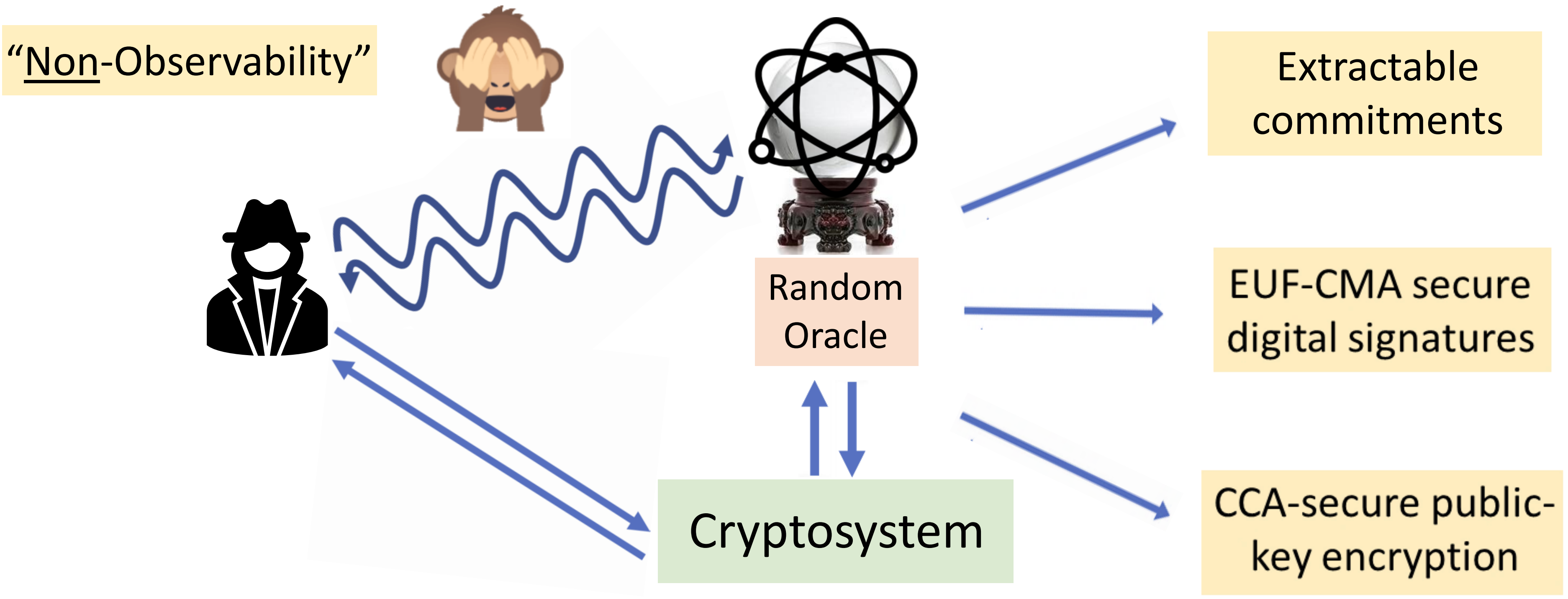




- Our above model also allows non-adaptive (but not adaptive) programmability.
- Classical NO ROM of [Ananth-Bhaskar'13] uses a stateful Turing machine to model random oracle.
  - Maintaining a state incompatible w.r.t. random oracle queries in quantum superposition.

Non-Observable QROM (NO QROM)



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Non-Observable QROM (NO QROM)

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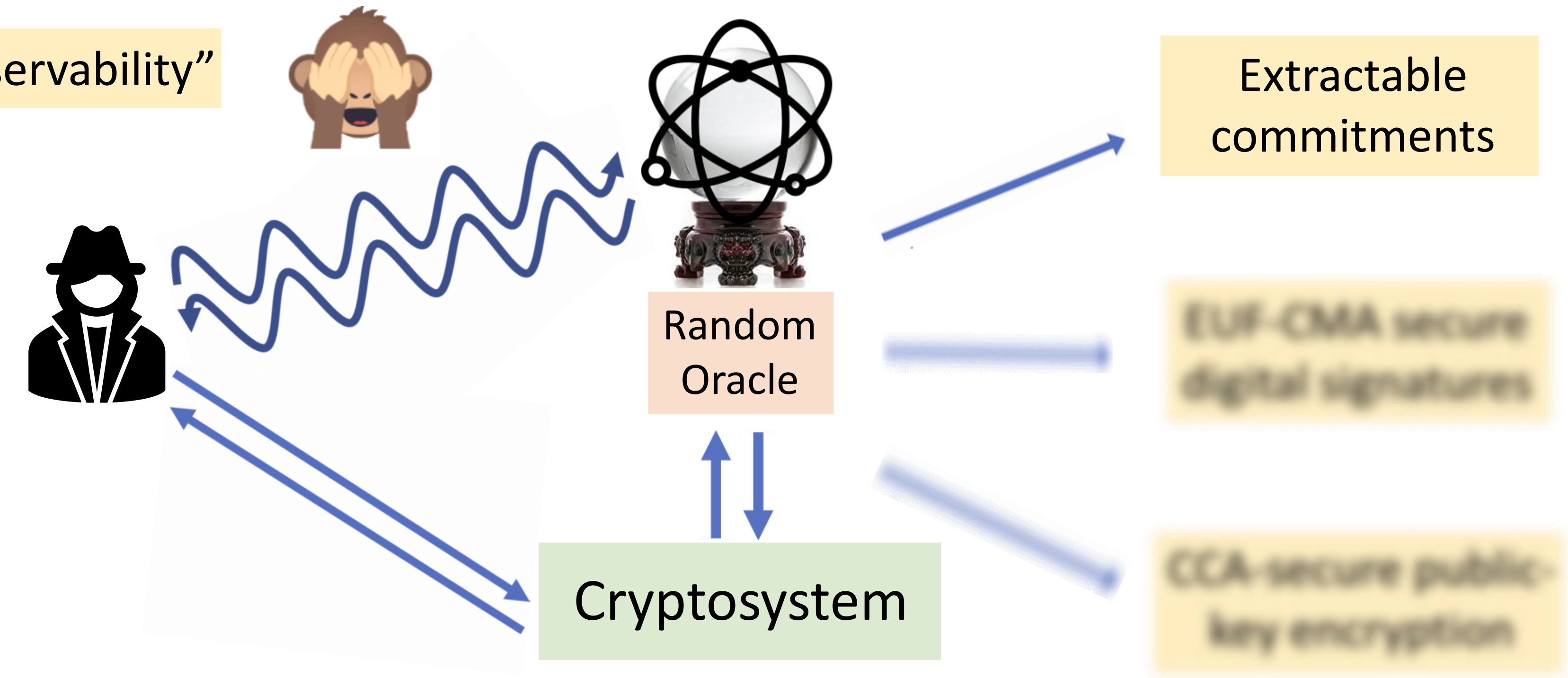

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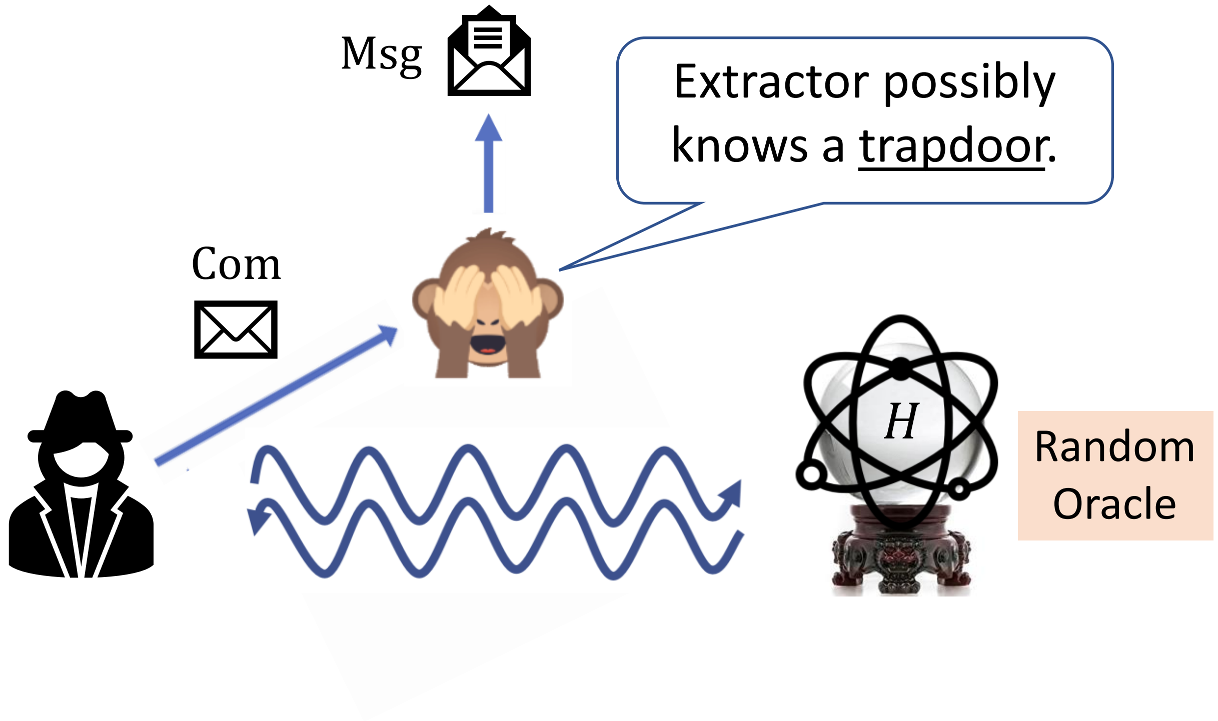
Extractable Commitments in NO QROM

“Textbook” hash-based commitment:
$\text{Com} = H(\text{Msg}, r)$



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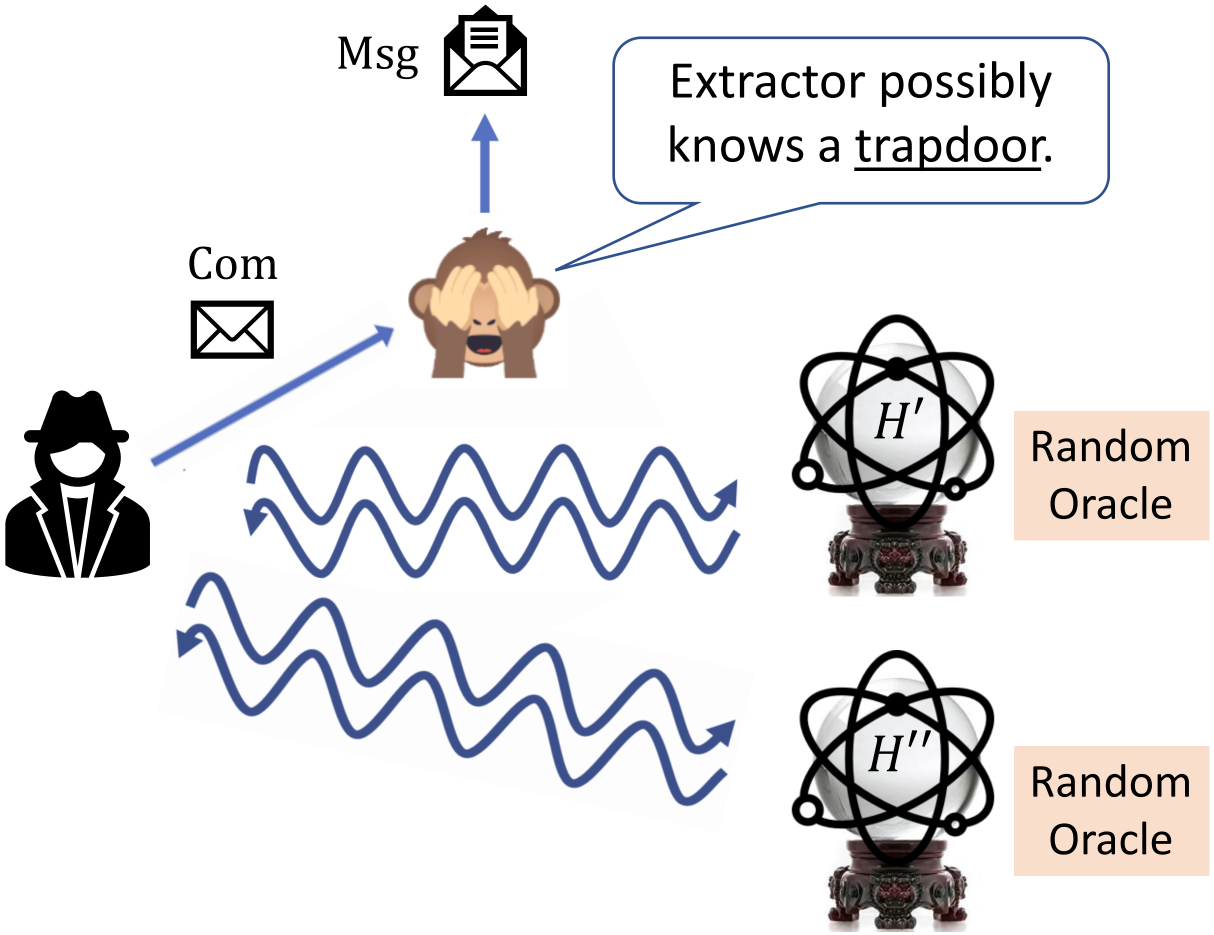
$$\begin{aligned}\mathrm{Com} &= H(\mathrm{Msg}, r)\\ &= H'(\mathrm{Msg}, r) || H''(\mathrm{Msg}, r)\end{aligned}$$



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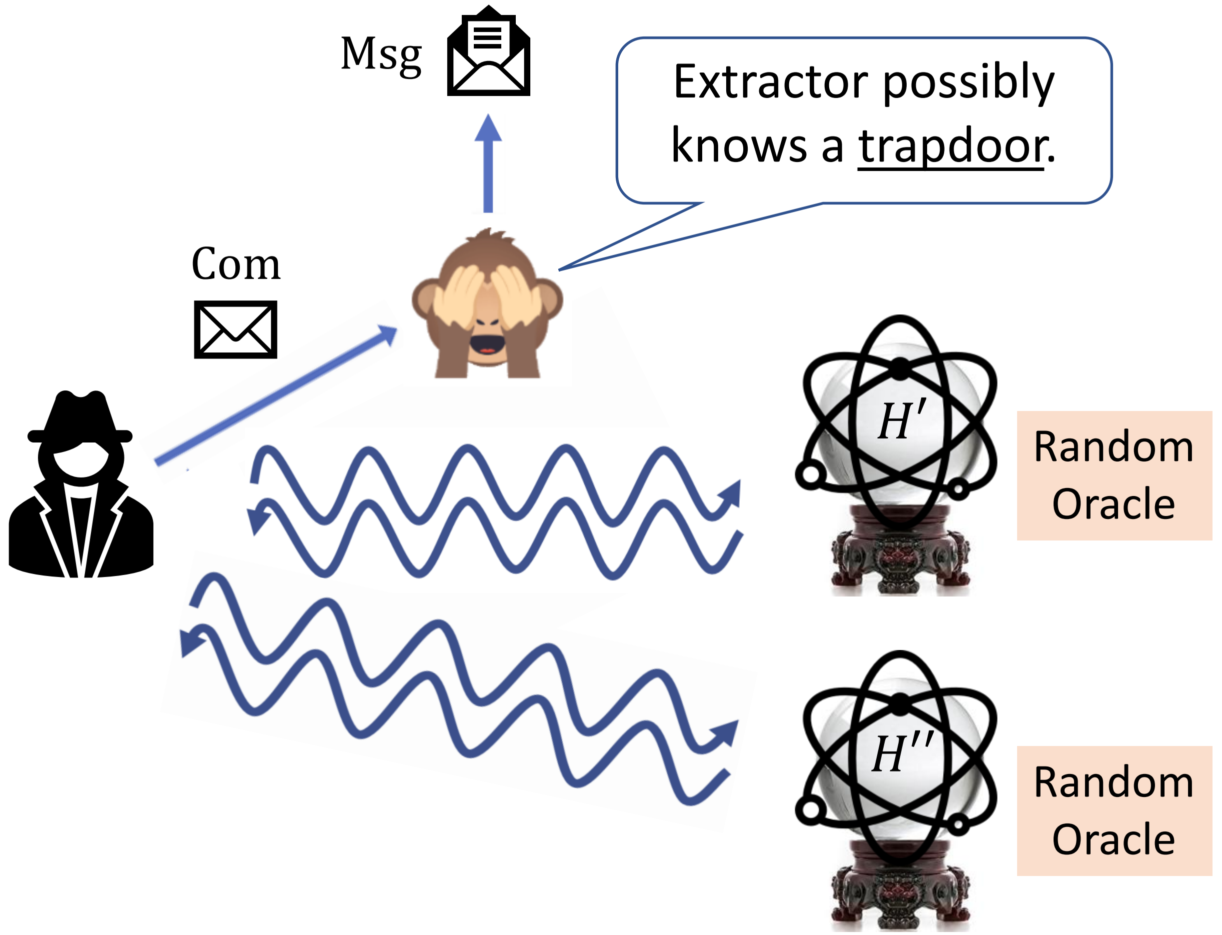
$H': \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{|\mathrm{Msg}|+|r|}$

<u>Same</u> domain and co-domain required for extraction.



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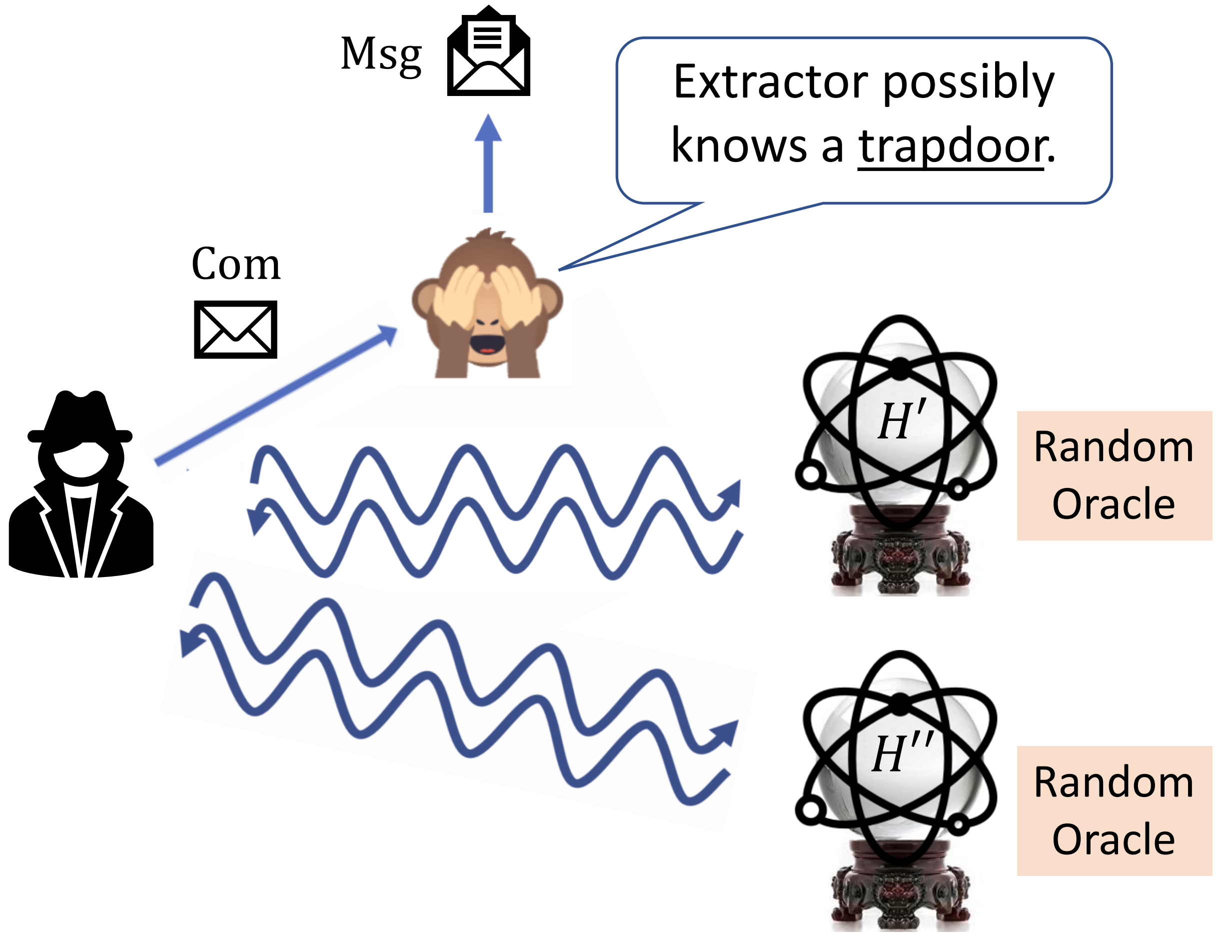
$$H'' : \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{\omega(\log \lambda)}$$

Same domain and co-domain required for extraction.

Required for (statistical) binding.



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Random Oracle

Random Oracle

Same domain and co-domain required for extraction.

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Setup phase

Extractable Commitments in NO QROM

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Makes at-most q queries to H'.

Random Oracle

Random Oracle

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Extractable Commitments in NO QROM

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$$\begin{aligned}\mathrm{Com} &= H(\mathrm{Msg}, r)\\ &= H'(\mathrm{Msg}, r)||H''(\mathrm{Msg}, r)\end{aligned}$$

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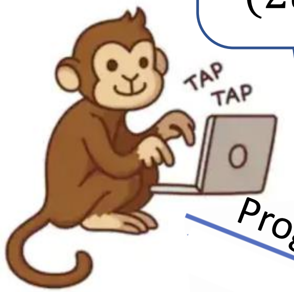

Replace H' with a random polynomial F of degree $(2q-1)$ over $\mathbb{F}_{2^{|\mathrm{Msg}|+|r|}}$.

Program H'

Random Oracle

Random Oracle

Setup phase

Extractable Commitments in NO QROM

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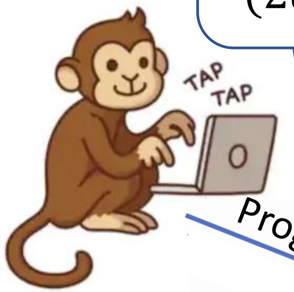

Program H'

<u>Perfect</u> indistinguishability of H' and F follows from [Zhandry’12a].

Makes at-most q queries to H'.

Random Oracle

Random Oracle

Setup phase

Extractable Commitments in NO QROM

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$H': \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{|\mathrm{Msg}|+|r|}$

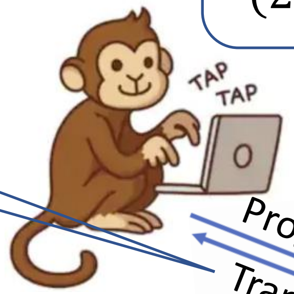
<u>Same</u> domain and co-domain required for extraction.

$H'': \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{\omega(\log \lambda)}$

Required for (statistical) <u>binding</u>.

Replace H' with a random polynomial F of degree $(2q-1)$ over $\mathbb{F}_{2^{|\mathrm{Msg}|+|r|}}$.

Polynomial F.



Program H'

Trapdoor

Makes at-most q queries to H'.

<u>Perfect</u> indistinguishability of H' and F follows from [Zhandry'12a].

Random Oracle

Random Oracle

Setup phase

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$H'' \colon \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{\omega(\log \lambda)}$

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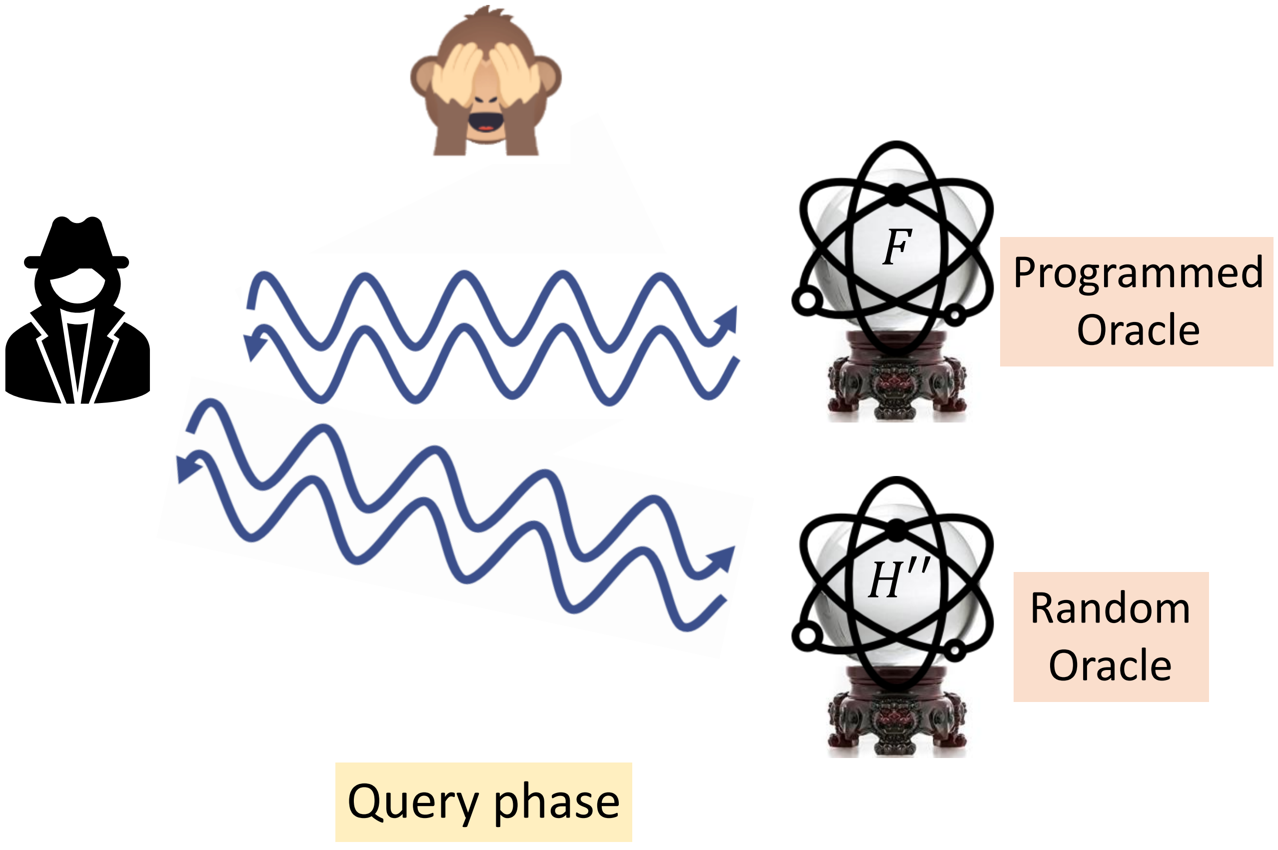

Extractable Commitments in NO QROM

$$\mathrm{Com} = F(\mathrm{Msg}, r) || H''(\mathrm{Msg}, r)$$

"Textbook" hash-based commitment:

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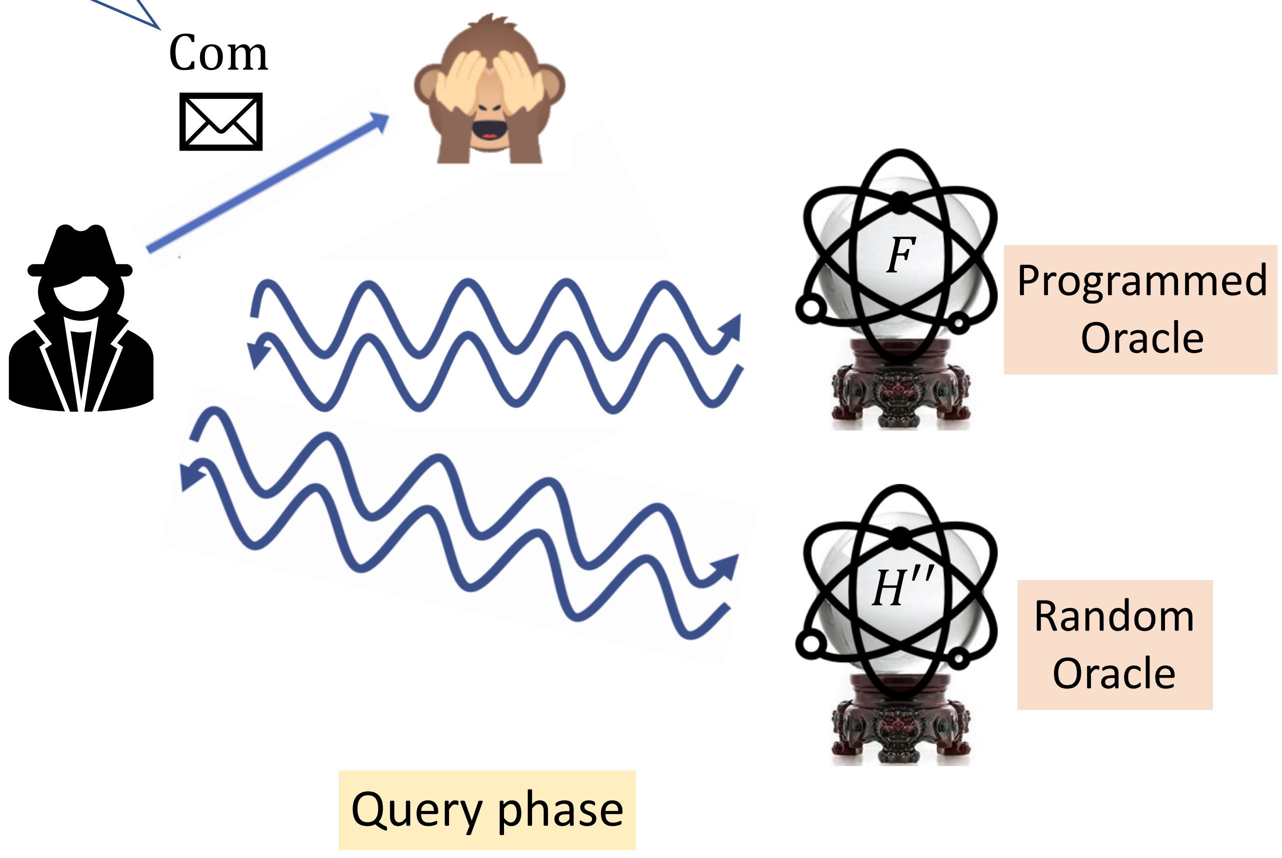

Extractable Commitments in NO QROM

$\mathrm{Com} = F(x)||H''(x)$

“Textbook” hash-based commitment:

$$\mathrm{Com} = H(\mathrm{Msg}, r)$$
$$= H'(\mathrm{Msg}, r)||H''(\mathrm{Msg}, r)$$

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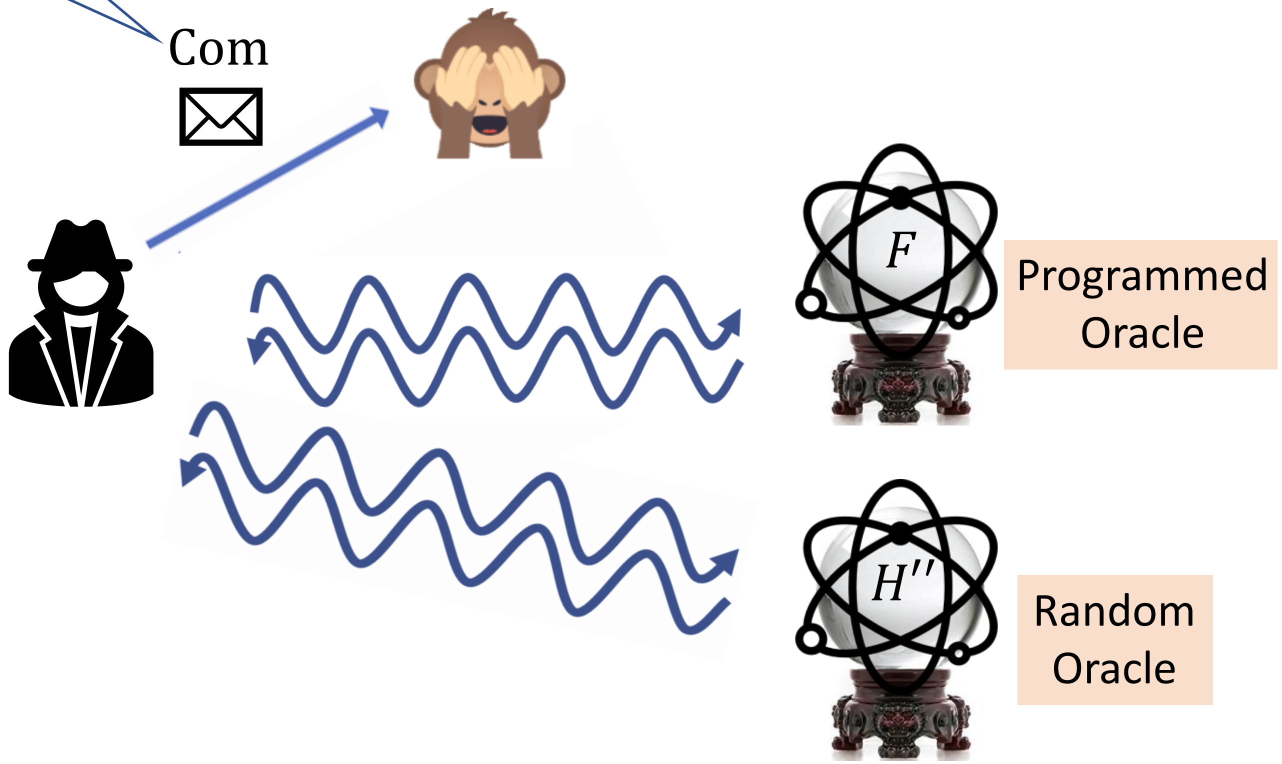
<u>Same</u> domain and co-domain required for extraction.

Required for (statistical) <u>binding</u>.



Query phase

Extractable Commitments in NO QROM

$$\mathrm{Com} = \underbrace{F(x)}_{y_1} || \underbrace{H''(x)}_{y_2}$$

“Textbook” hash-based commitment:

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$H' : \{0,1\}^{|\mathrm{Msg}|+|r|} \rightarrow \{0,1\}^{|\mathrm{Msg}|+|r|}$

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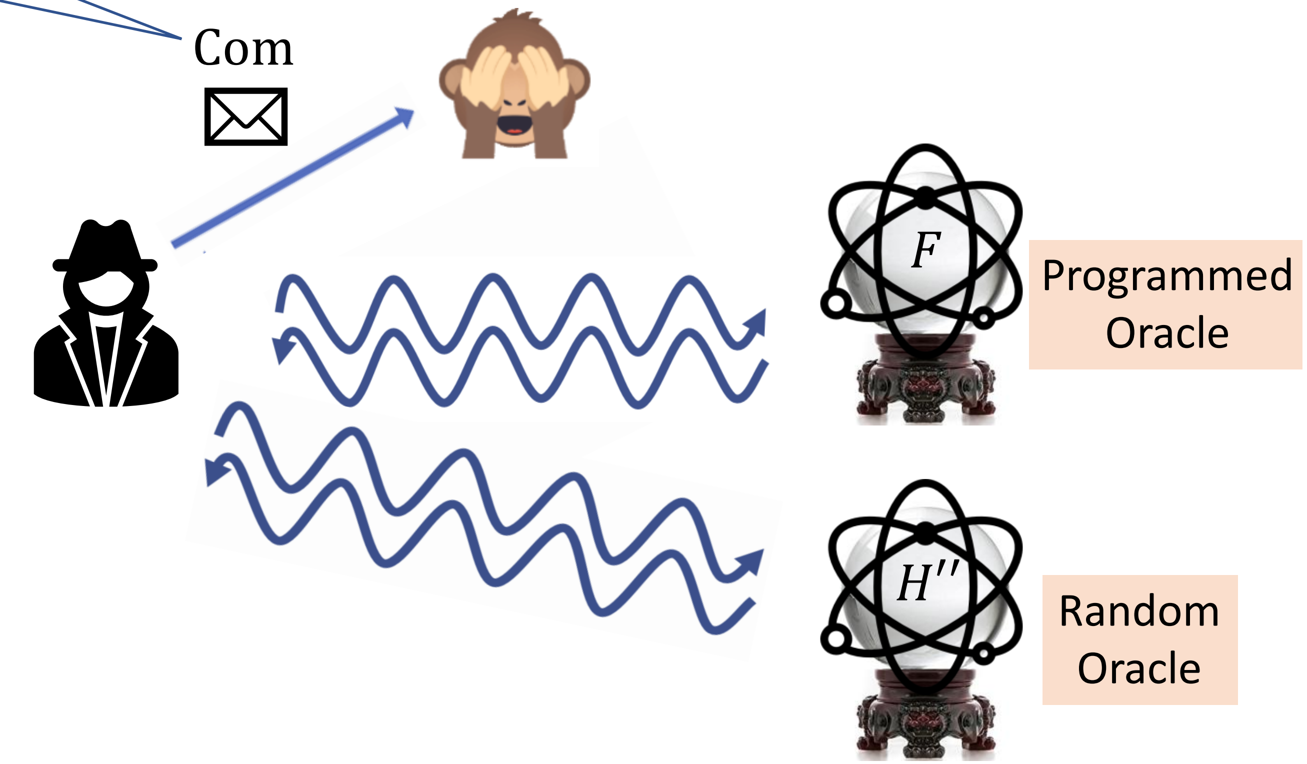

Query phase

Extractable Commitments in NO QROM

$$\mathrm{Com} = \underbrace{F(x)}_{y_1}||\underbrace{H''(x)}_{y_2}$$

Computes roots of polynomial $F(X) - y_1$.

"Textbook" hash-based commitment:

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$$= H'(\mathrm{Msg}, r)||H''(\mathrm{Msg}, r)$$

$H': \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{|\mathrm{Msg}|+|r|}$

$H'': \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{\omega(\log \lambda)}$

Same domain and co-domain required for extraction.

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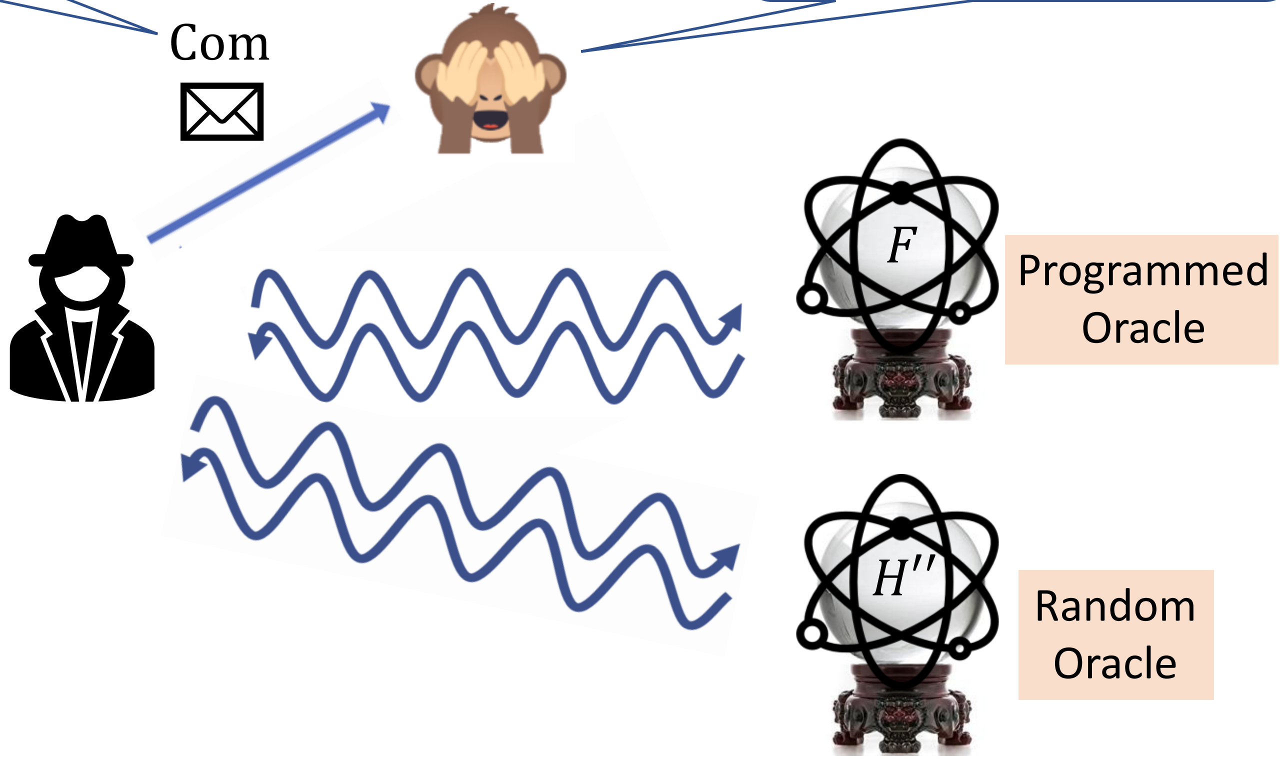

Query phase

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"Textbook" hash-based commitment:

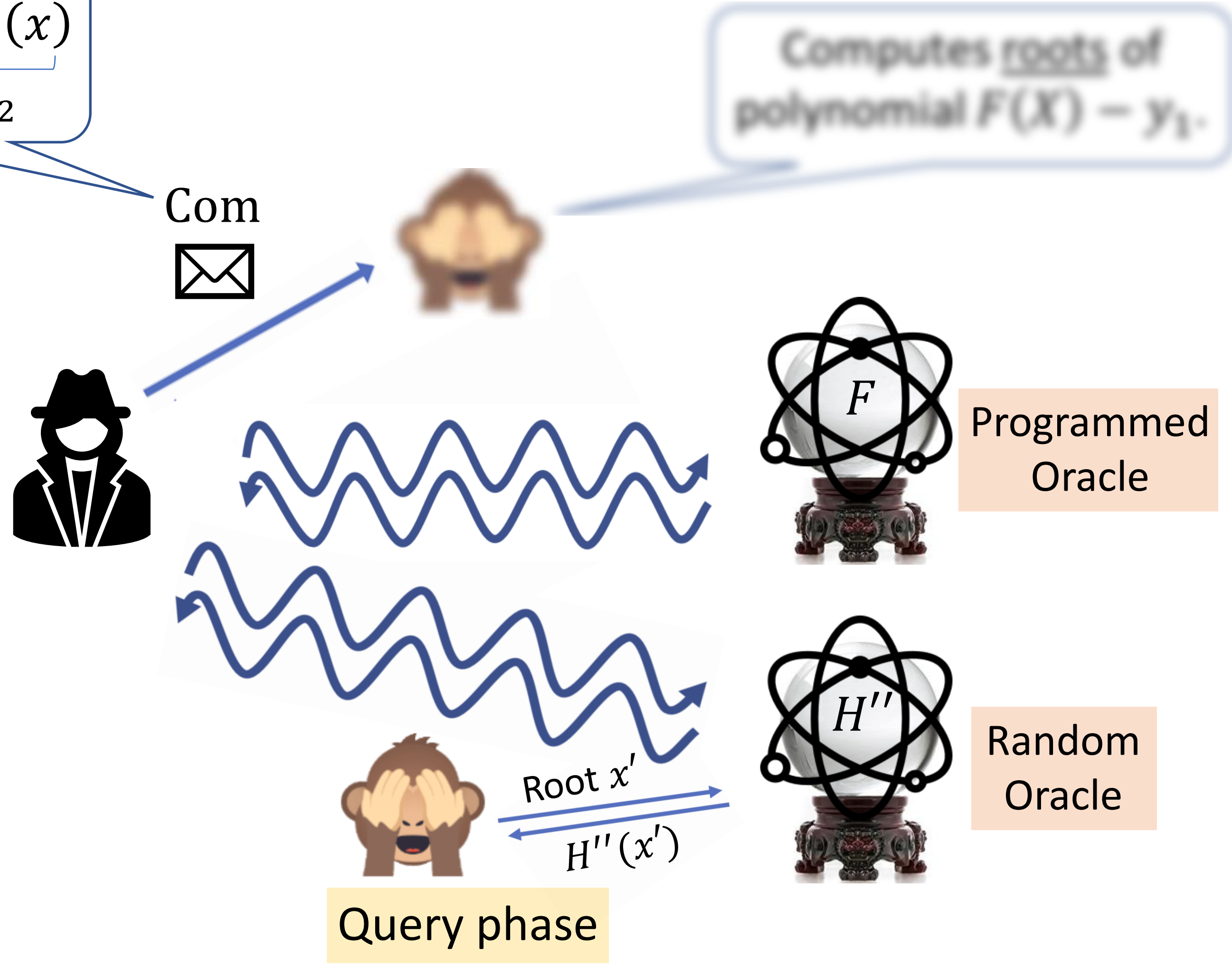
$$\begin{aligned}\mathrm{Com} &= H(\mathrm{Msg}, r)\\ &= H'(\mathrm{Msg}, r)||H''(\mathrm{Msg}, r)\end{aligned}$$

$$H' : \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{|\mathrm{Msg}|+|r|}$$

$$H'' : \{0,1\}^{|\mathrm{Msg}|+|r|} \to \{0,1\}^{\omega(\log \lambda)}$$

Same domain and co-domain required for extraction.

Required for (statistical) binding.



Extractable Commitments in NO QROM

$$\mathrm{Com} = \underbrace{F(x)}_{y_1}||\underbrace{H''(x)}_{y_2}$$

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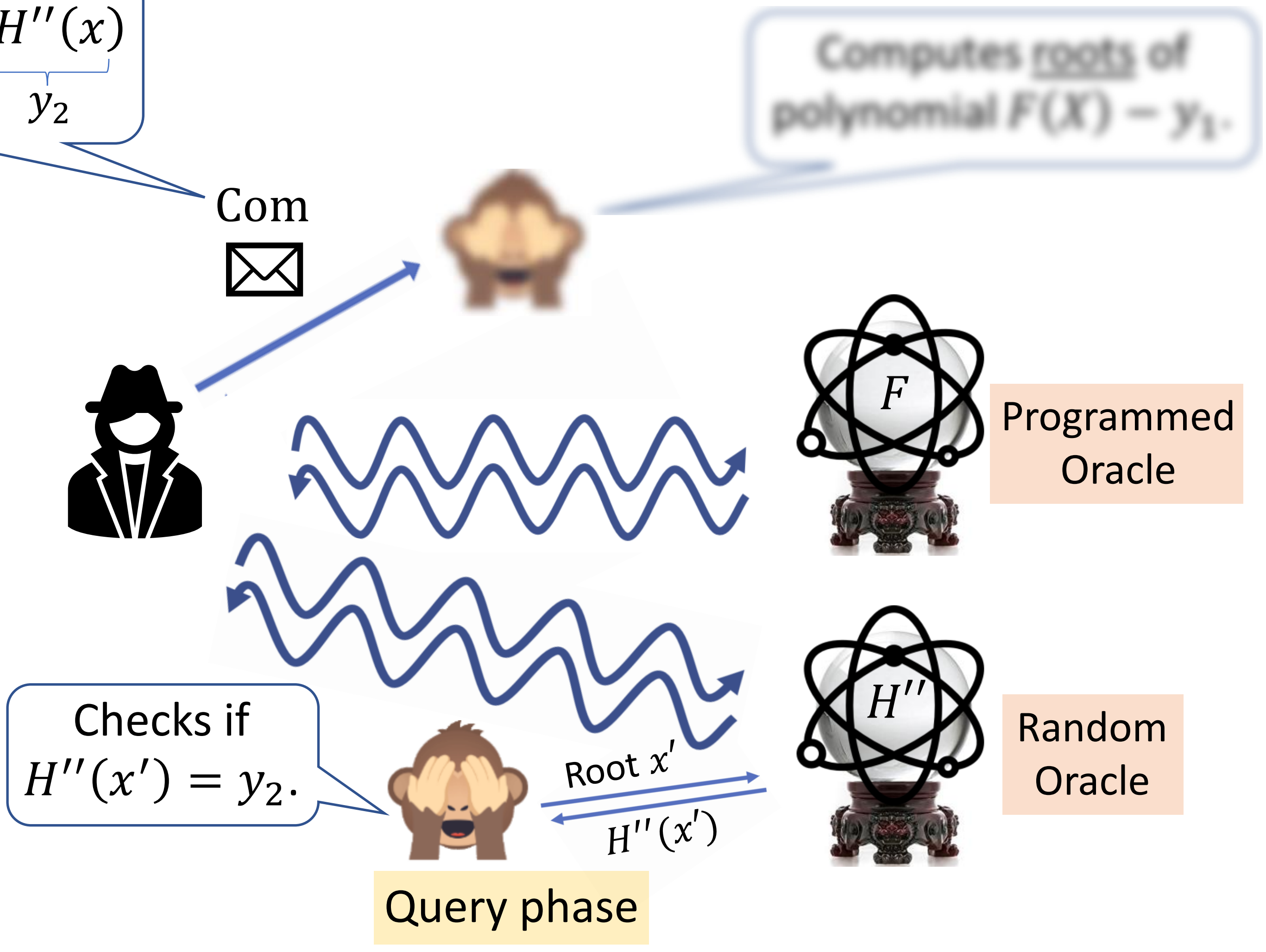

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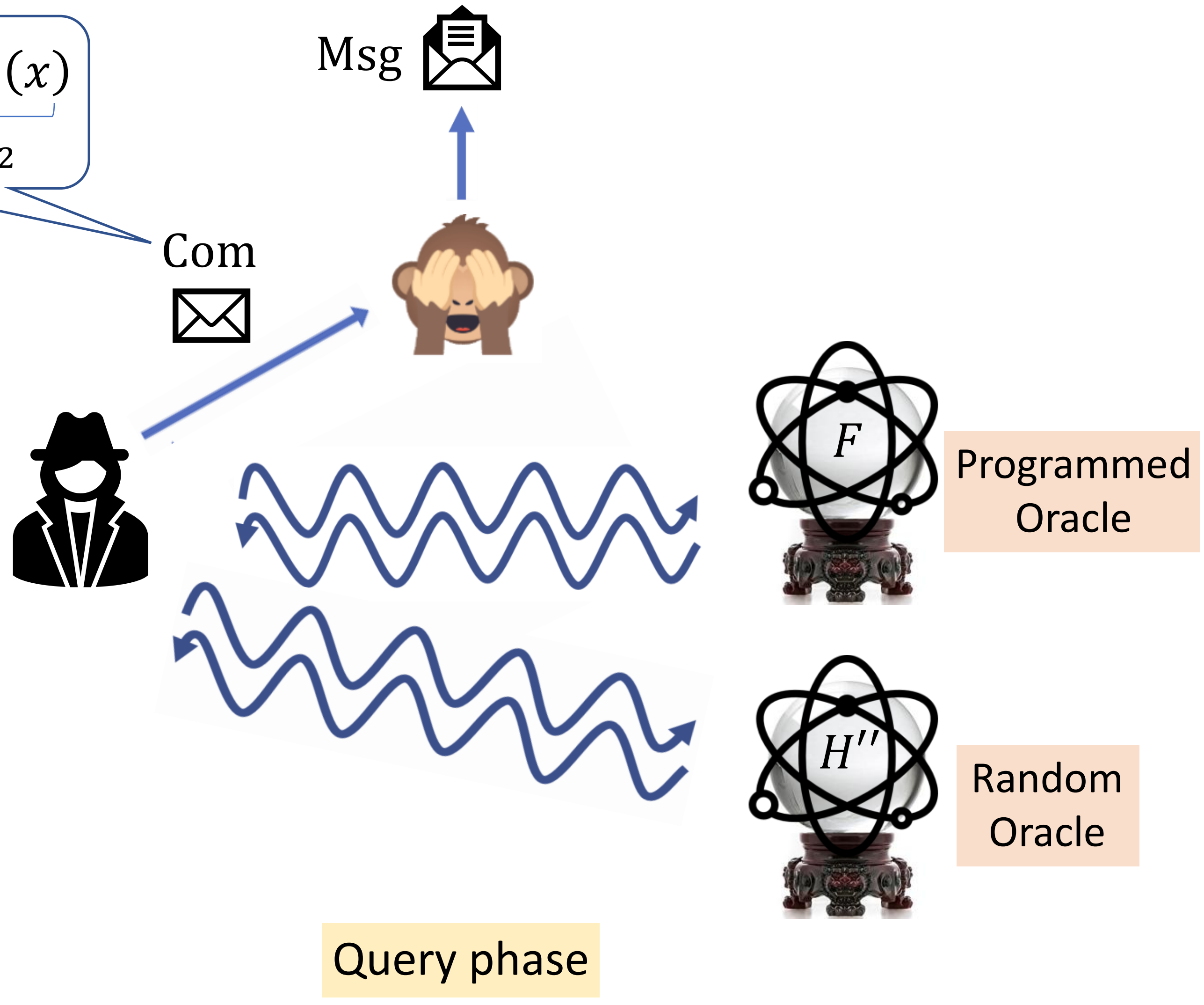

Extractable Commitments in NO QROM

$$\text{Com} = \underbrace{F(x)}_{y_1} || \underbrace{H''(x)}_{y_2}$$

"Textbook" hash-based commitment:

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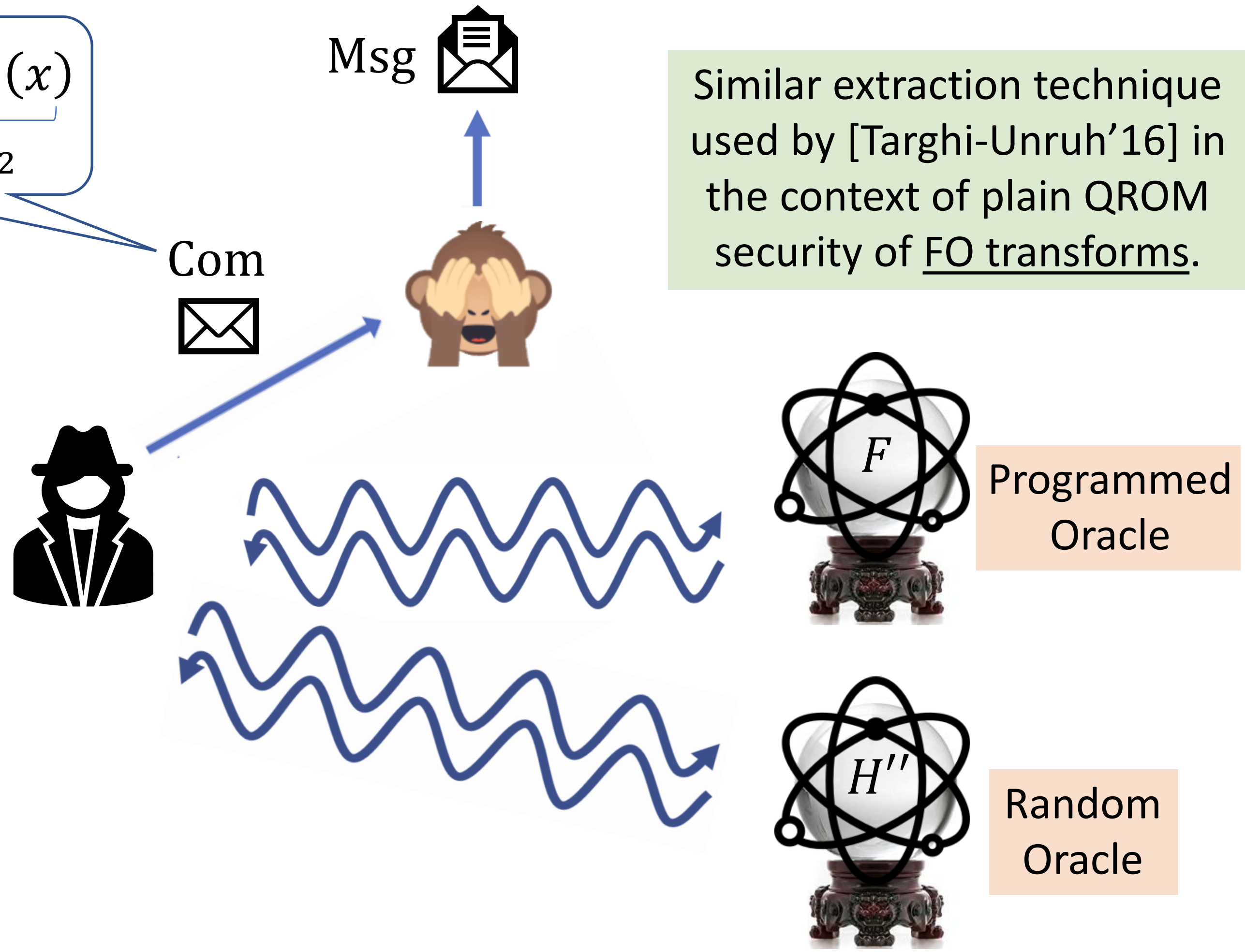
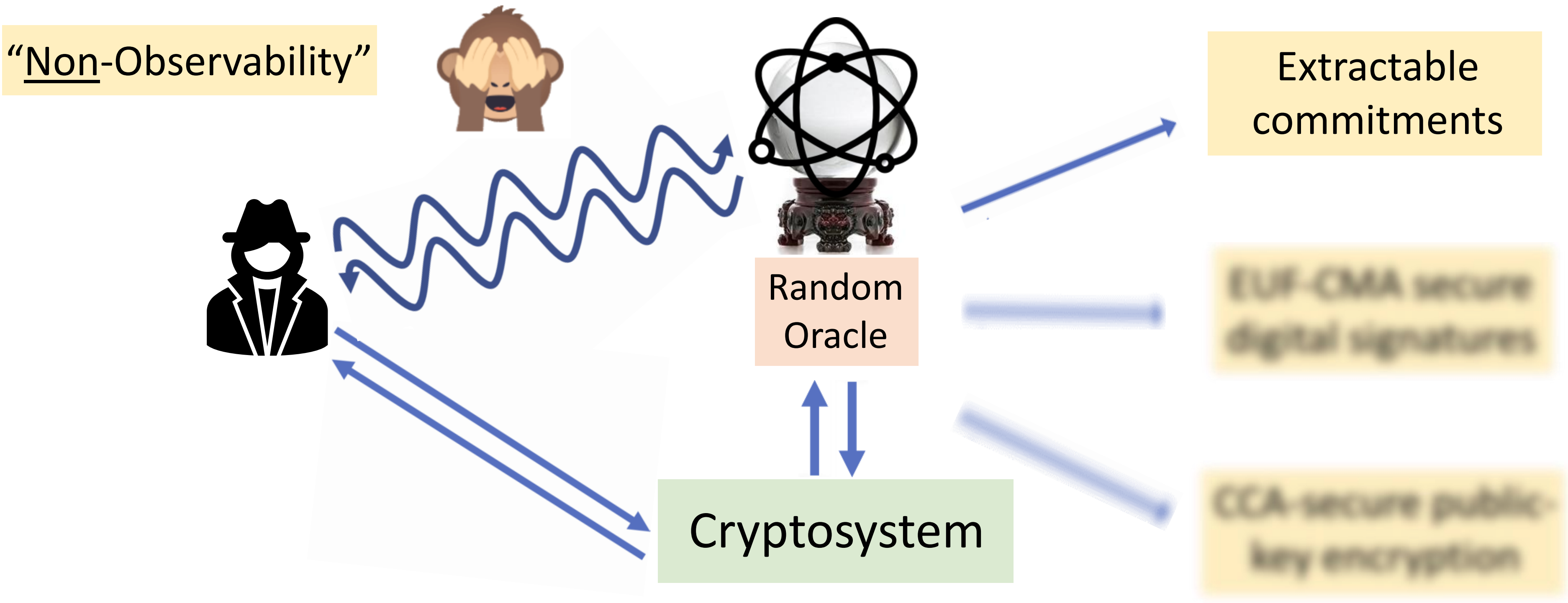


Similar extraction technique used by [Targhi-Unruh'16] in the context of plain QROM security of <u>FO transforms</u>.

Query phase

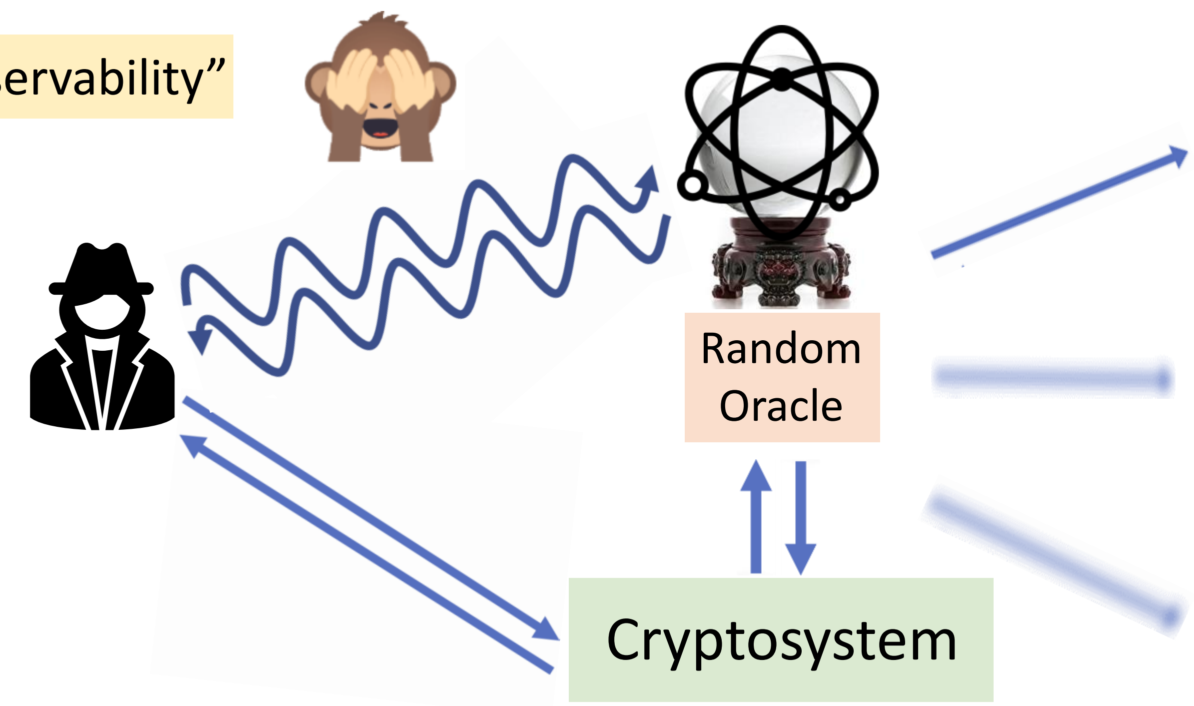
Non-Observable QROM (NO QROM)



Formalized by [Alamati-Maram-Masny’23].

Non-Observable QROM (NO QROM)

"Non-Observability"



Extractable commitments

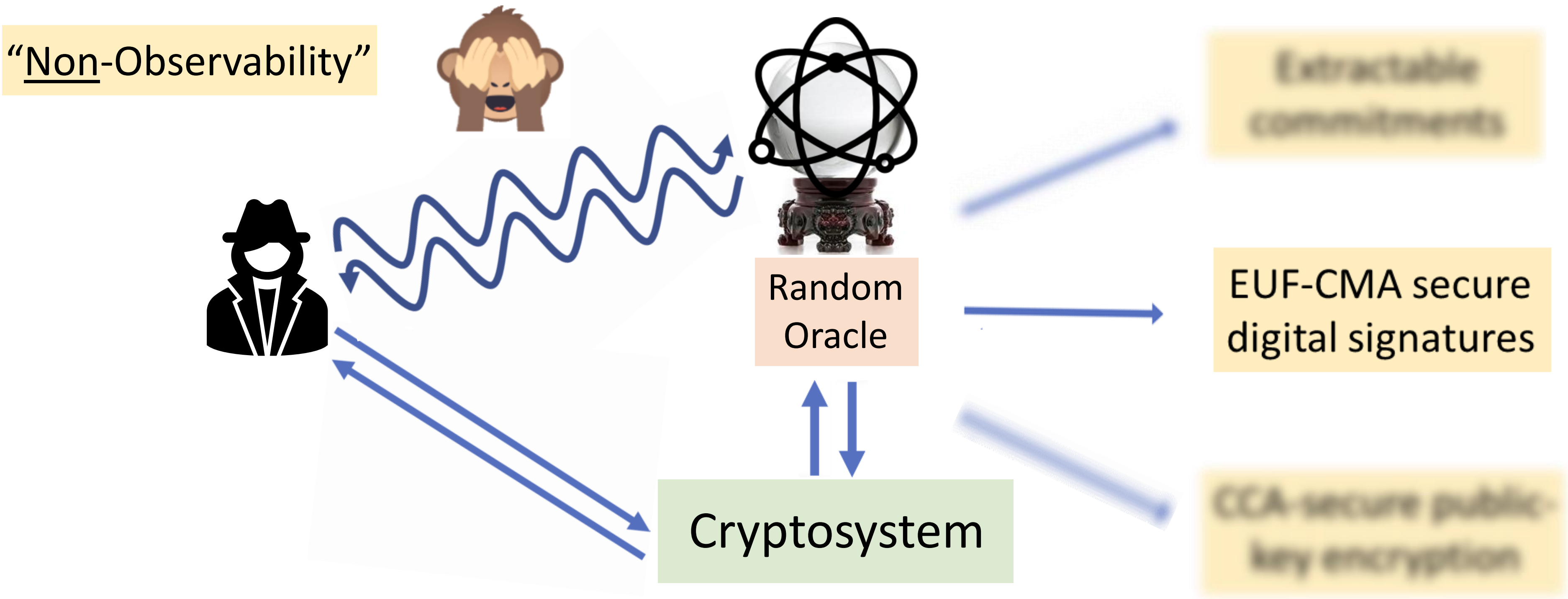
EUF-CMA secure digital signatures

CCA-secure public-key encryption

- Obtained shorter commitments using "small-range distribution" technique of [Zhandry'12b]
  - However, requires superpolynomial extractors.
- Showed hiding property of our commitments via the notion of non-malleability.

Formalized by [Alamati-Maram-Masny'23].

Non-Observable QROM (NO QROM)



Formalized by [Alamati-Maram-Masny’23].

EUF-CMA Secure Signatures in NO QROM

Full-Domain Hash (FDH) Signature

Formalized by [Bellare-Rogaway'93].

EUF-CMA Secure Signatures in NO QROM

Trapdoor Permutation (TDP)

+

Random Oracle

Full-Domain Hash (FDH) Signature

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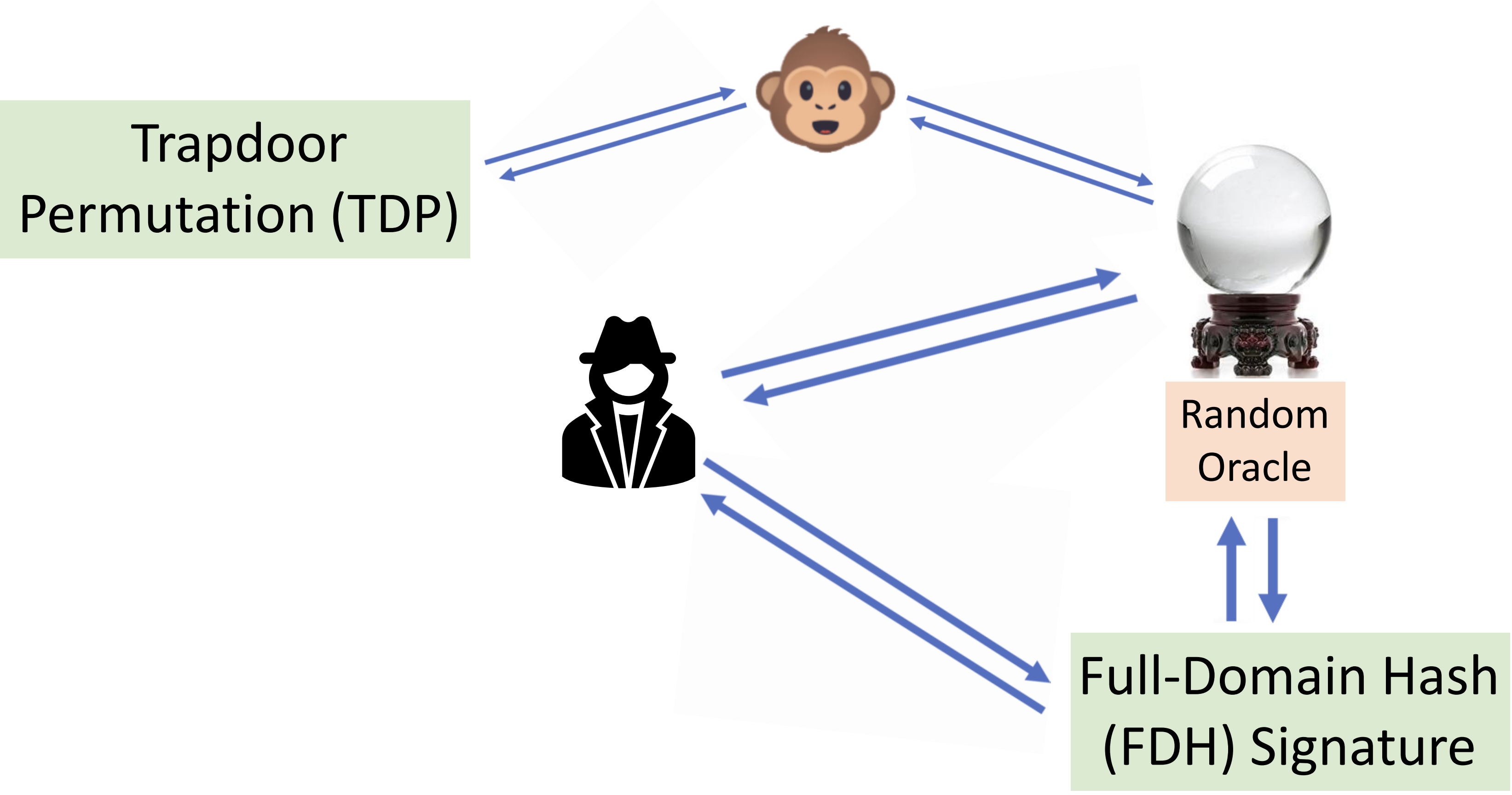
EUF-CMA Secure Signatures in NO QROM



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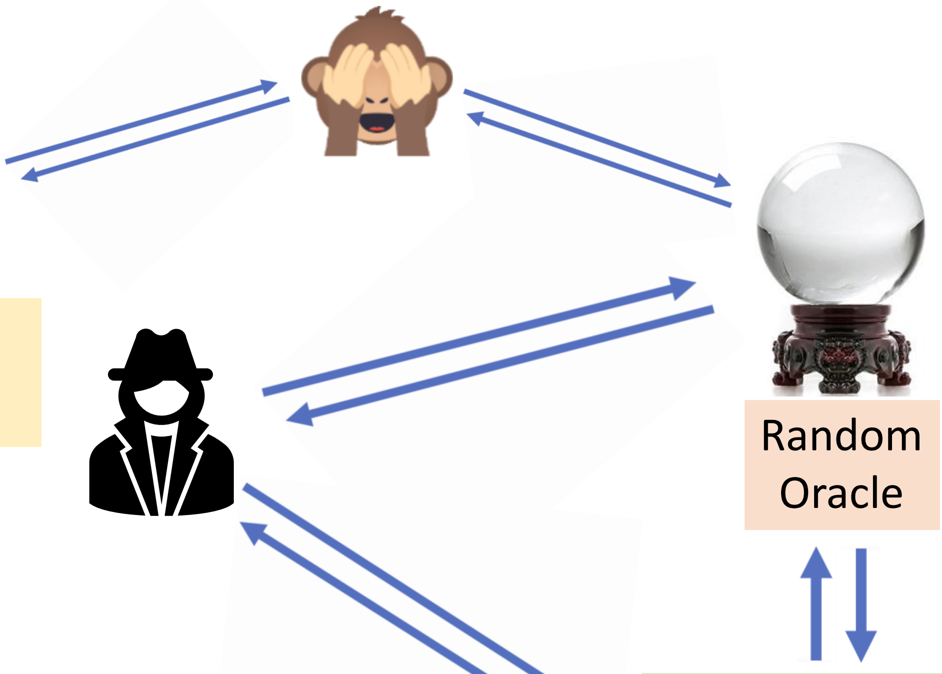

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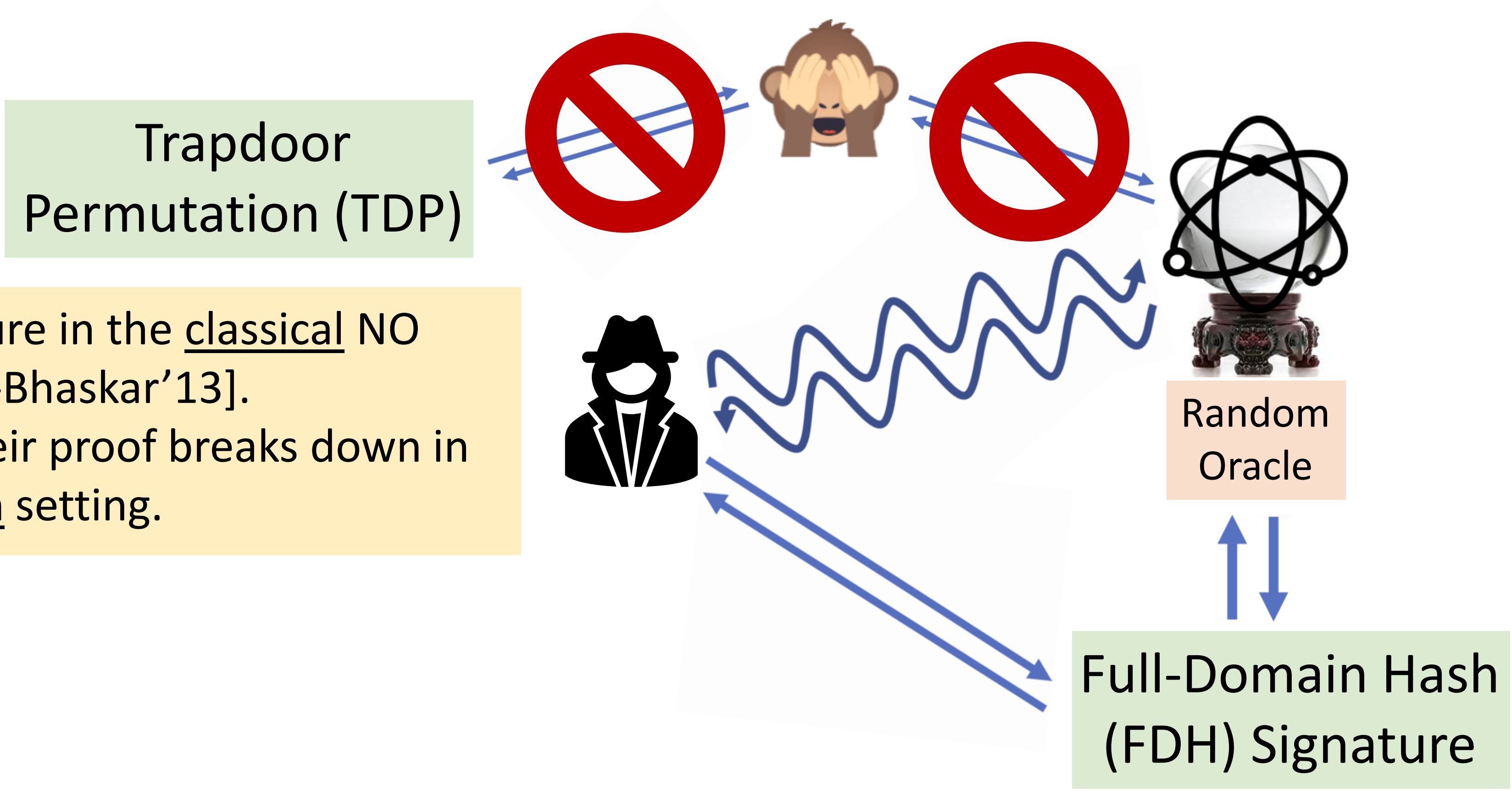
EUF-CMA Secure Signatures in NO QROM



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EUF-CMA Secure Signatures in NO QROM

Trapdoor Permutation (TDP)

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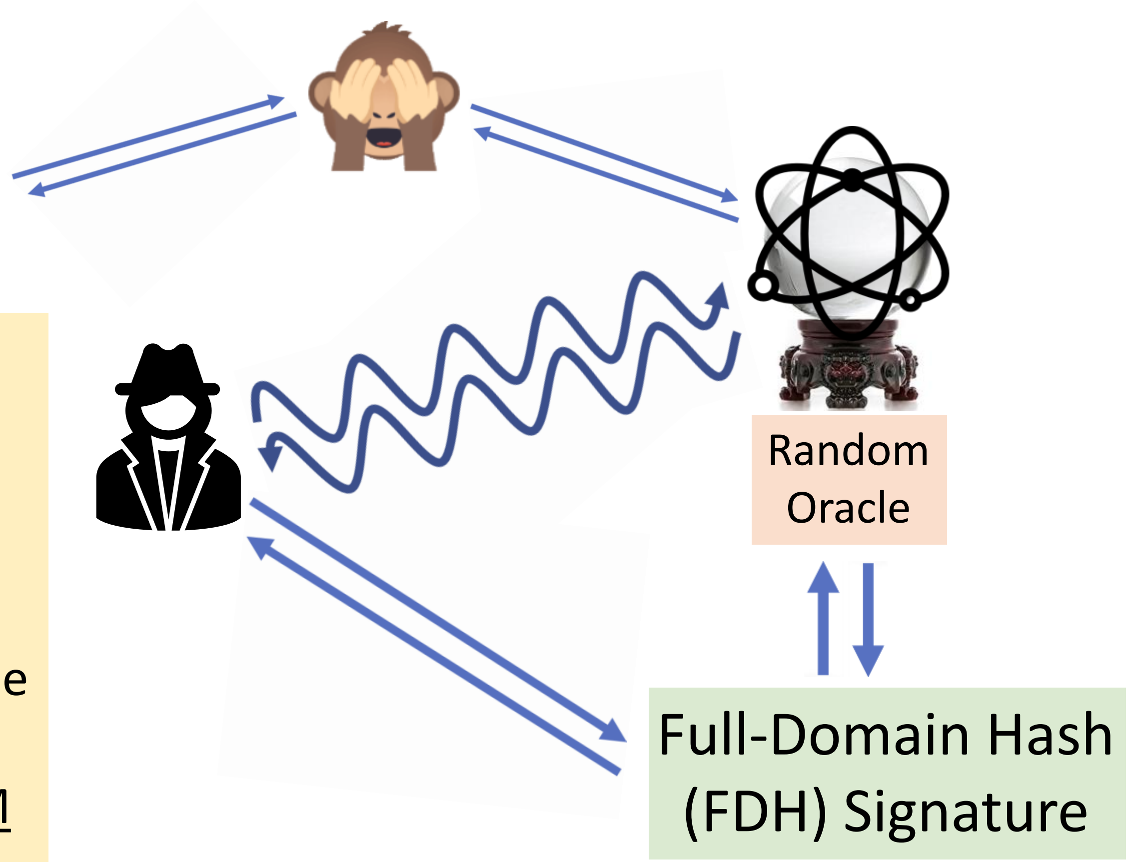
  - Adapted [Zhandry'12a]'s plain QROM security proof.

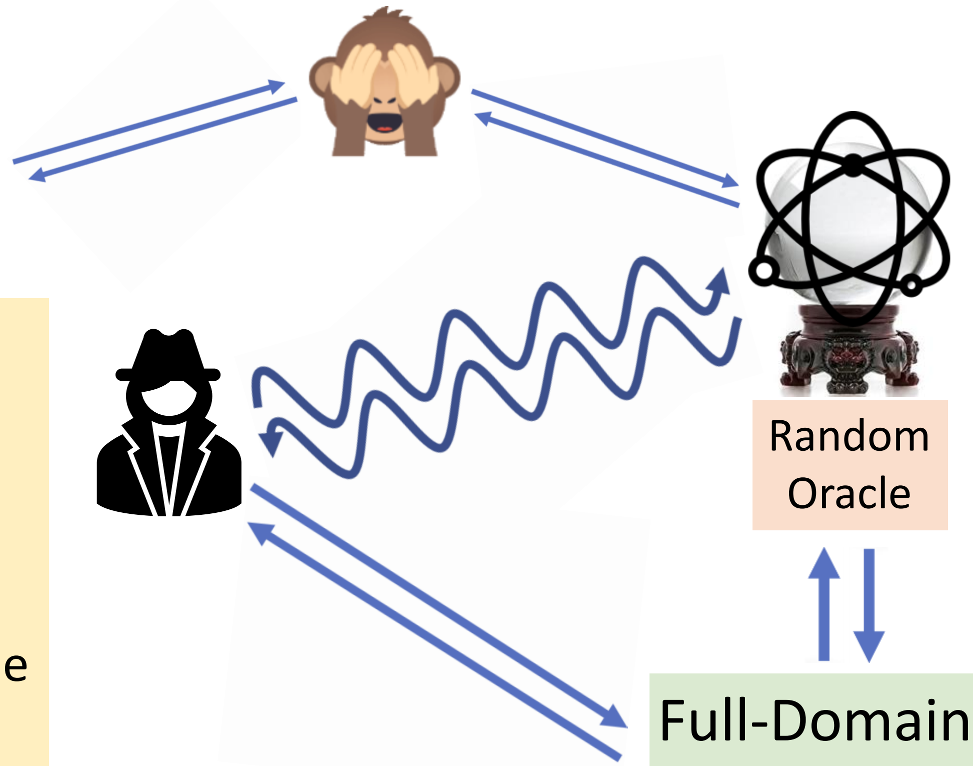


Formalized by [Bellare-Rogaway'93].

EUF-CMA Secure Signatures in NO QROM

Quantum-secure?

Trapdoor Permutation (TDP)



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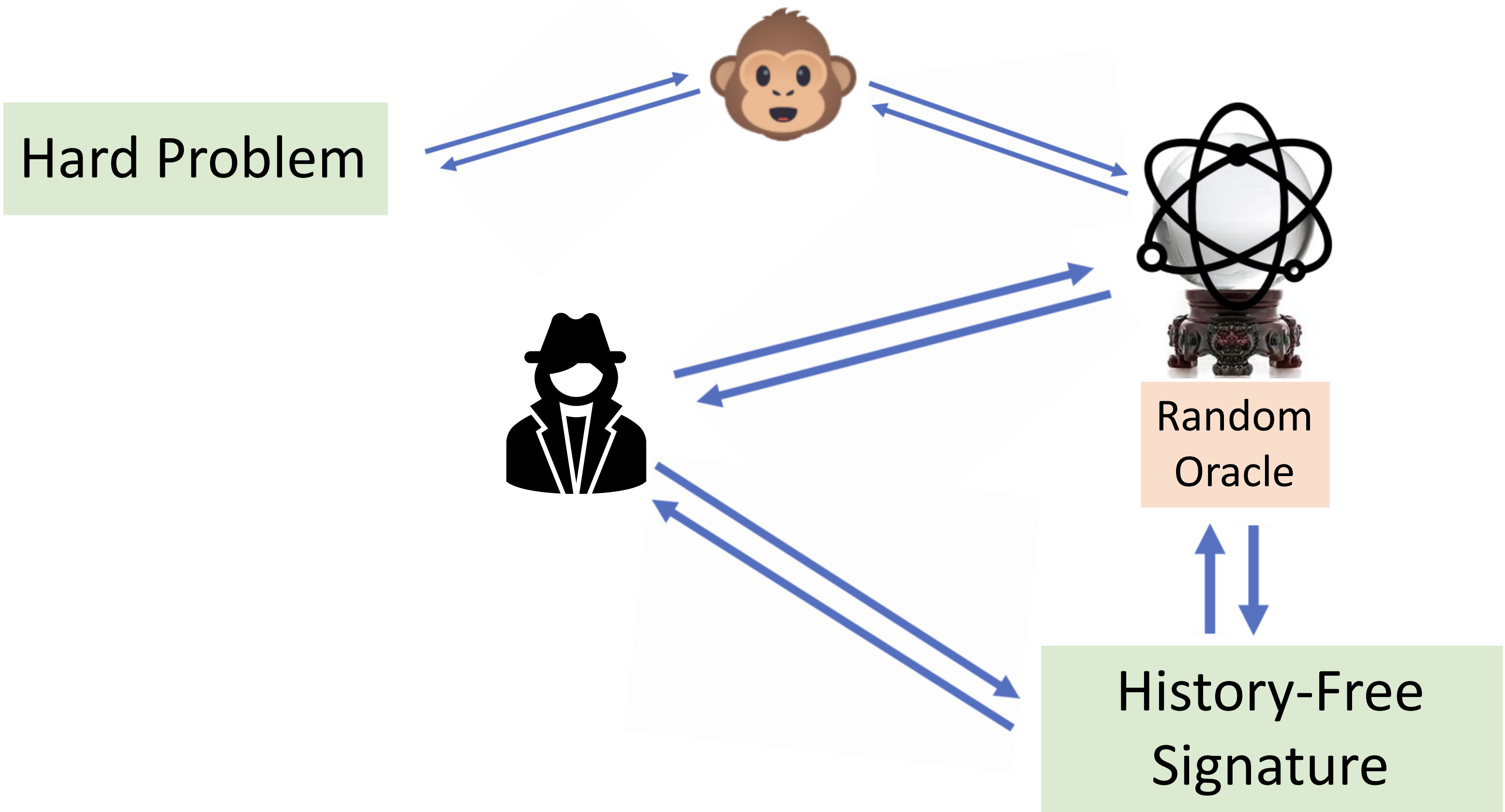
  - Adapted [Zhandry'12a]'s <u>plain QROM</u> security proof.
- However, <u>no concrete instantiations</u> of post-quantum TDPs known.

EUF-CMA Secure Signatures in NO QROM



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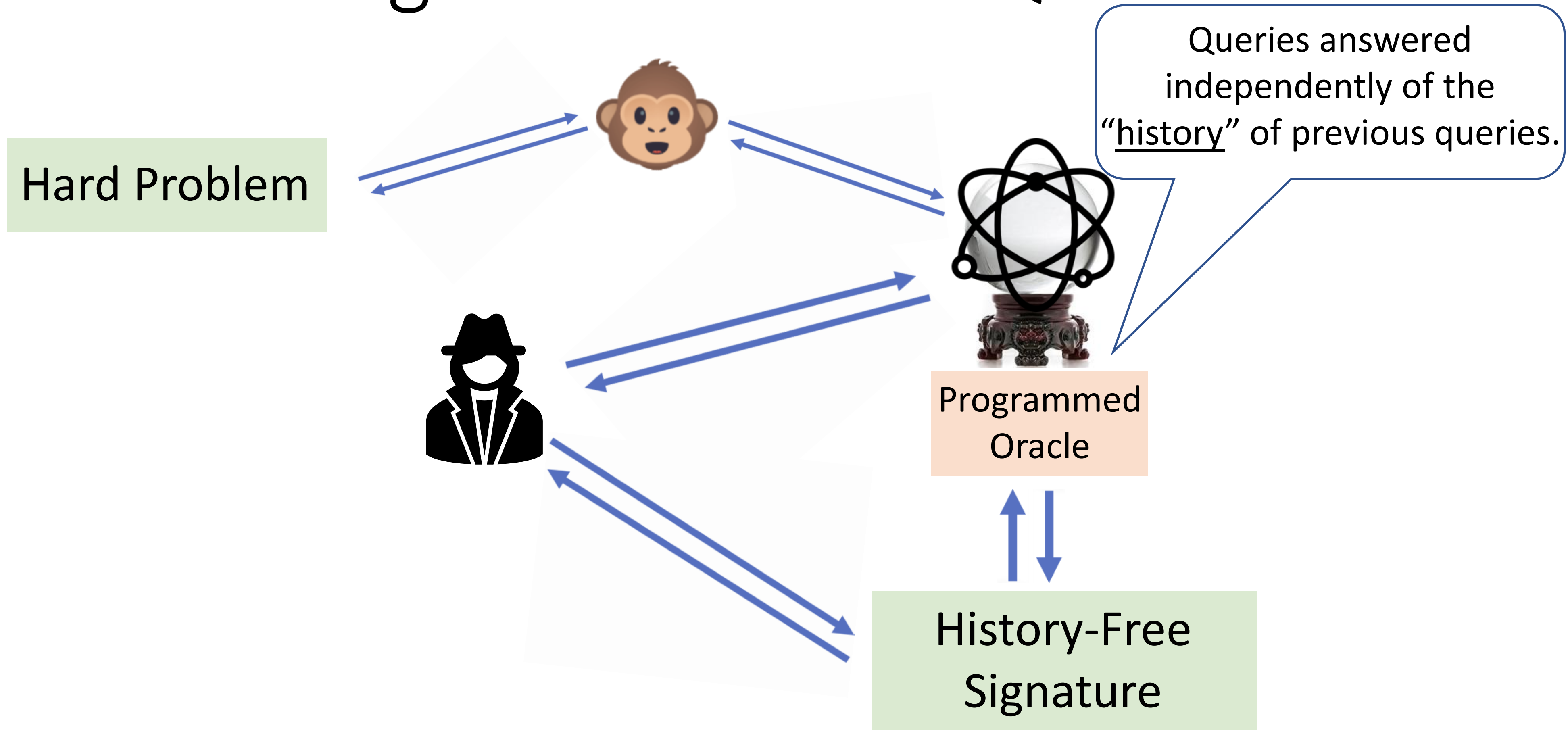
EUF-CMA Secure Signatures in NO QROM



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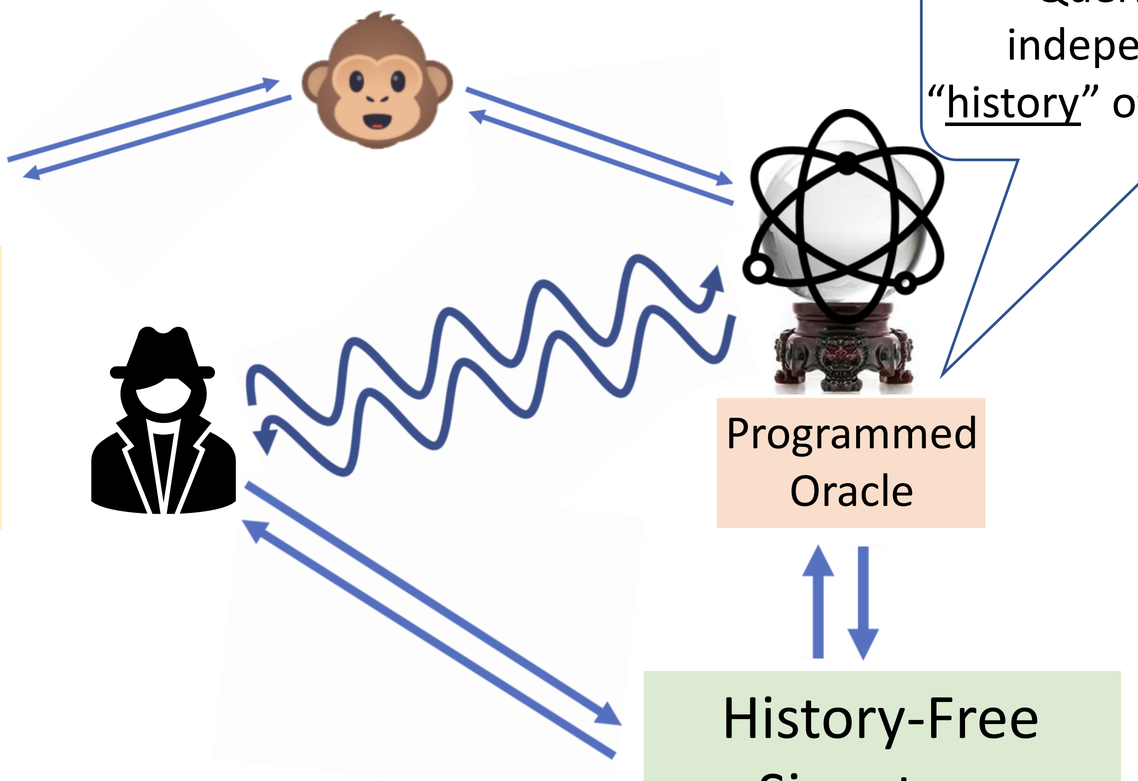
EUF-CMA Secure Signatures in NO QROM

Hard Problem



- ROM security proof of history-free signatures can be lifted to (plain) QROM [Boneh-Dagdelen-Fischlin-Lehmann-Schaffner-Zhandry'11].

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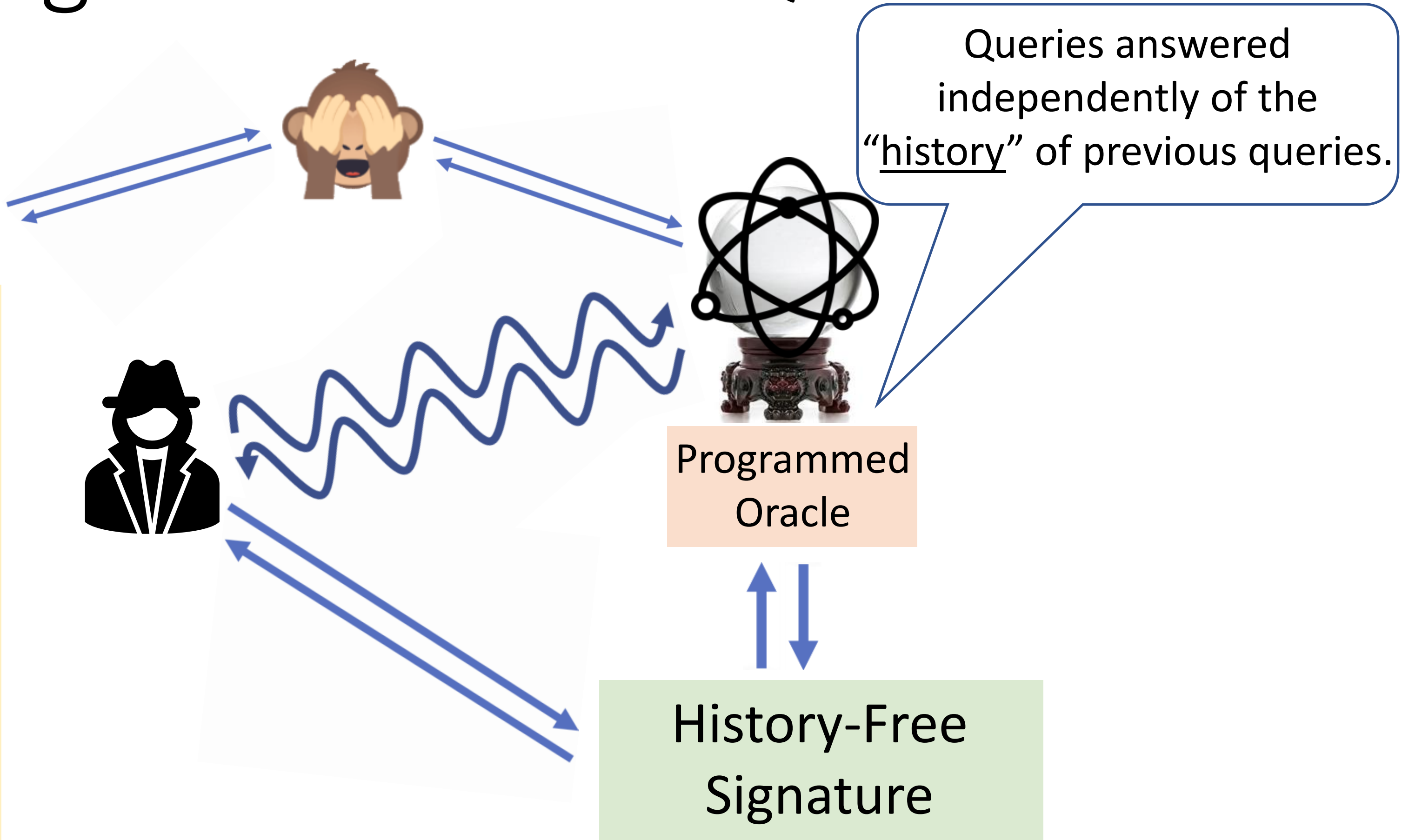

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- Lattice-based signatures of [Gentry-Peikert-Vaikuntanathan'08] and Fiat-Shamir signatures in [Kiltz-Lyubashevsky-Schaffner'18] are history-free.

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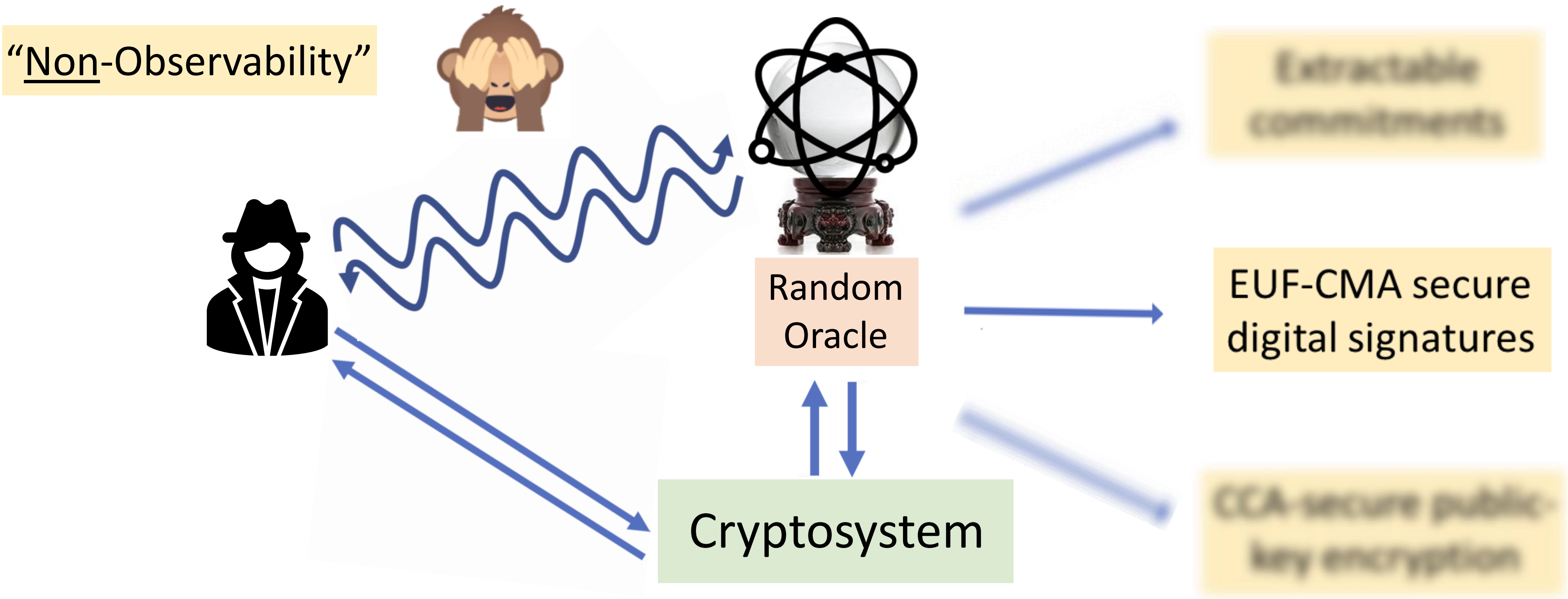
Non-Observable QROM (NO QROM)



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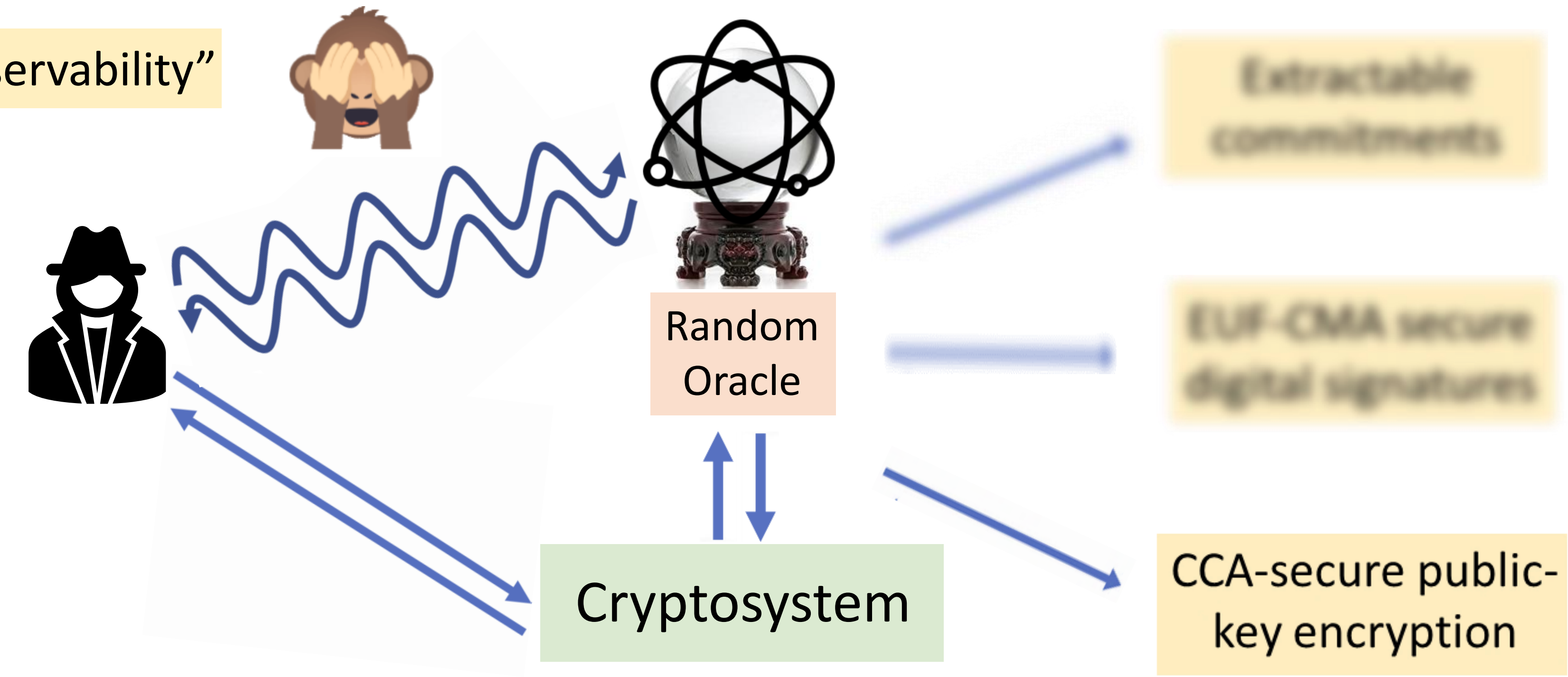

Formalized by [Alamati-Maram-Masny'23].

CCA-Secure Public-Key Encryption in NO QROM

CCA-Secure PKE

CCA-Secure Public-Key Encryption in NO QROM

CPA-Secure PKE

Random Oracle

+

CCA-Secure PKE

Transformation introduced by [Fujisaki-Okamoto’99].

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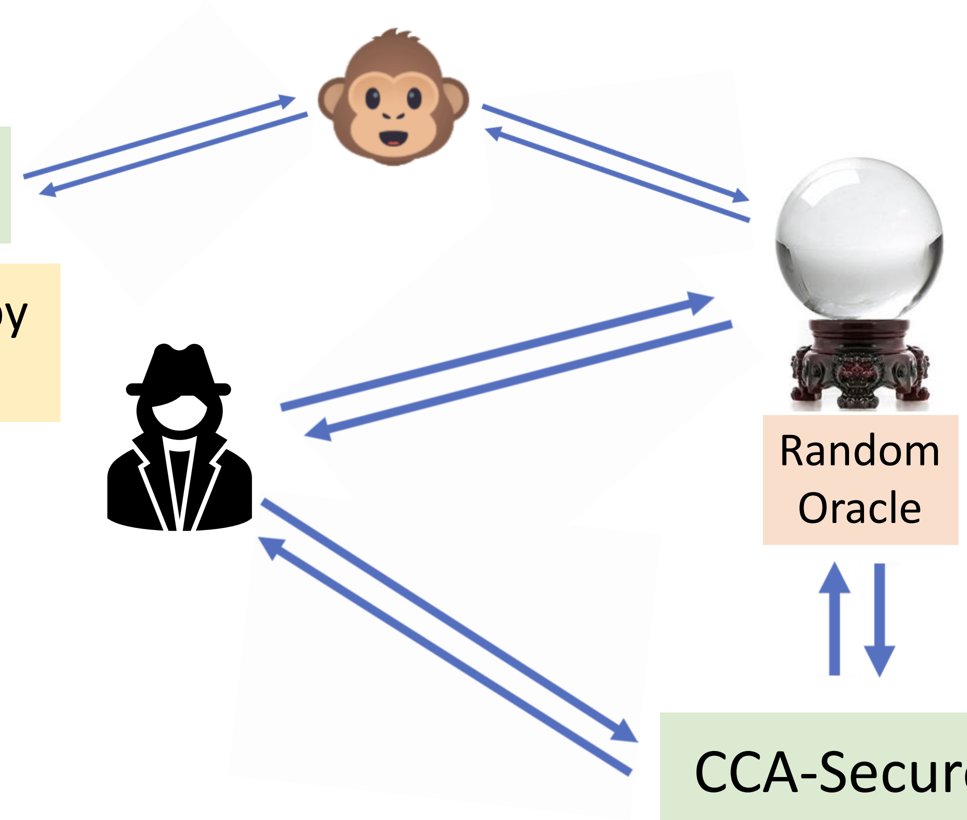

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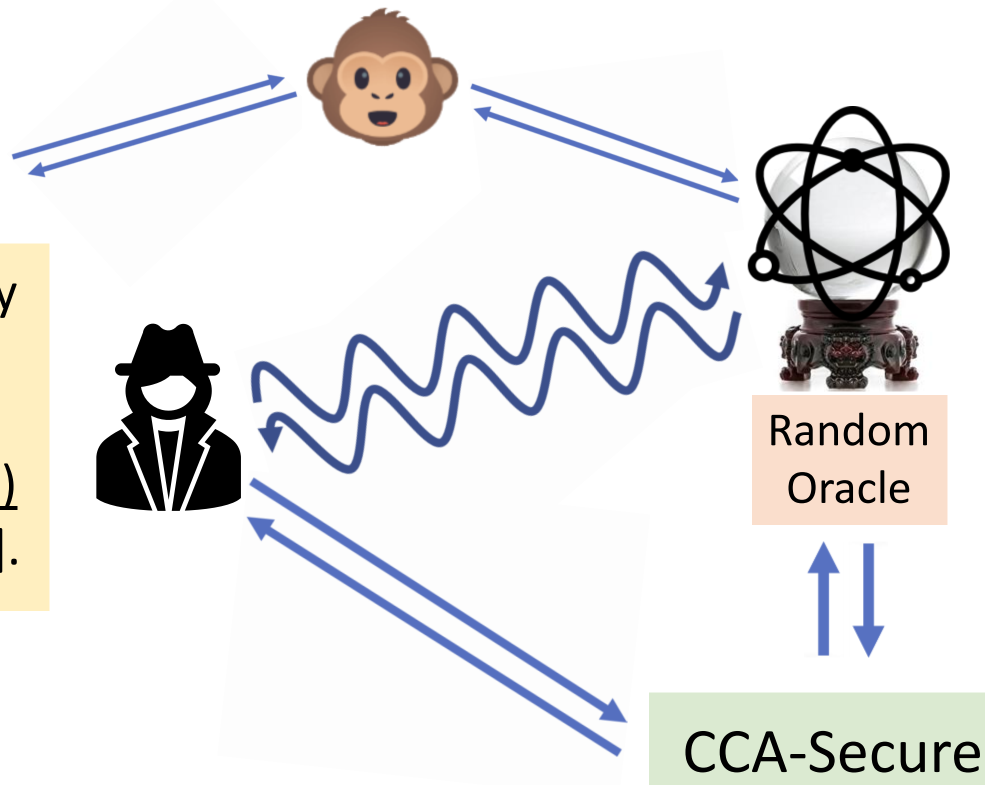

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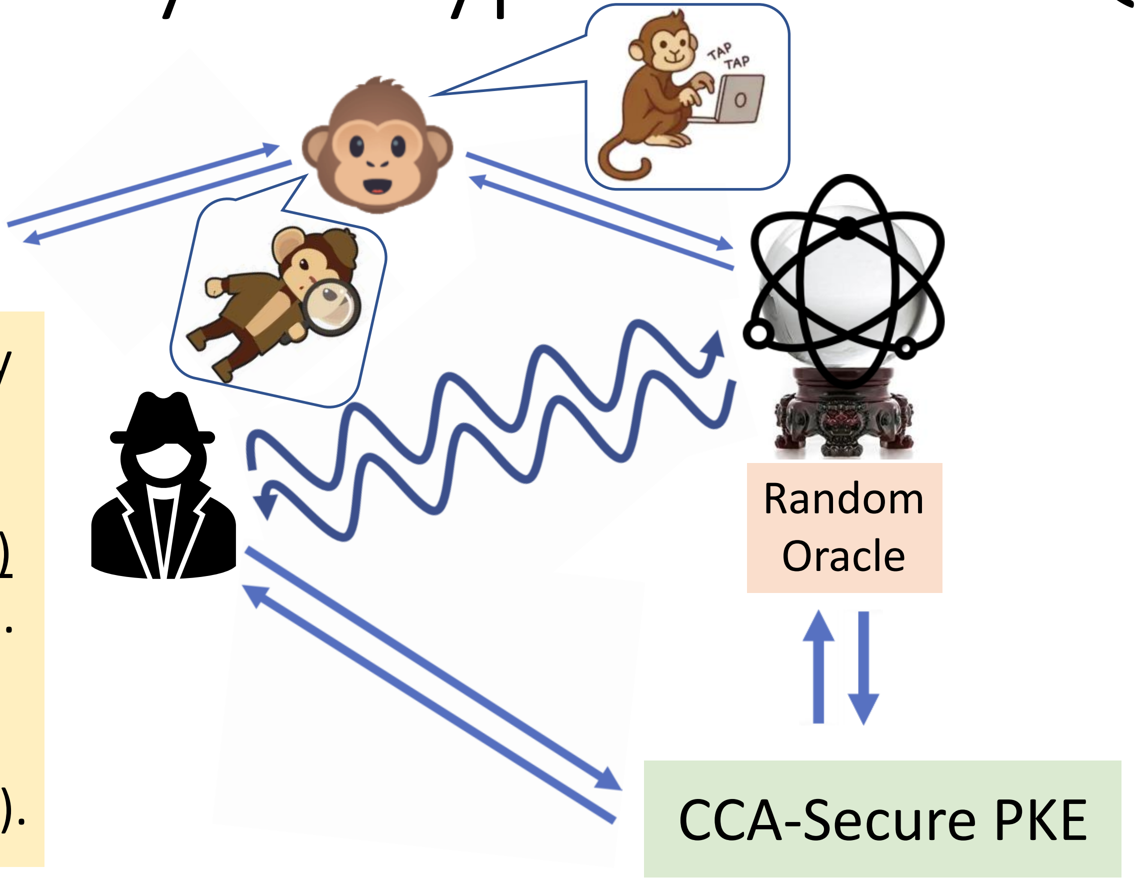

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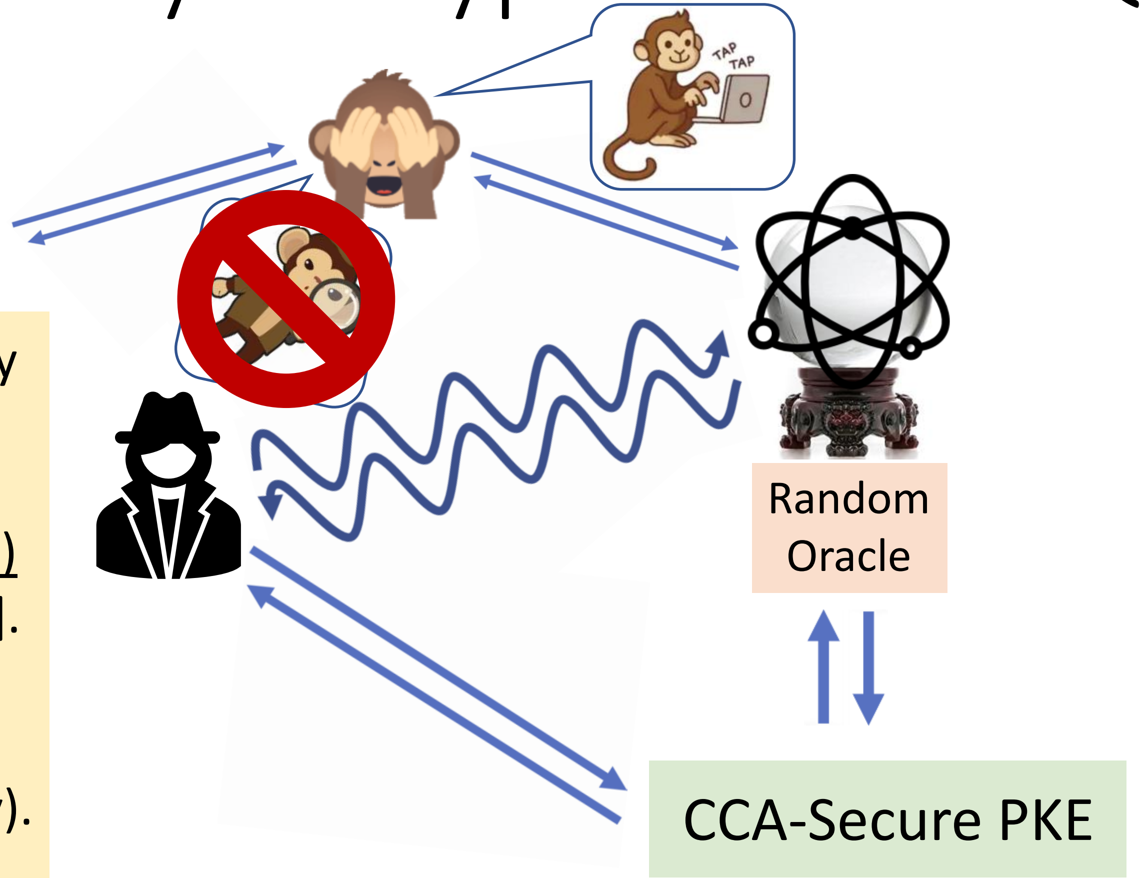

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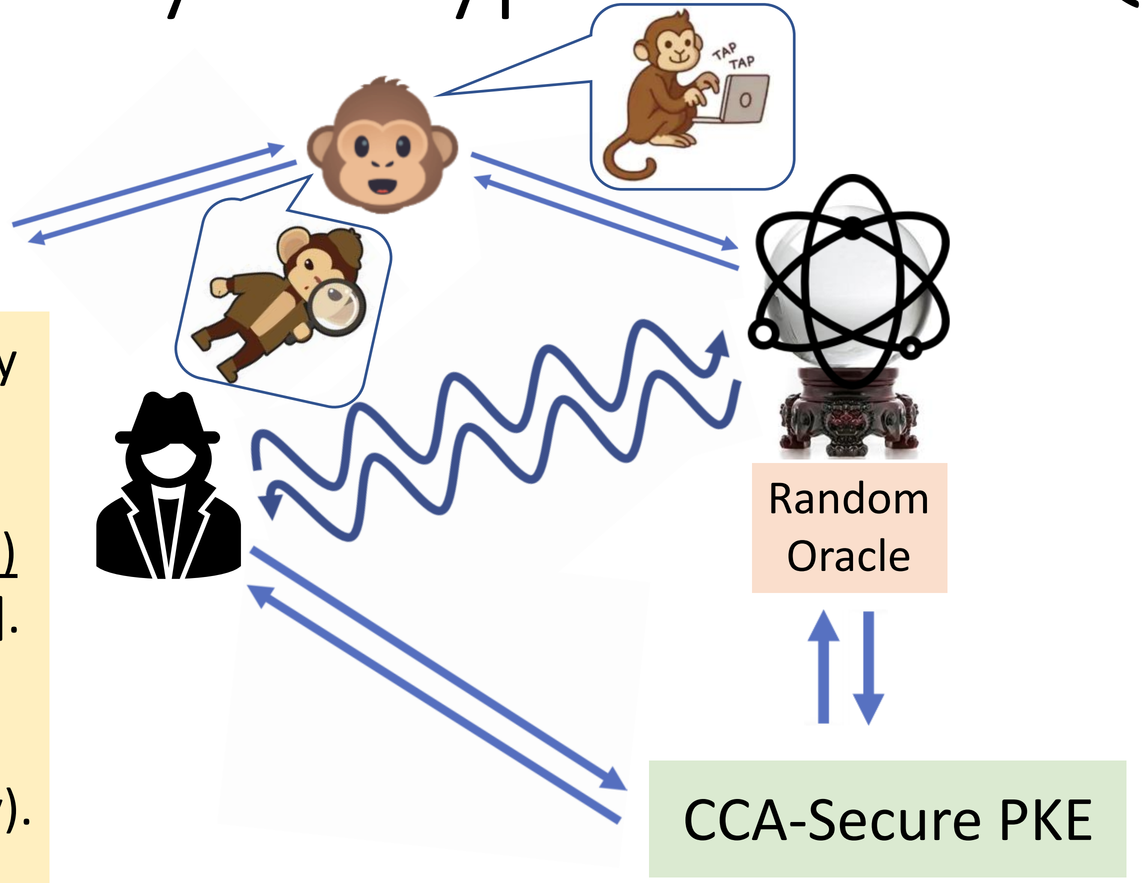
CCA-Secure Public-Key Encryption in NO QROM

Msg Ctxt CPA-Secure PKE



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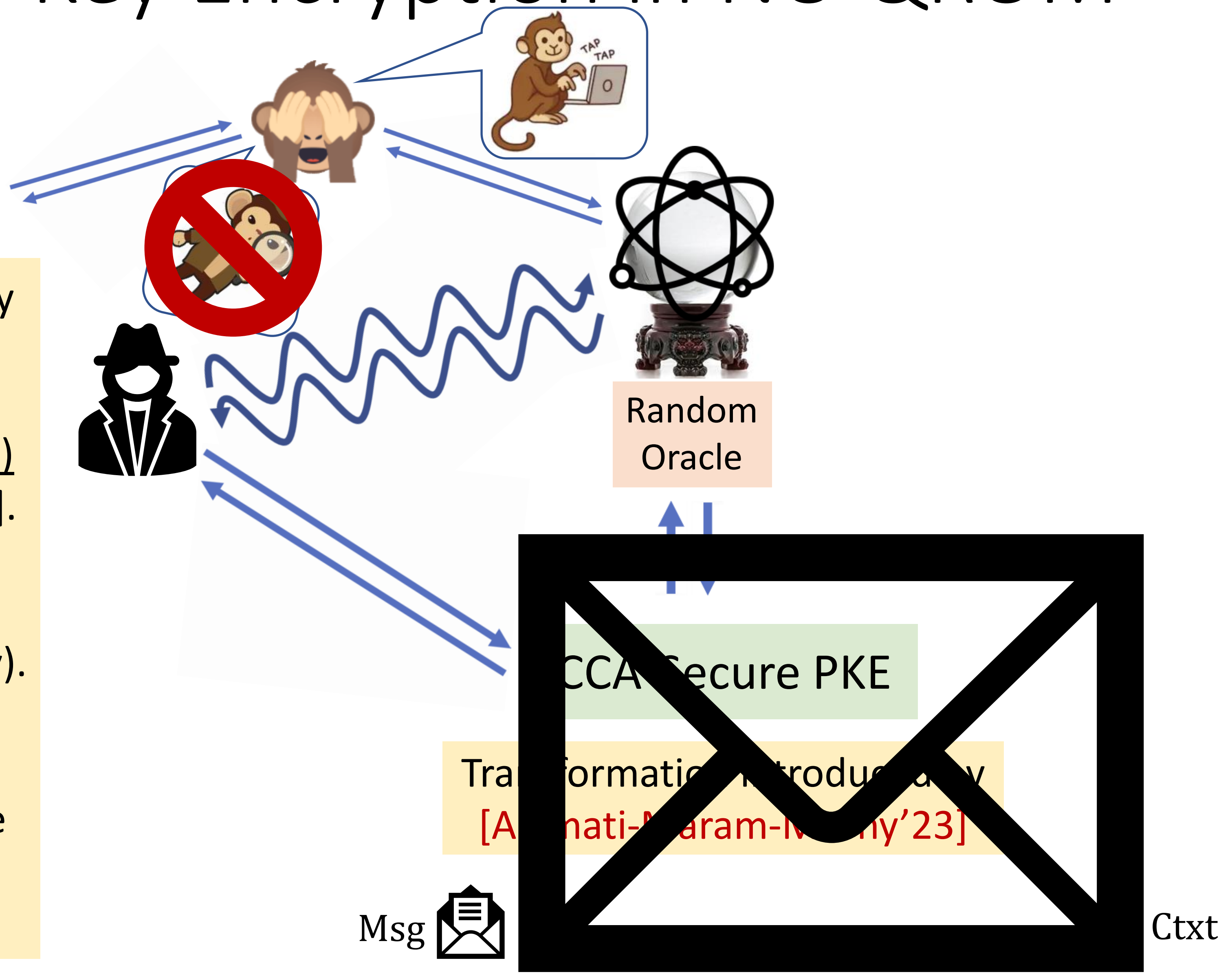

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+

"Hinting" PRG

CCA-Secure PKE

Construction by [Koppula-Waters'19].

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"Hinting" PRG

PRG with a stronger security guarantee.

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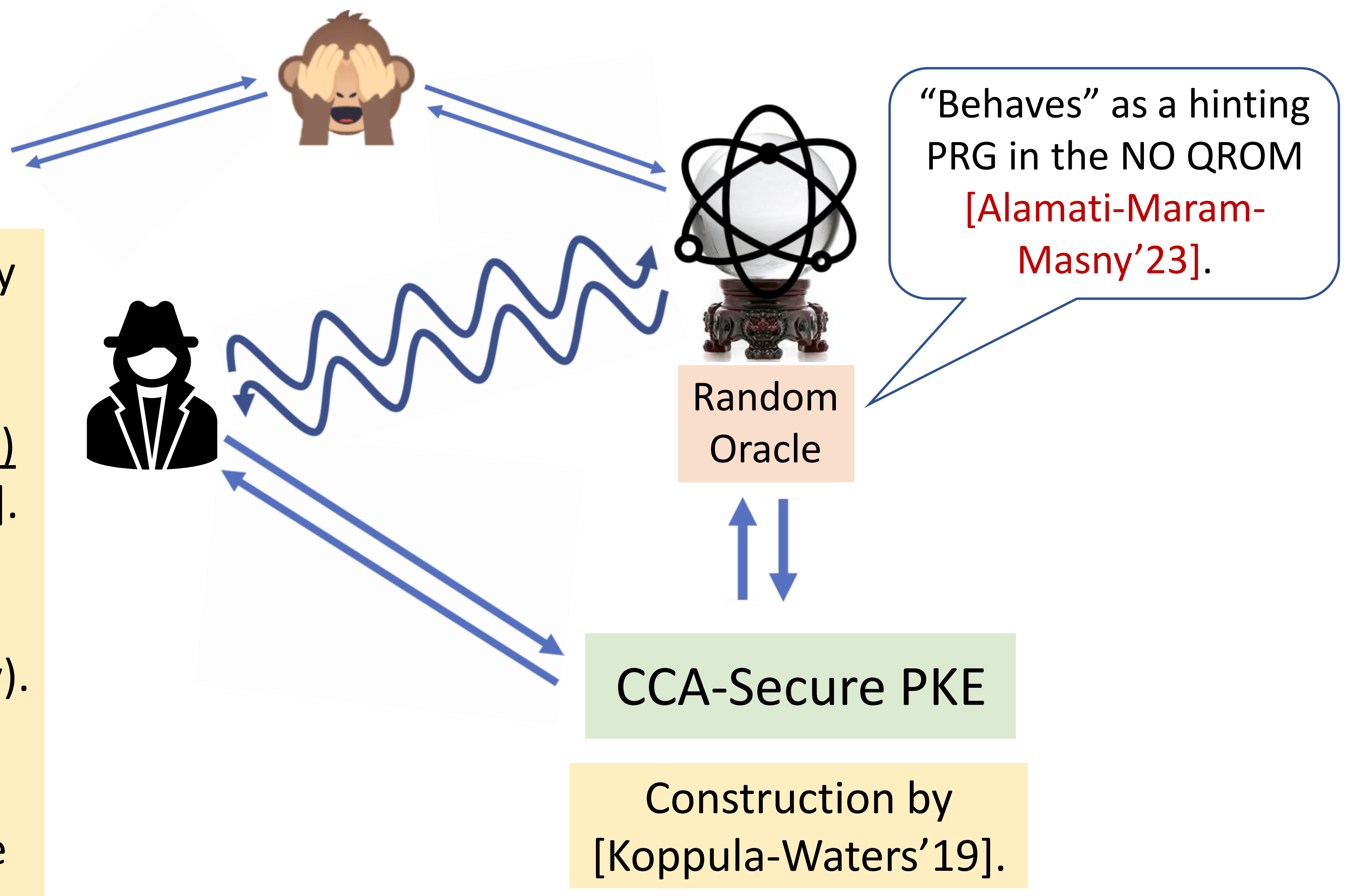

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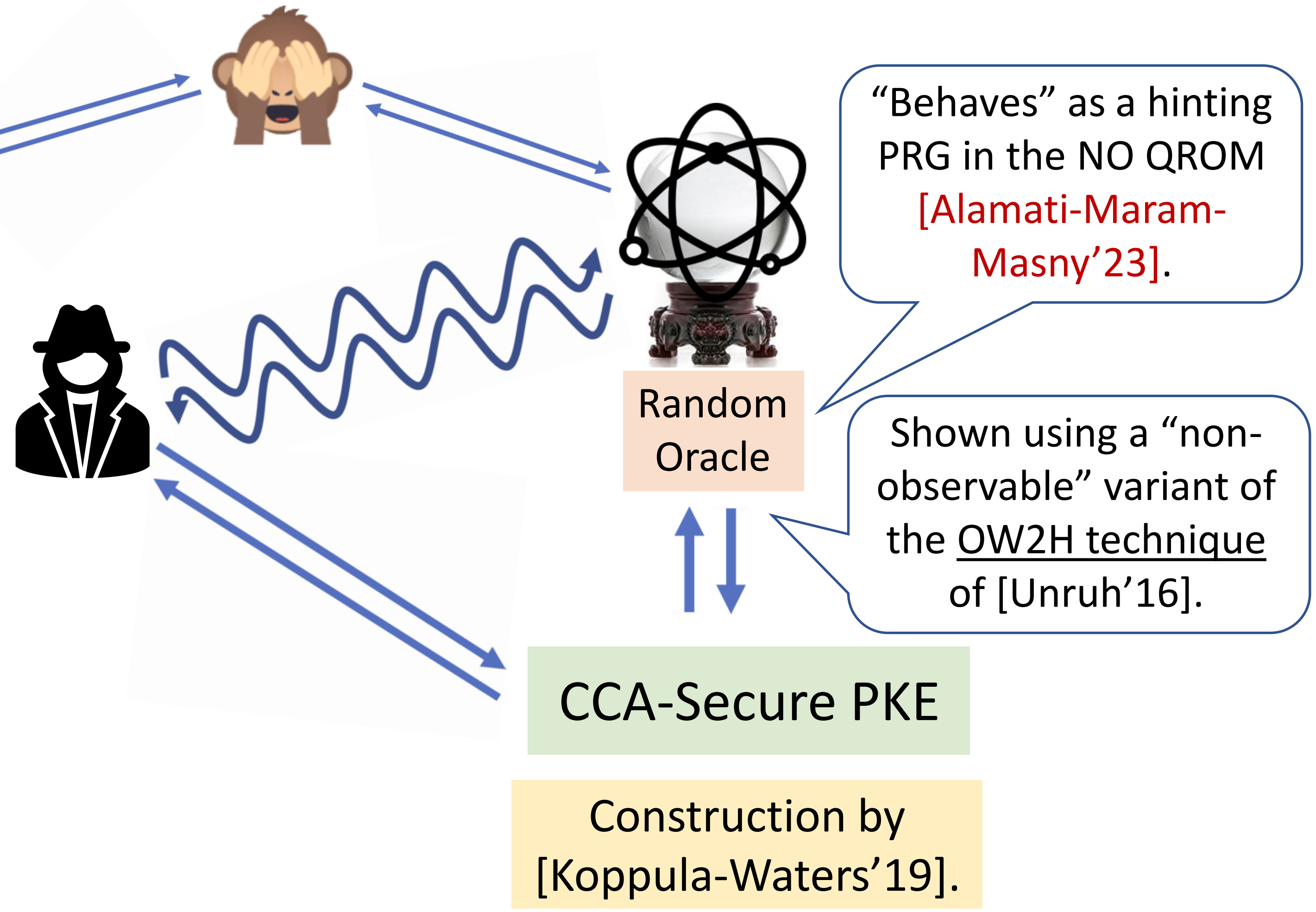

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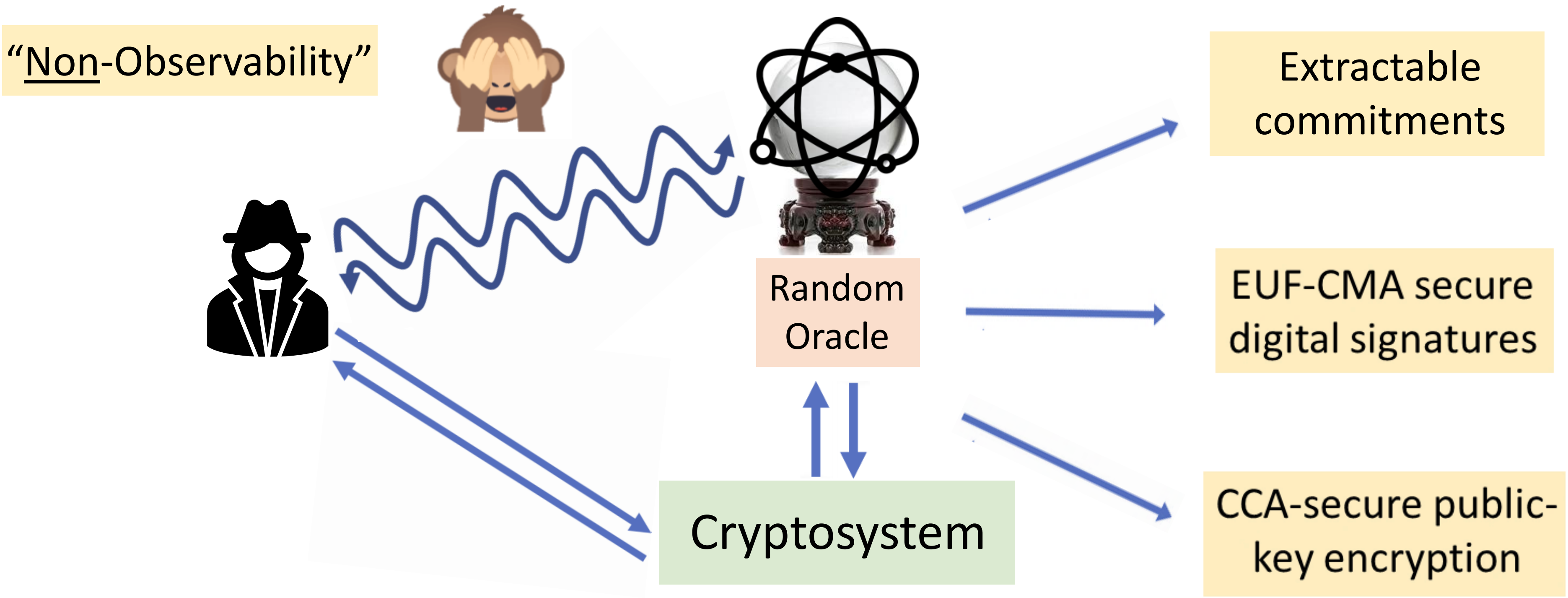

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