Hash functions in post-quantum cryptography

Christian Majenz
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QuSoft
Research Center for Quantum Software

CWI
Centrum Wiskunde & Informatica

Cryptography is everywhere

Cryptography is everywhere

https://

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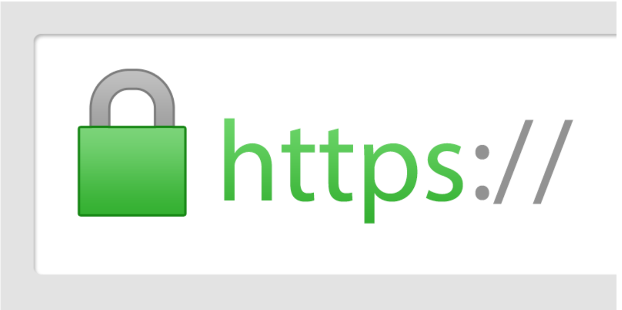

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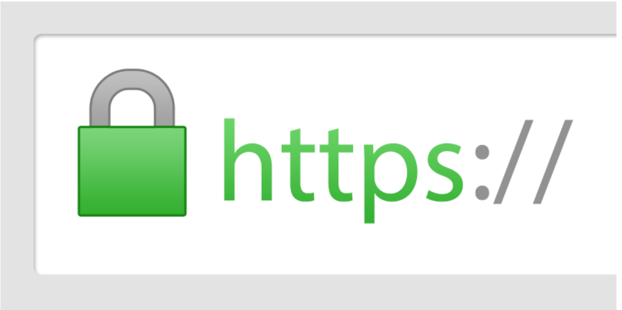

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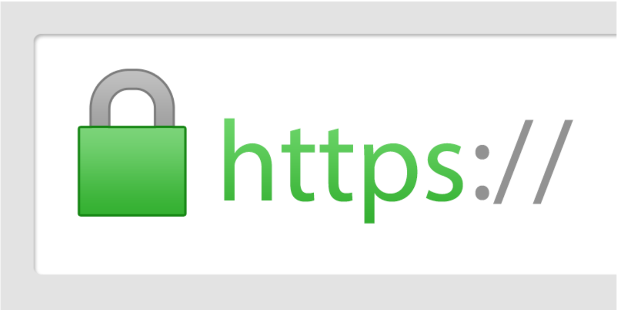

BITCOIN·DIGITAL·DECENTRALIZED·PEER TO PEER
MONETARY METALS
MJB COPPER 999 FINE 1 TROY OZ

Quantum computers

Quantum computers

- Accelerating effort to build a quantum computer

Quantum computers

- Accelerating effort to build a quantum computer
- Major investments:

Google
IBM
CHINESE ACADEMY OF SCIENCES
intel
Microsoft
QUANTUM
FLAGSHIP

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CHINESE ACADEMY OF SCIENCES

QUANTUM FLAGSHIP

We need to prepare cryptography for the arrival of quantum computers!

Quantum computers

- Accelerating effort to build a quantum computer
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CHINESE ACADEMY OF SCIENCES

intel Microsoft

QUANTUM FLAGSHIP

We need to prepare cryptography for the arrival of quantum computers!

- Security against quantum attackers

nationale wetenschaps agenda

- Quantum cryptography

Quantum computers

- Accelerating effort to build a quantum computer
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We need to prepare cryptography for the arrival of quantum computers!

- **This talk: Security against quantum attackers (post-quantum cryptography)**

Elements of post-quantum crypto

Elements of post-quantum crypto

- Quantum Cryptanalysis

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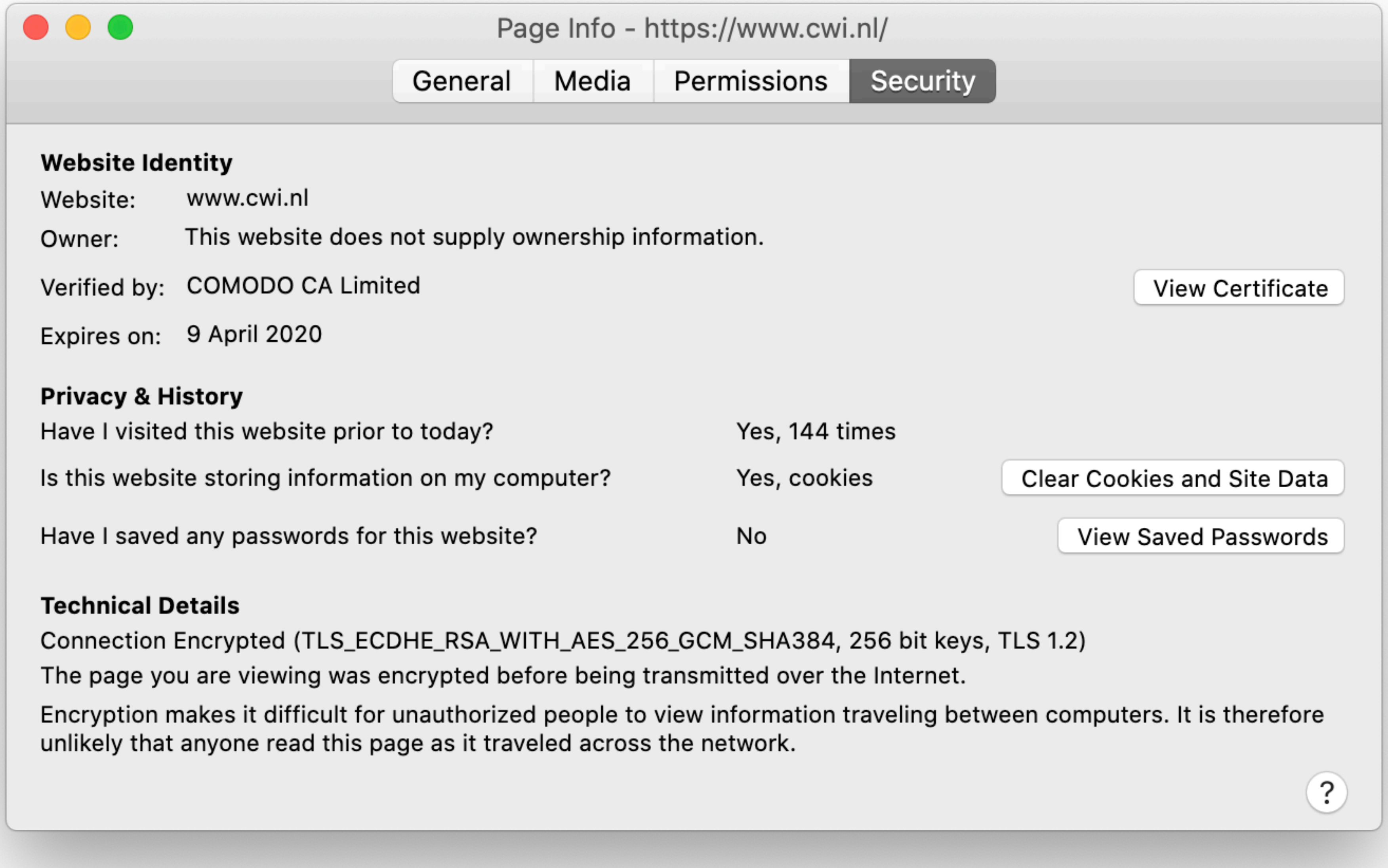

Website Identity

Website:	www.cwi.nl
Owner:	This website does not supply ownership information.
Verified by:	COMODO CA Limited
Expires on:	9 April 2020

Privacy & History

Have I visited this website prior to today?	Yes, 144 times
Is this website storing information on my computer?	Yes, cookies
Have I saved any passwords for this website?	No

Technical Details

Connection Encrypted (TLS_ECDHE_RSA_WITH_AES_256_GCM_SHA384, 256 bit keys, TLS 1.2)

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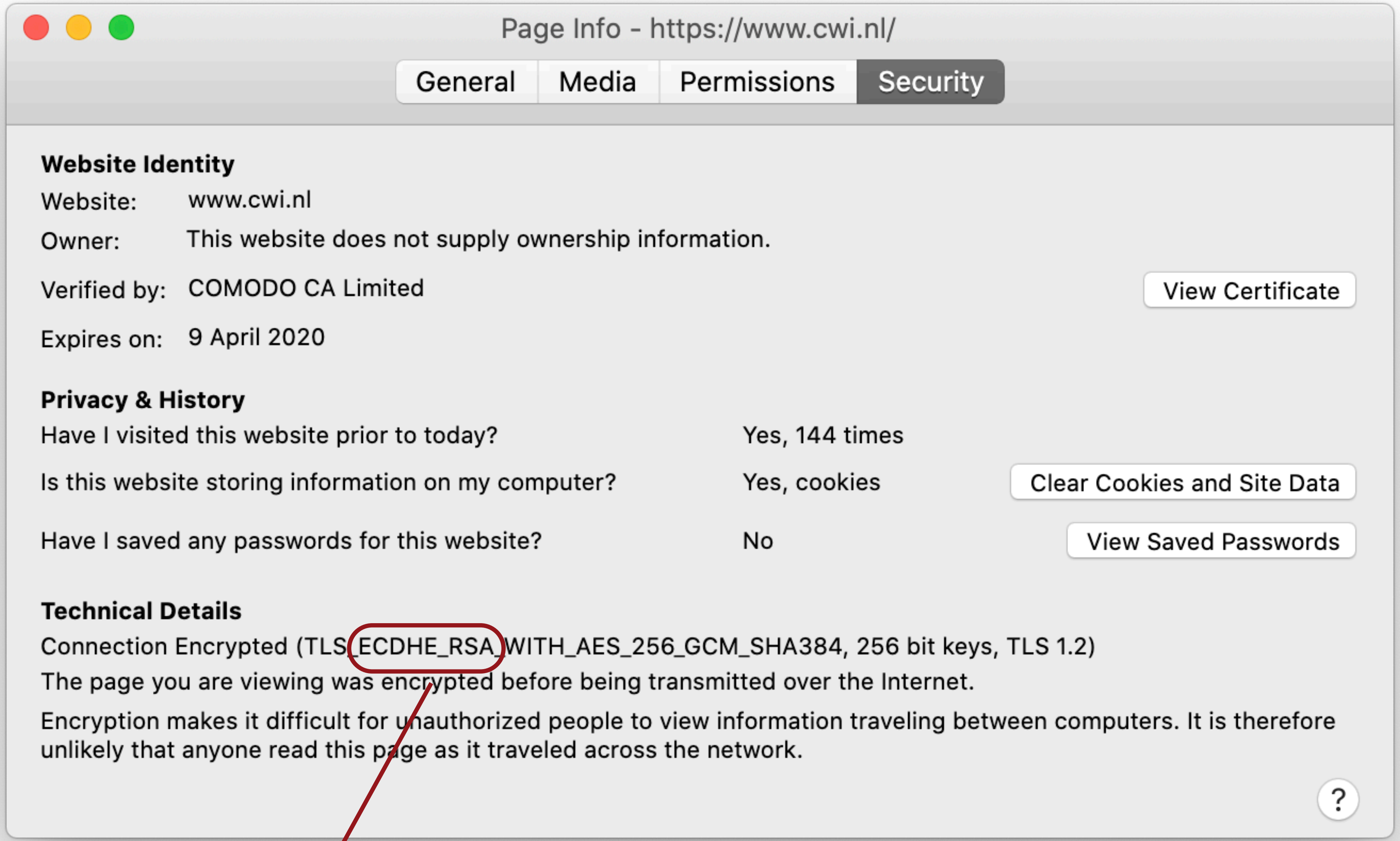
Elements of post-quantum crypto

- Quantum Cryptanalysis



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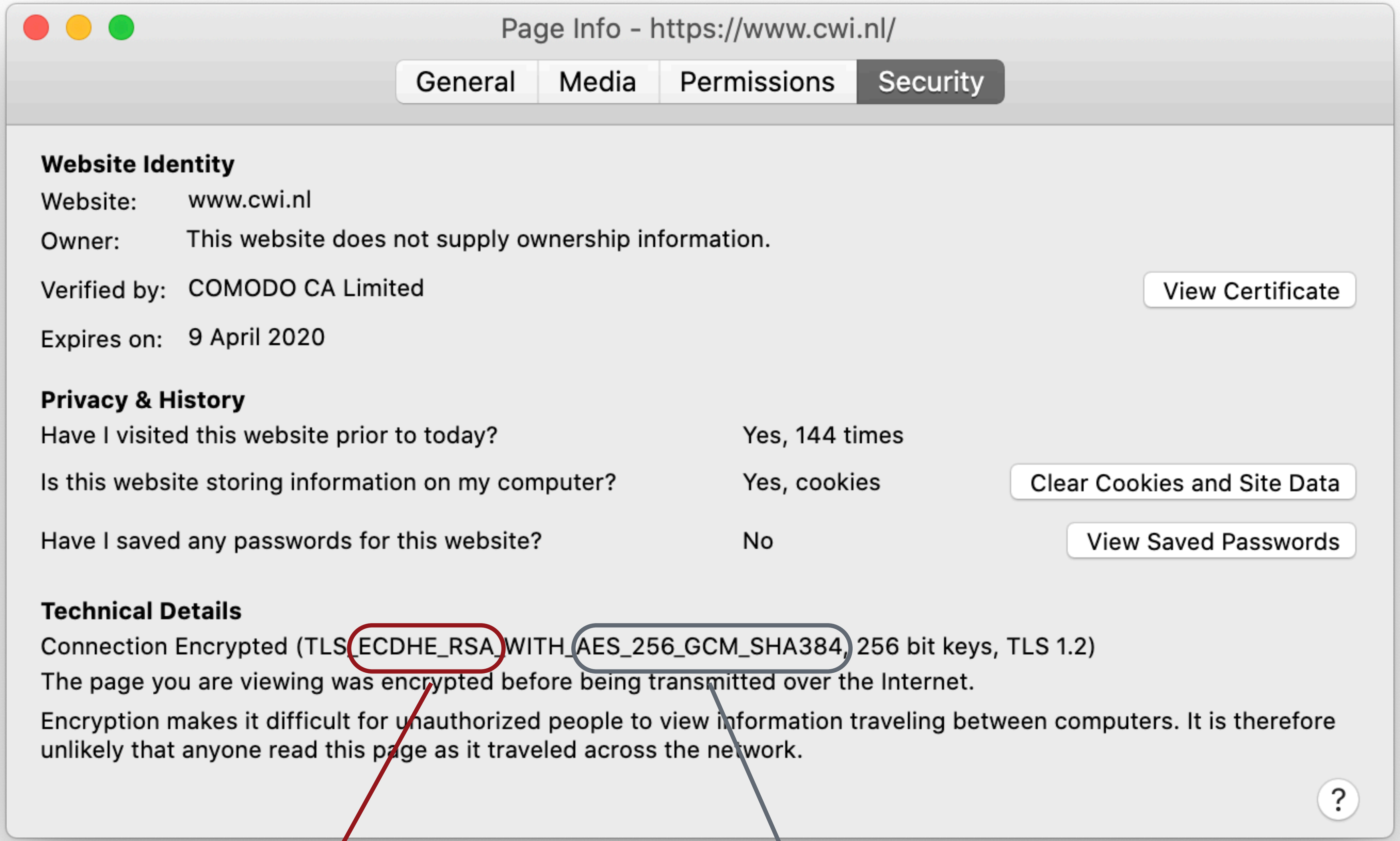
Shor's algorithm:
Complete break

Elements of post-quantum crypto

- Quantum Cryptanalysis



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Shor's algorithm:
Complete break

Grover's algorithm:
Might necessitate increased key lengh

Elements of post-quantum crypto

- Quantum Cryptanalysis: Shor, Grover

- Quantum-secure computational assumptions
  - Lattice problems
  - Decoding random codes
  - Inverting multivariate polynomials
  - Secure hash functions
  - Supersingular isogeny Diffie-Hellman

Elements of post-quantum crypto

- Quantum Cryptanalysis: Shor, Grover

- Quantum-secure computational assumptions
    - Lattice problems
    - Decoding random codes
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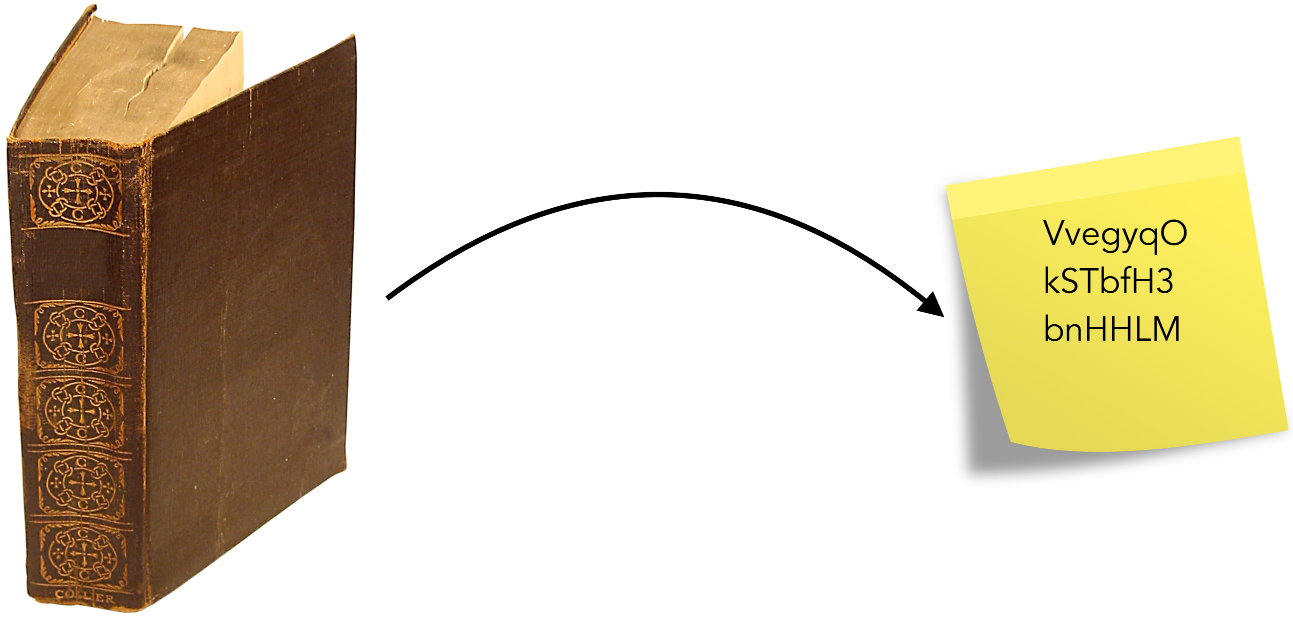
    - Secure hash functions
    - Supersingular isogeny Diffie-Hellman

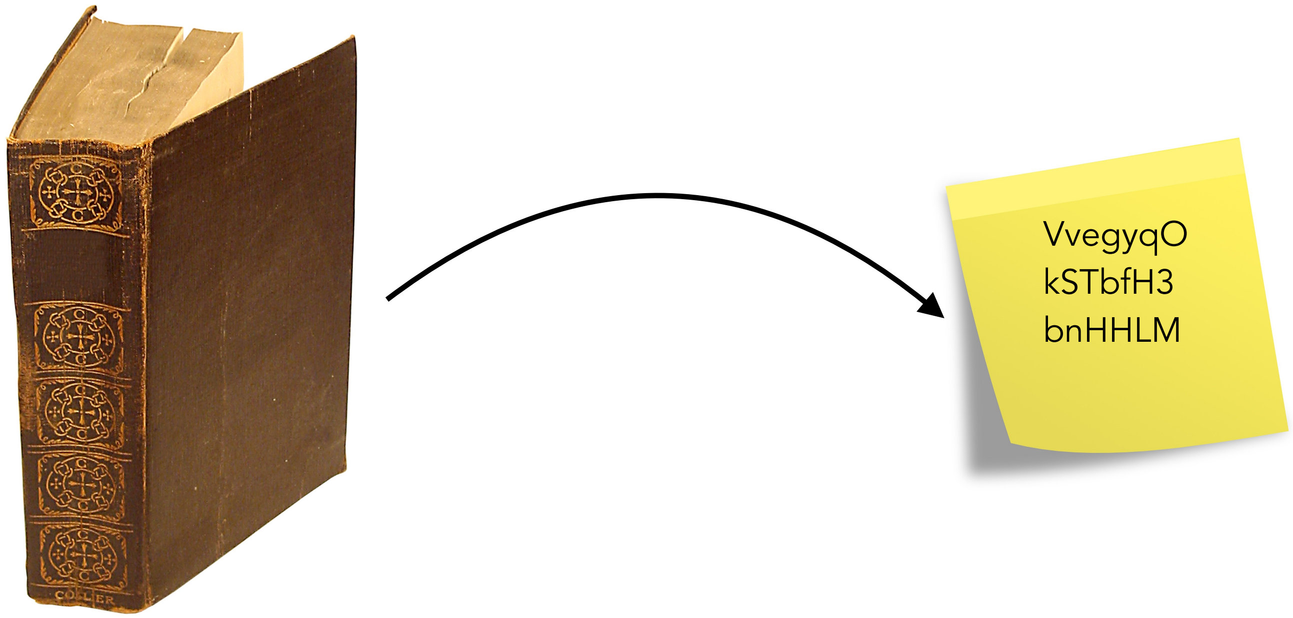
- Models: Quantum Random Oracle Model (QROM)

Hash functions



VvegyqO
kSTbfH3
bnHHLM

Hash functions



Ubiquitous in cryptography. Example: digital signatures

The (Q)ROM

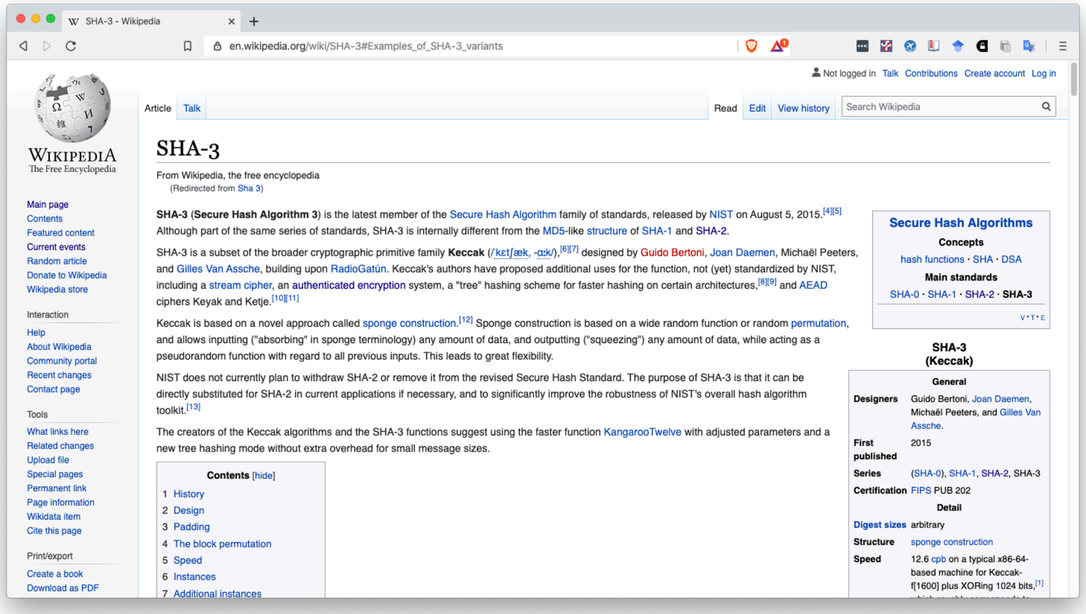
The (Q)ROM

Reality

Model

The (Q)ROM

Reality



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NIST does not currently plan to withdraw SHA-2 or remove it from the revised Secure Hash Standard. The purpose of SHA-3 is that it can be directly substituted for SHA-2 in current applications if necessary, and to significantly improve the robustness of NIST's overall hash algorithm toolkit.[13]

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V · T · E

SHA-3
(Keccak)

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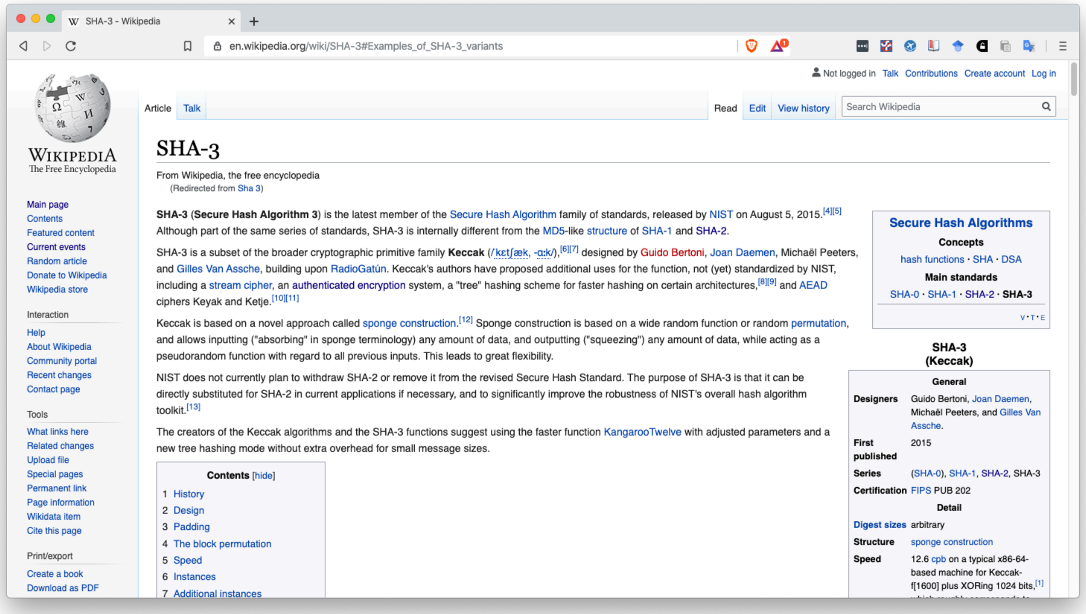
Designers	Guido Bertoni, Joan Daemen, Michaël Peeters, and Gilles Van Assche.
First published	2015
Series	(SHA-0), SHA-1, SHA-2, SHA-3
Certification	FIPS PUB 202
Detail	
Digest sizes	arbitrary
Structure	sponge construction
Speed	12.6 cpb on a typical x86-64-based machine for Keccak-f[1600] plus XORing 1024 bits,[1]

Model

The (Q)ROM

Reality



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Uniformly random

The (Q)ROM

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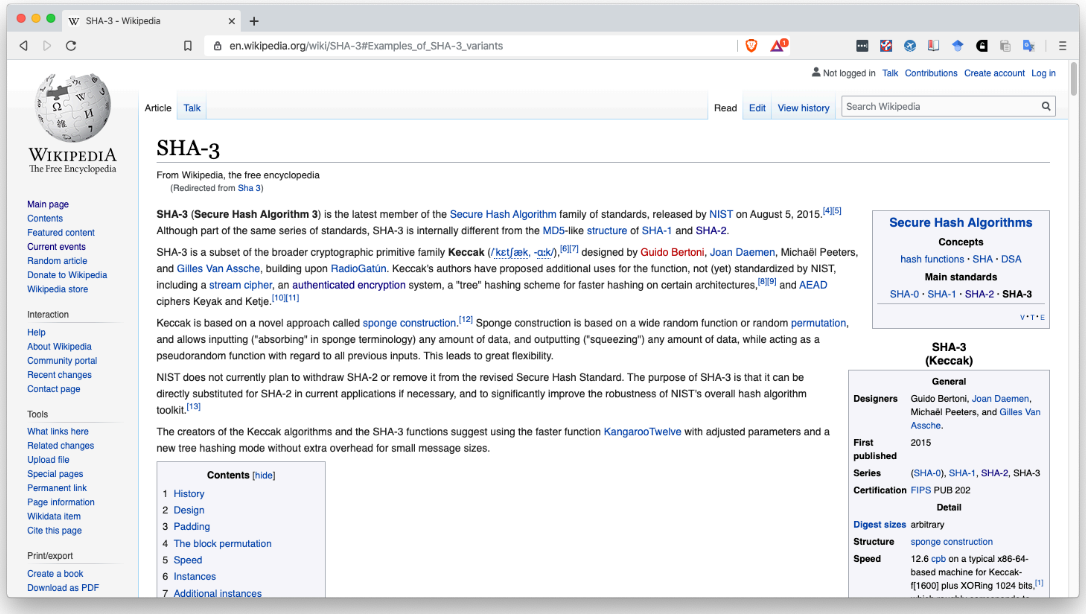

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All agents have (quantum) oracle access to H

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The (Q)ROM

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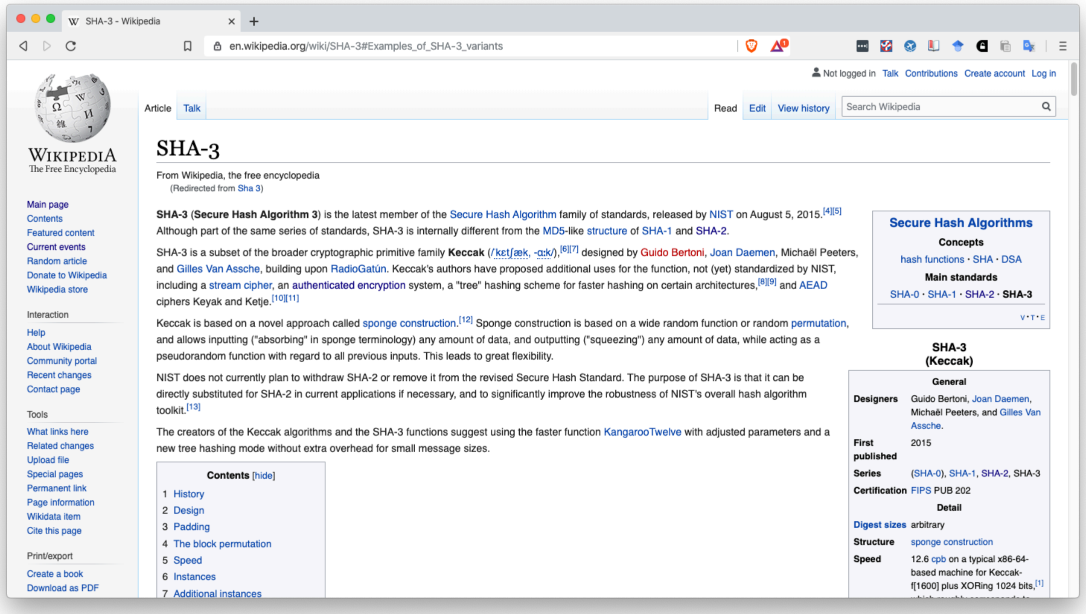

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- Outrageosly optimistic

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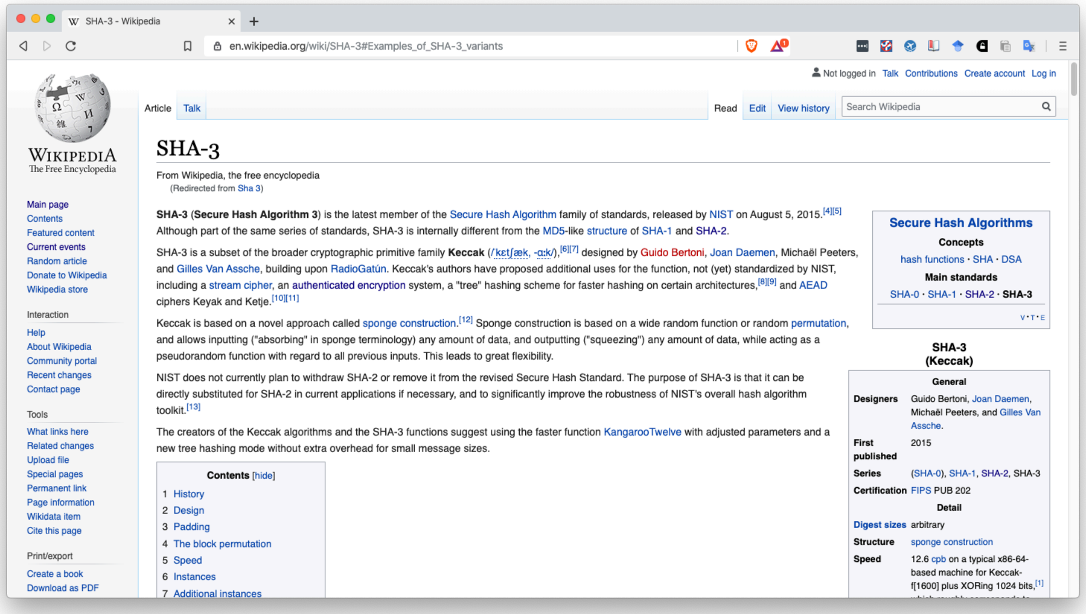

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- Outrageosly optimistic
- Seems to work in practice

Model

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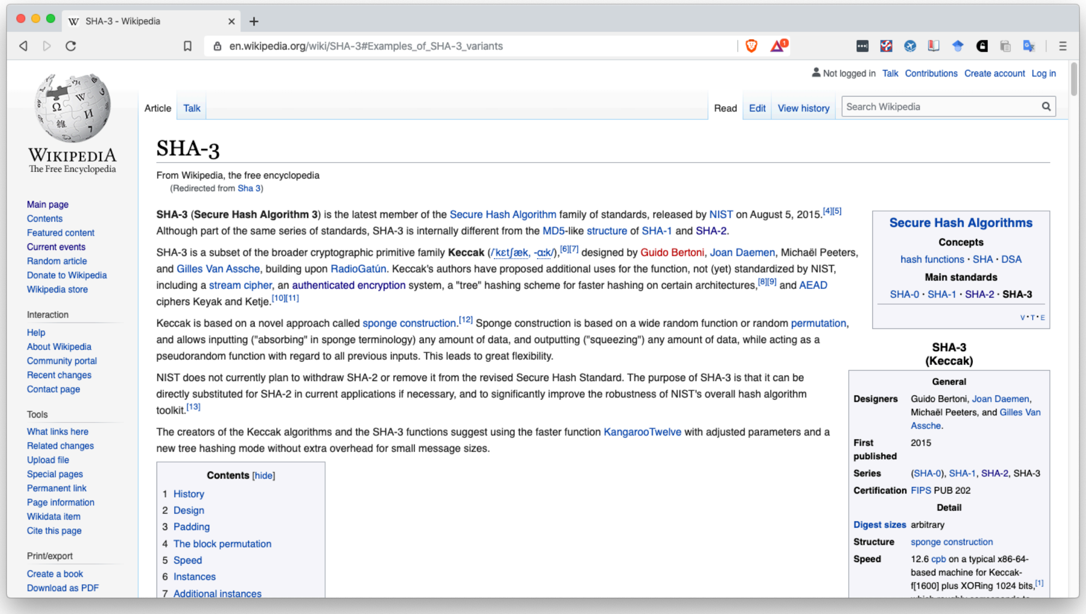

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$H : \{0,1\}^* \to \{0,1\}^n$

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All agents have (quantum) oracle access to H

$$(x, y) \mapsto (x, y \oplus H(x))$$

- Outrageosly optimistic
- Seems to work in practice
- Enables very efficient crypto

QROM challenges

QROM challenges

ROM techniques:

1. Query transcripts

QROM challenges

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2. ~~Rewinding~~ $\Longrightarrow$ 3 specialized rewinding techniques that don't cover all applications

QROM challenges

ROM techniques:

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2. Rewinding
3. Reprogramming

Quantum theory makes things difficult! No-cloning, Measurement disturbance

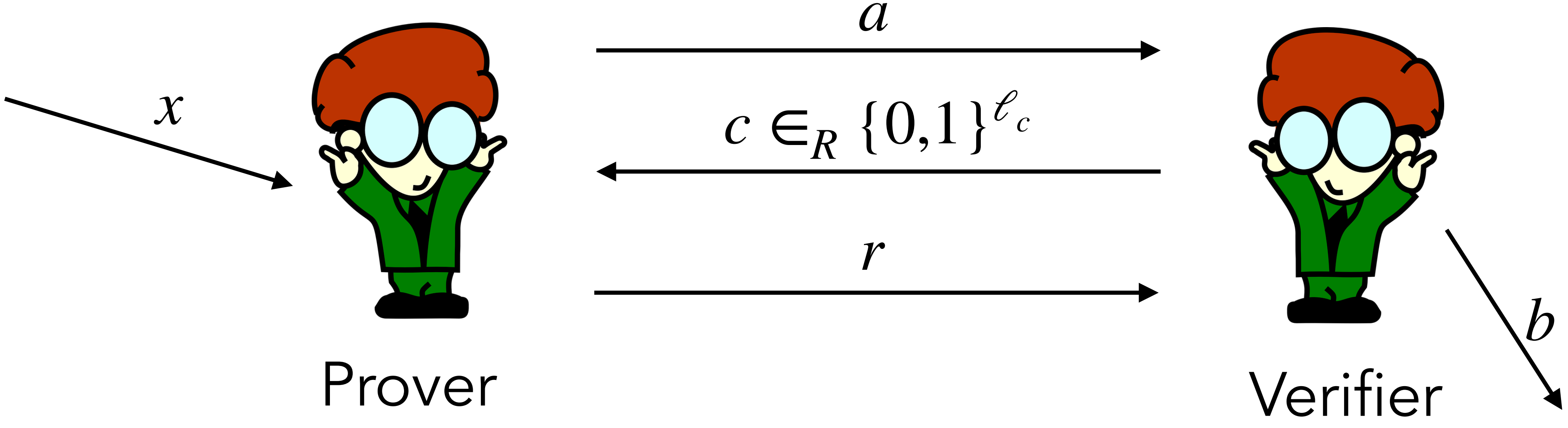
QROM:

1. ~~Query transcripts~~
2. ~~Rewinding~~ $\Longrightarrow$ 3 specialized rewinding techniques that don't cover all applications
3. Reprogramming: Sure, if you know how without 1. and 2.

The Fiat Shamir transformation

The Fiat Shamir transformation

Σ-protocol: Interactive proof system



x

a

$c \in_R \{0,1\}^{\ell_c}$

r

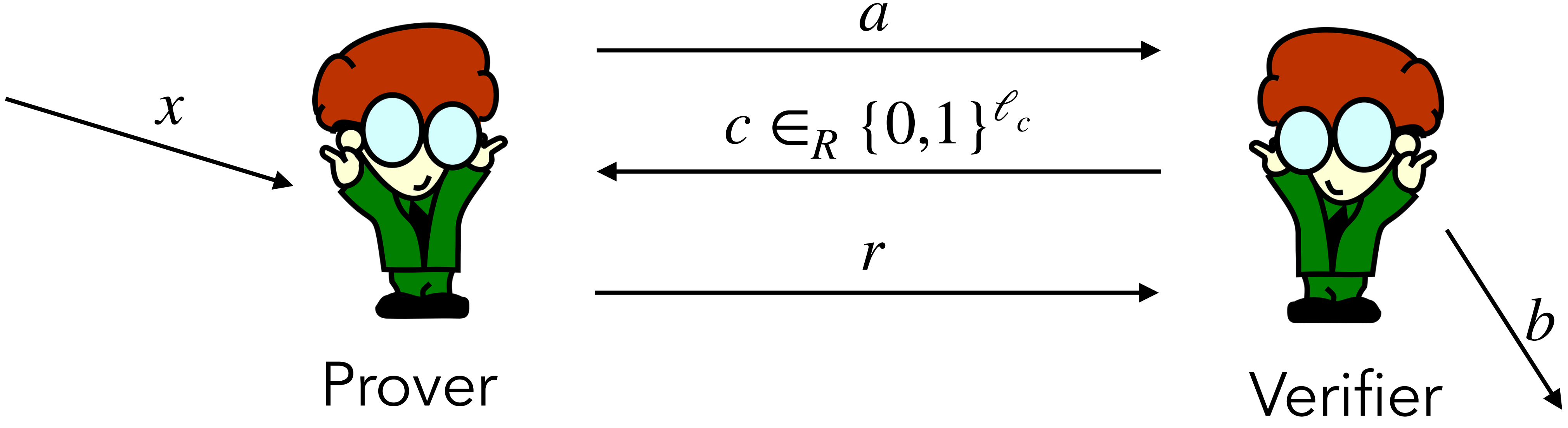
b

Prover

Verifier

The Fiat Shamir transformation

Σ-protocol: Interactive proof system



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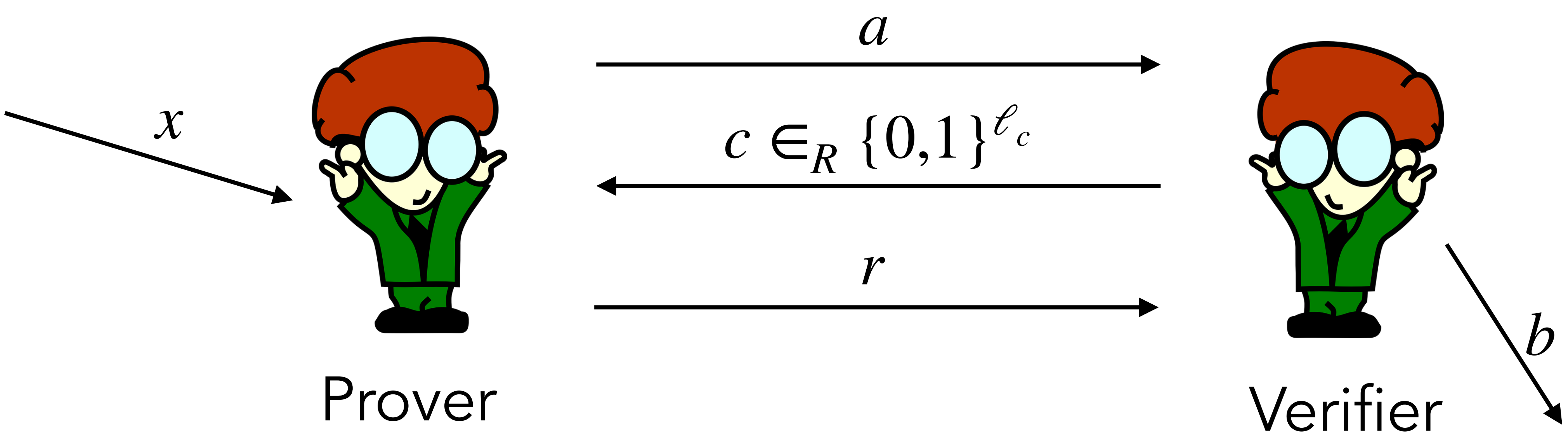
Fiat Shamir (FS) transformation: $c = H(x, a)$

The Fiat Shamir transformation

Σ-protocol: Interactive proof system



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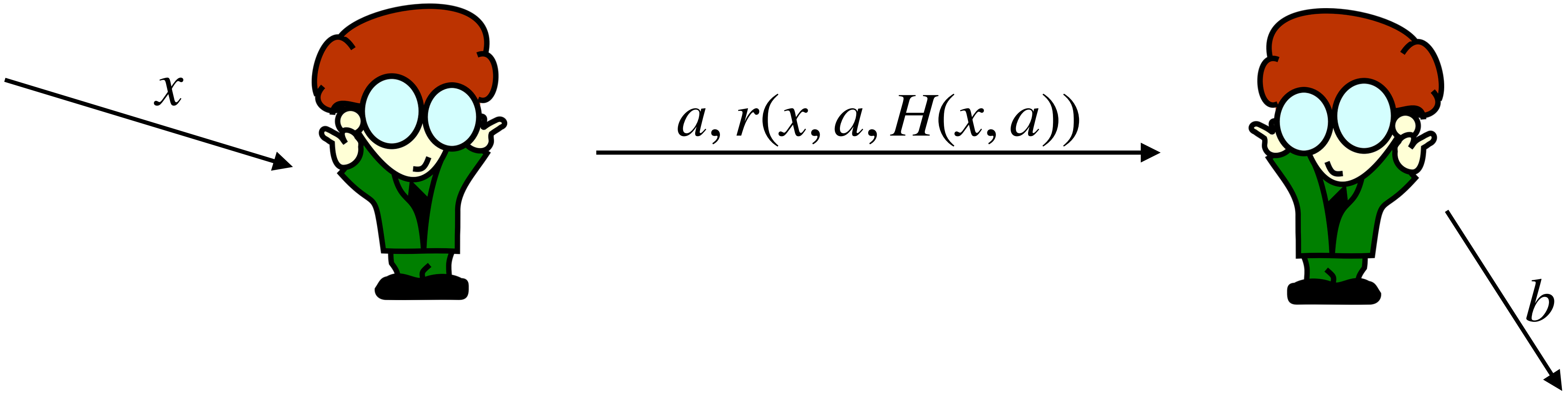


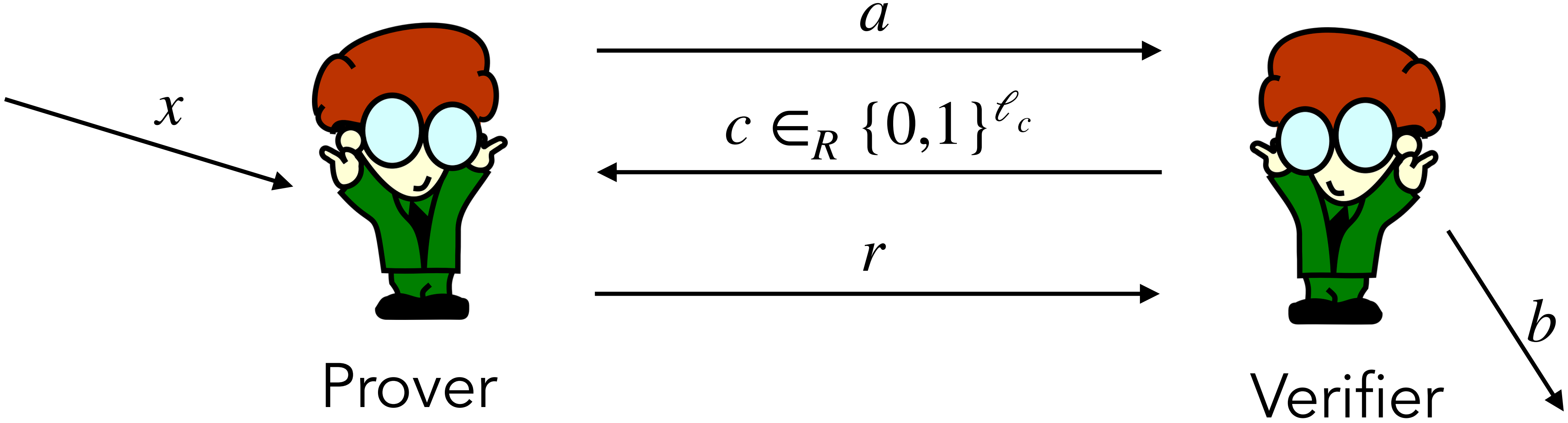
x

$a, r(x, a, H(x, a))$

b

The Fiat Shamir transformation

Σ-protocol: Interactive proof system



x

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r

b

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Verifier

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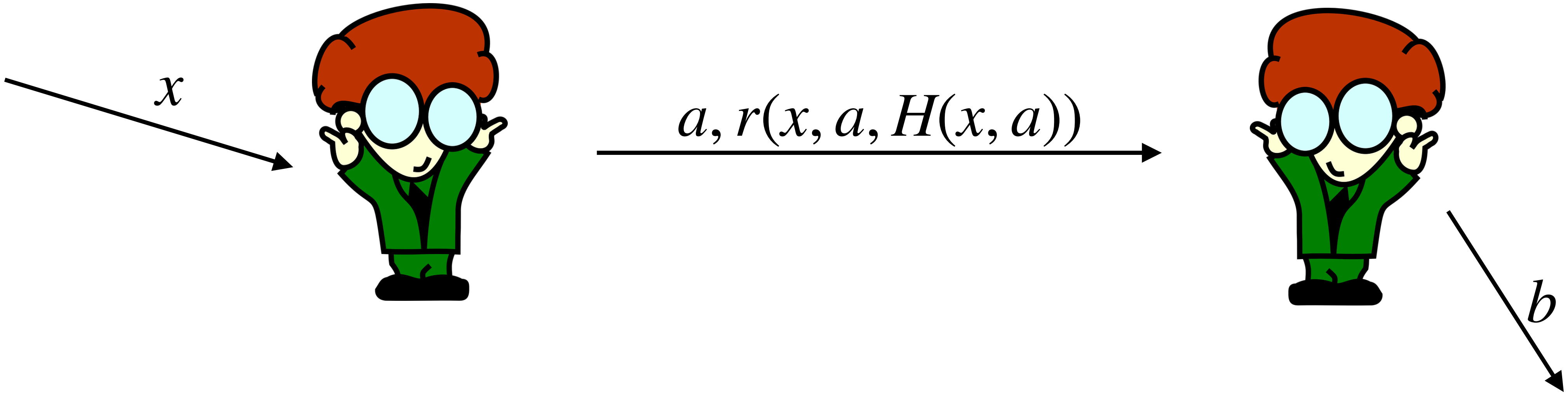


x

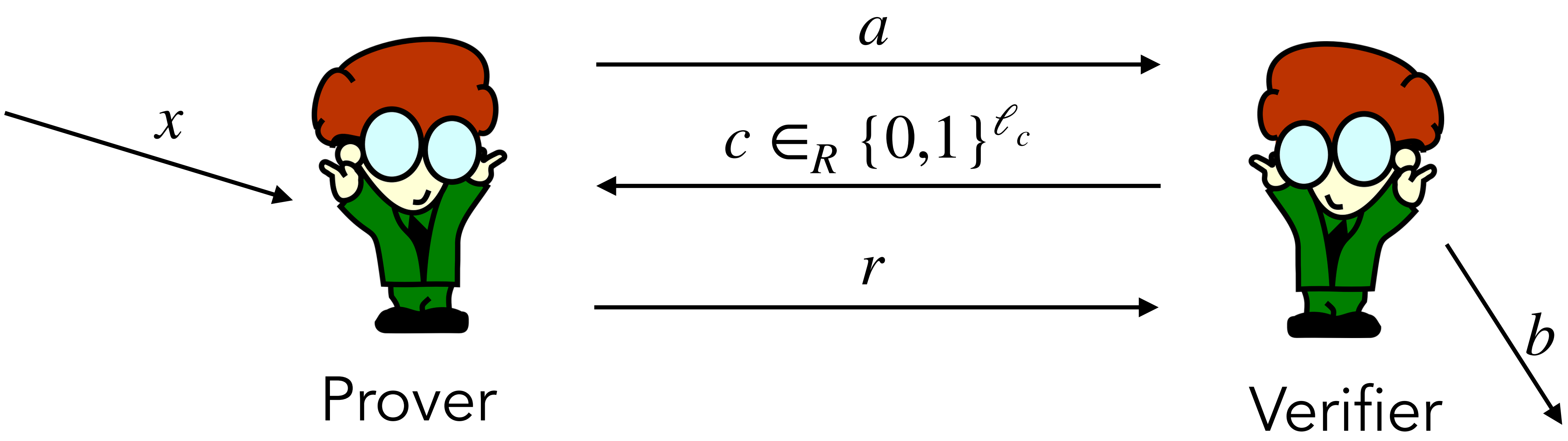
$a, r(x, a, H(x, a))$

b

non-interactive!!!

The Fiat Shamir transformation

Σ-protocol: Interactive proof system



x

a

$c \in_R \{0,1\}^{\ell_c}$

r

b

Prover

Verifier

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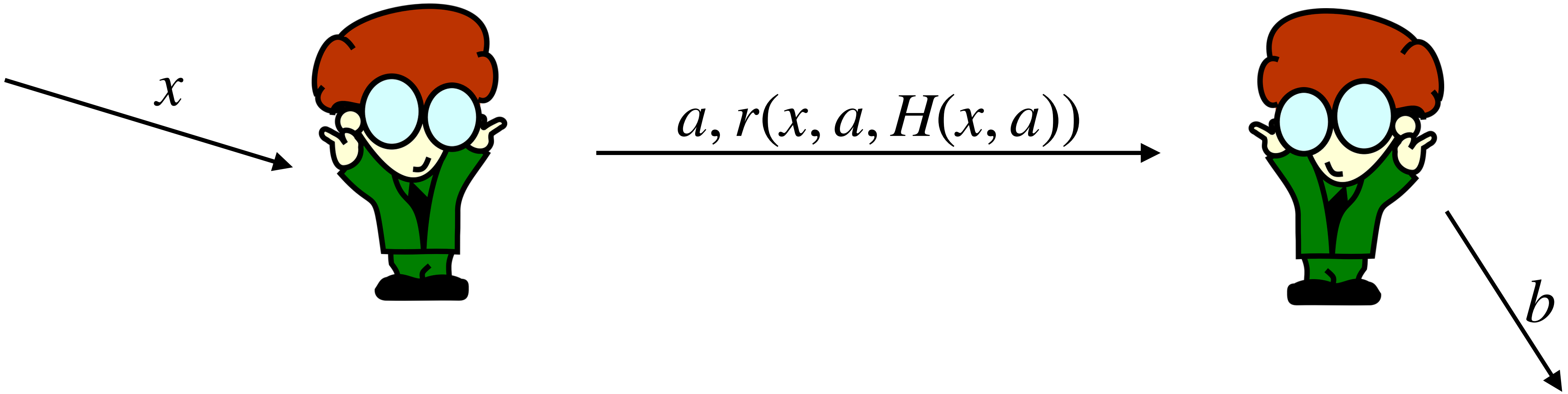

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non-interactive!!! ⟹used for efficient digital signatures

ROM security

The FS transformation is secure in the ROM (Pointcheval, Stern 96):

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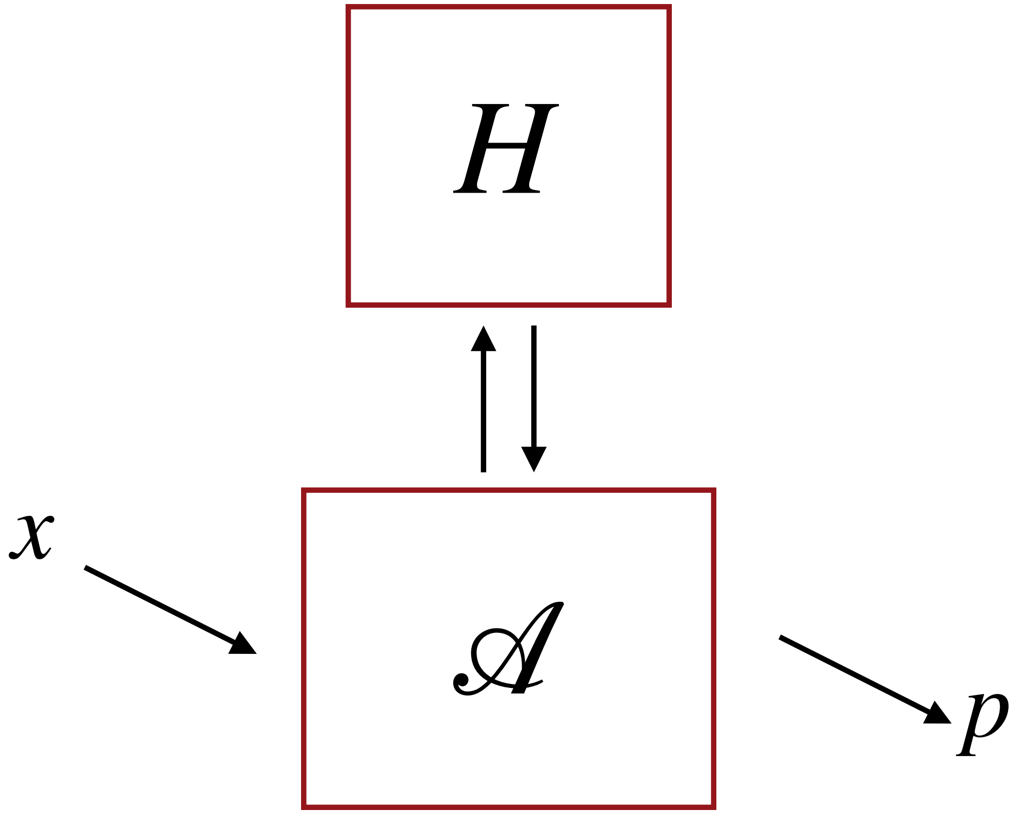

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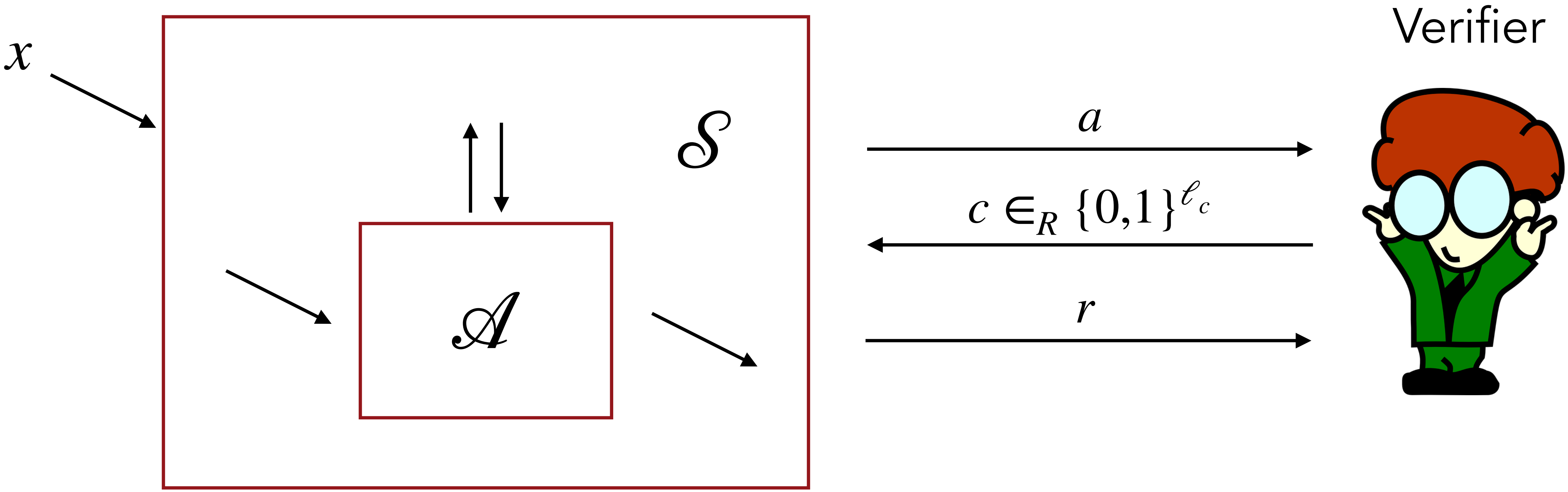

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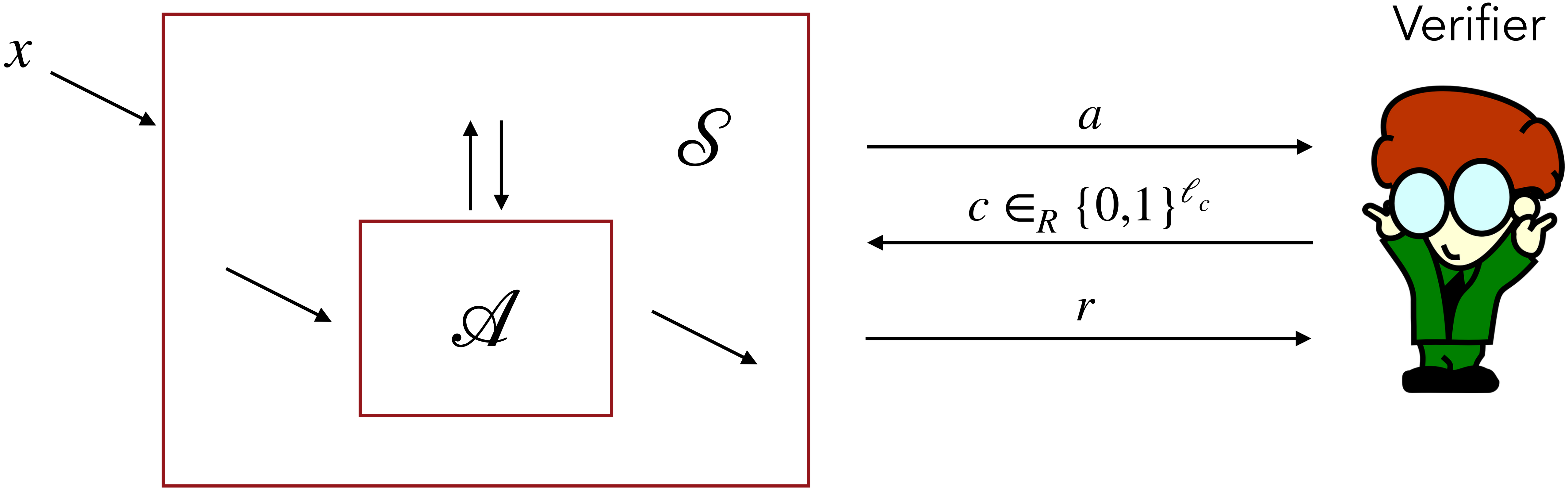

Success probability: $\varepsilon(\mathscr{S}[\mathscr{A}]) \geq \dfrac{\varepsilon(\mathscr{A})}{O(q)}$

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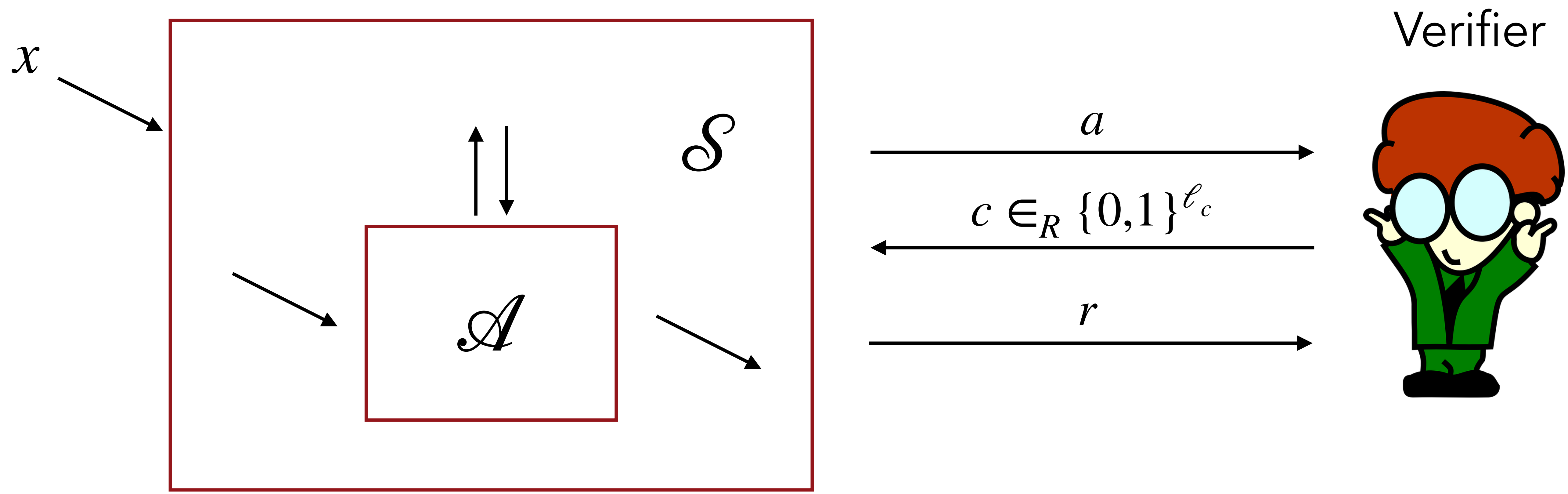

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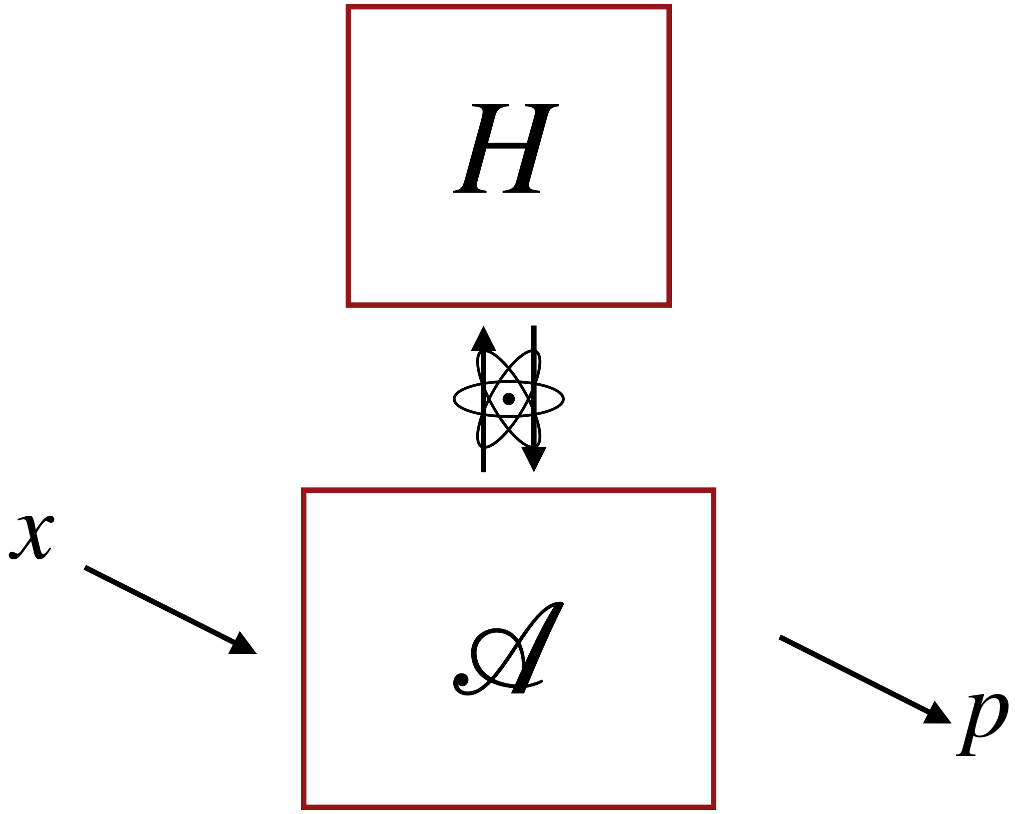
# of queries $\mathcal{A}$ makes to H

QROM security

The FS transformation is secure in the QROM (Don, Fehr, M, Schaffner ’19):



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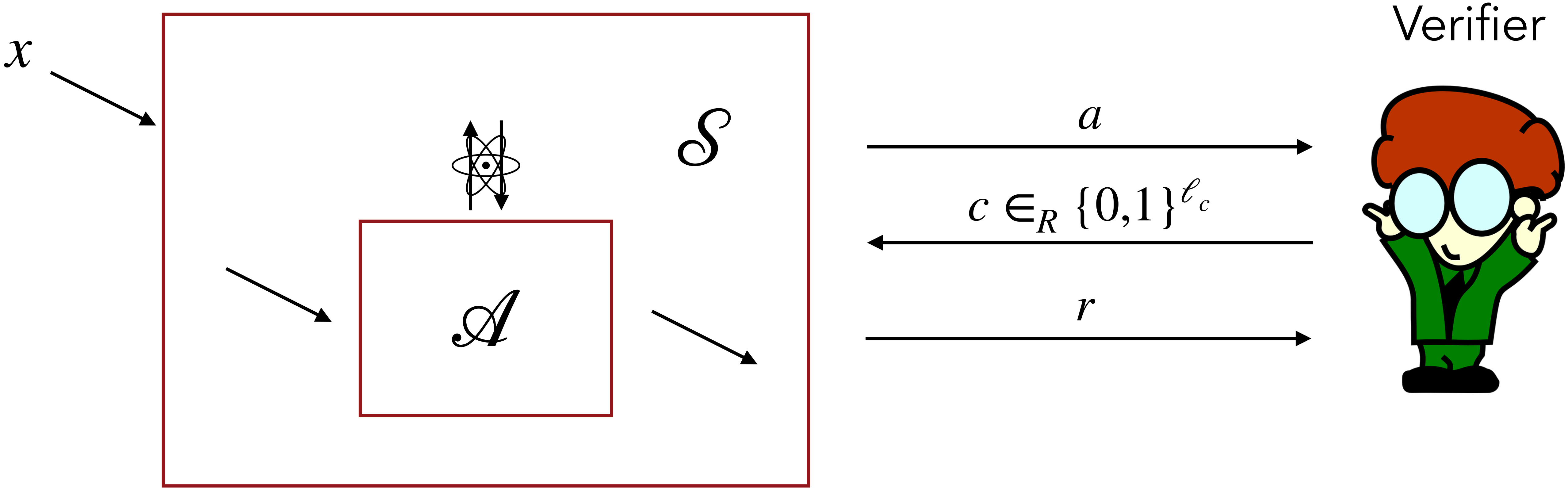

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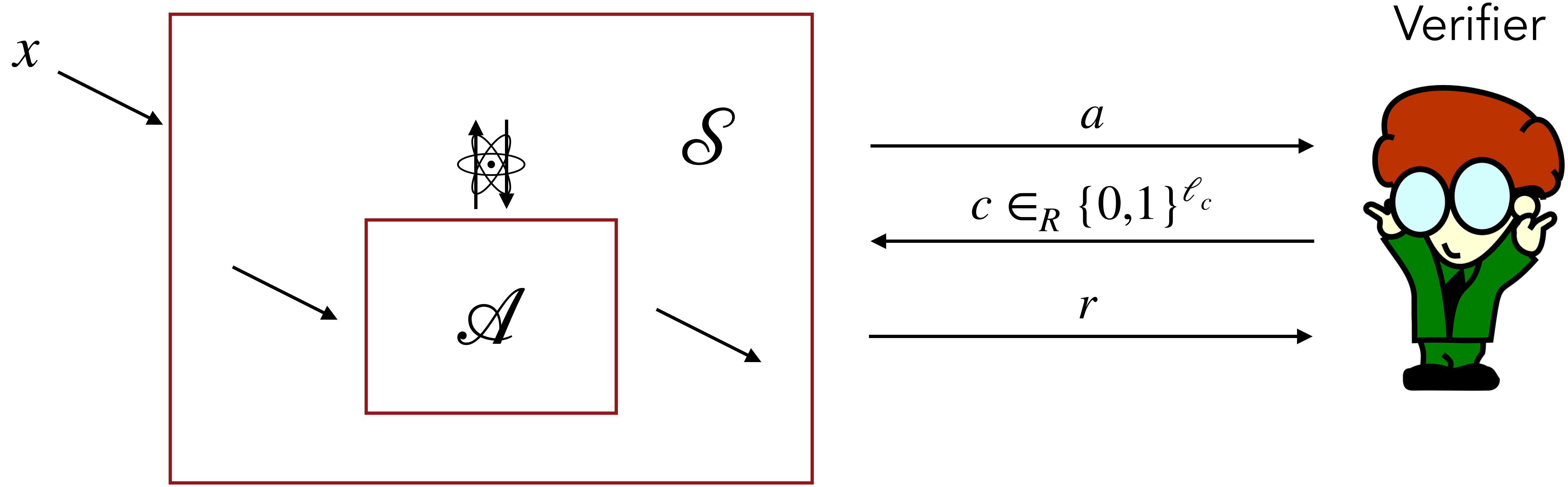
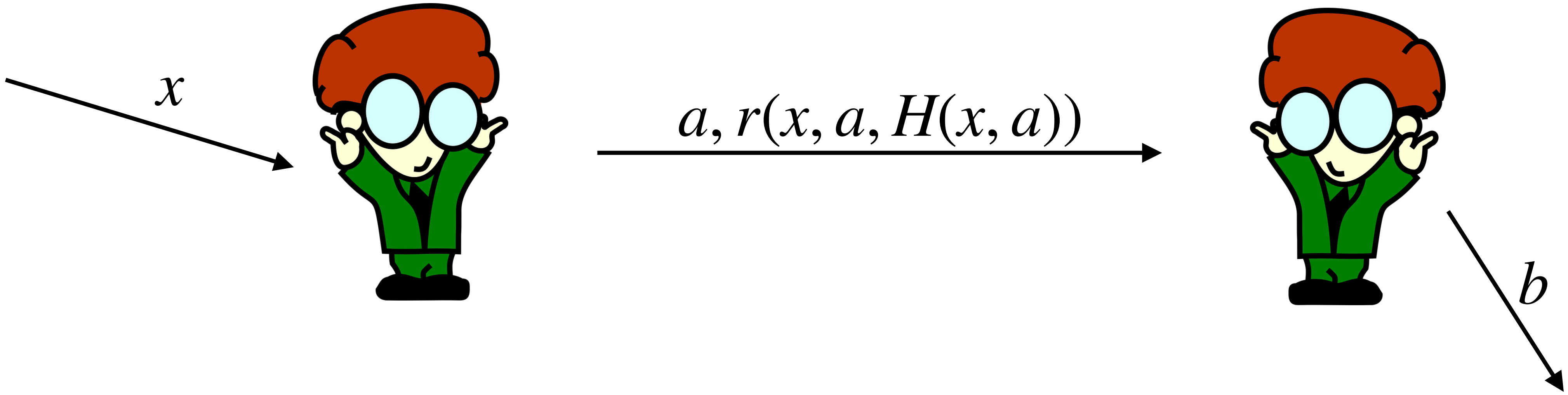


Success probability: $\varepsilon(\mathscr{S}[\mathscr{A}]) \geq \dfrac{\varepsilon(\mathscr{A})}{O(q^2)}$

Technique



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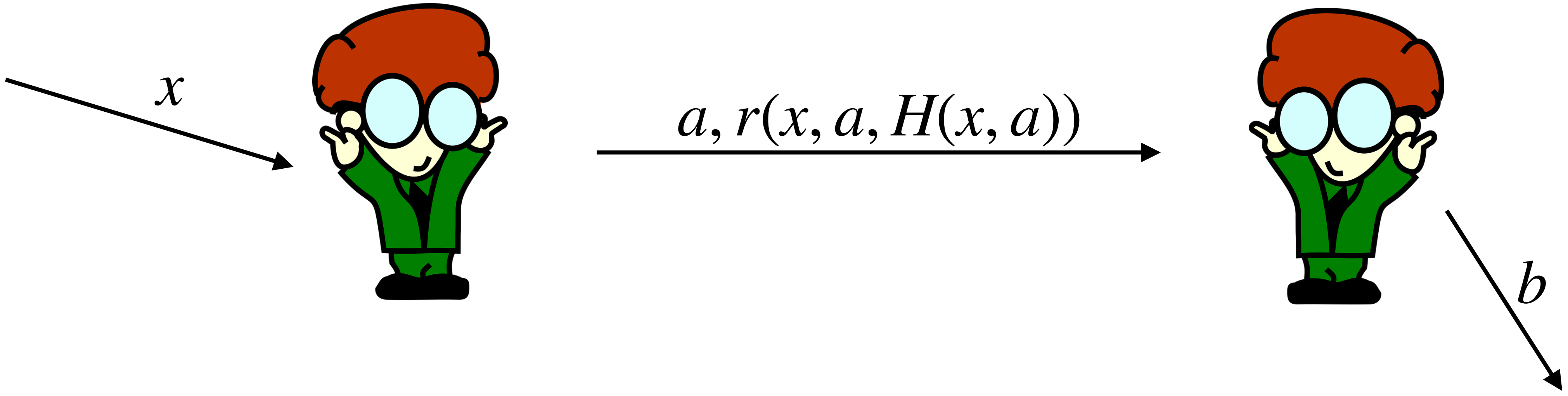

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Suppose r was injective $\implies$ $\mathscr{A}$ essentially needs to classically query H on (x, a).

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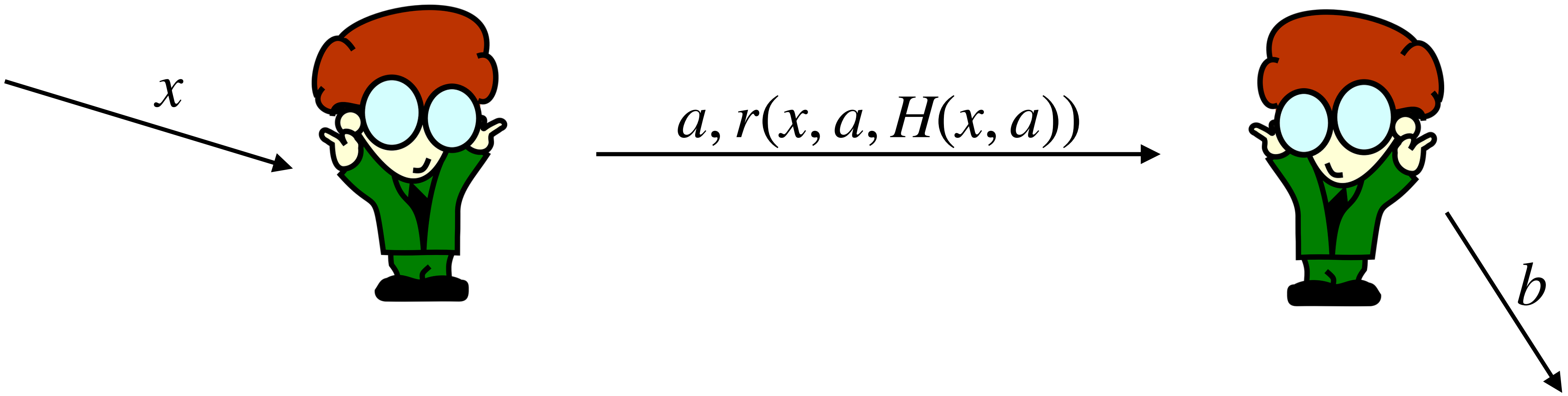

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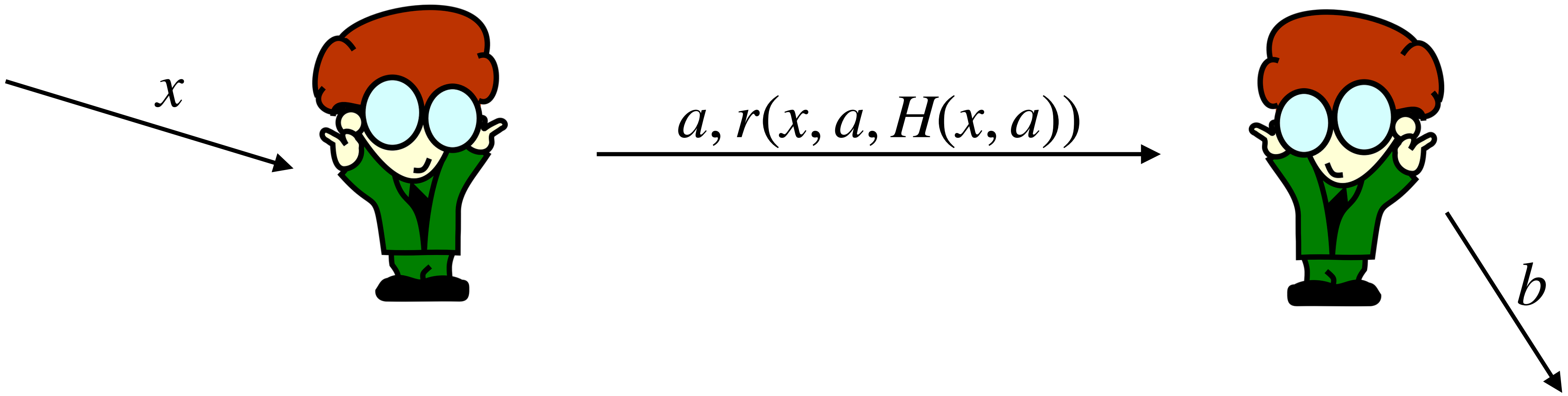

Suppose r was injective $\Longrightarrow$ $\mathscr{A}$ essentially needs to classically query H on (x, a).

Measure-and-Reprogram: Pick a random query, measure it and reprogram with c from the Σ-protocol.

Long term goal

Popular belief about QROM: Grover speed-up is as good as it gets.

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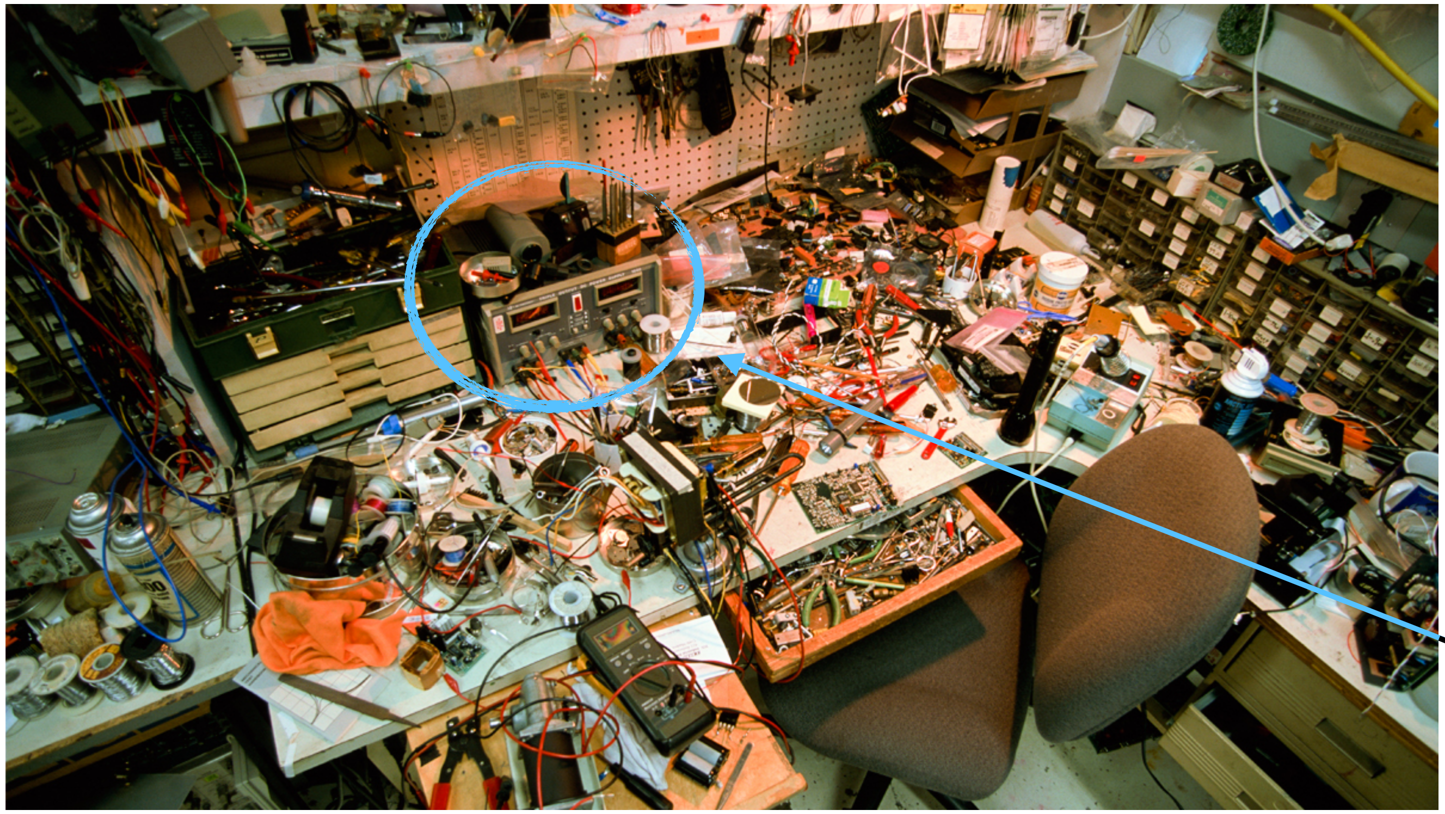

QROM security of FS

Summary

- The (Q)ROM is extremely useful for efficient cryptography
- Quantum theory complicates things, much less coherent picture of QROM security
- Important cases solved, e.g. Fiat Shamir
- General reduction from QROM to ROM would be nice to have!