On Attacking Hash functions in Cryptographic schemes

Workshop "Quantum cryptanalysis of post-quantum cryptography"
Simons institute for the Theory of Computing

Christian Majenz

CWI
Centrum Wiskunde & Informatica

QuSoft
Research Center for Quantum Software

Hash functions…

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…are everywhere in cryptography.

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- Commitments
- Noninteractive zero knowledge
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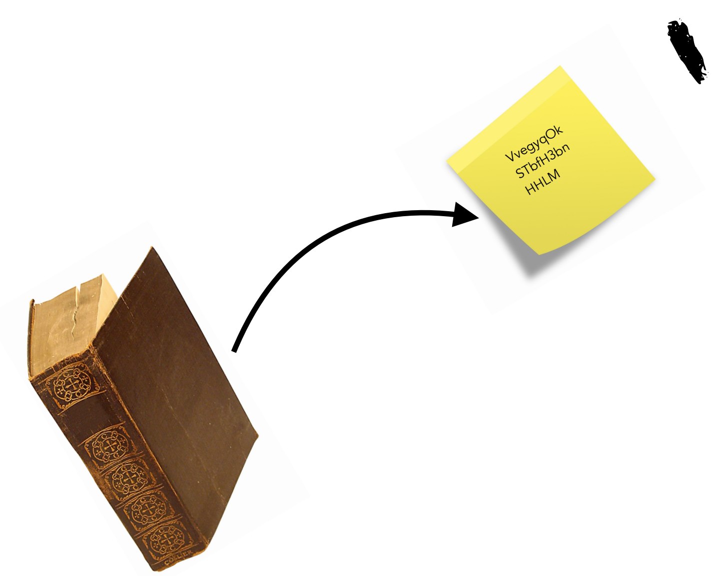
Outline

1. Intro: Hash functions
    i. Basics, security
    ii. The (quantum) random oracle model
    iii. Domain extension
2. Points of attack
3. Hash-function-based generic transformations: Fiat-Shamir and Fujisaki-Okamoto
4. Attacks and attack approaches against Fiat-Shamir and Fujisaki-Okamoto

Intro: Hash functions

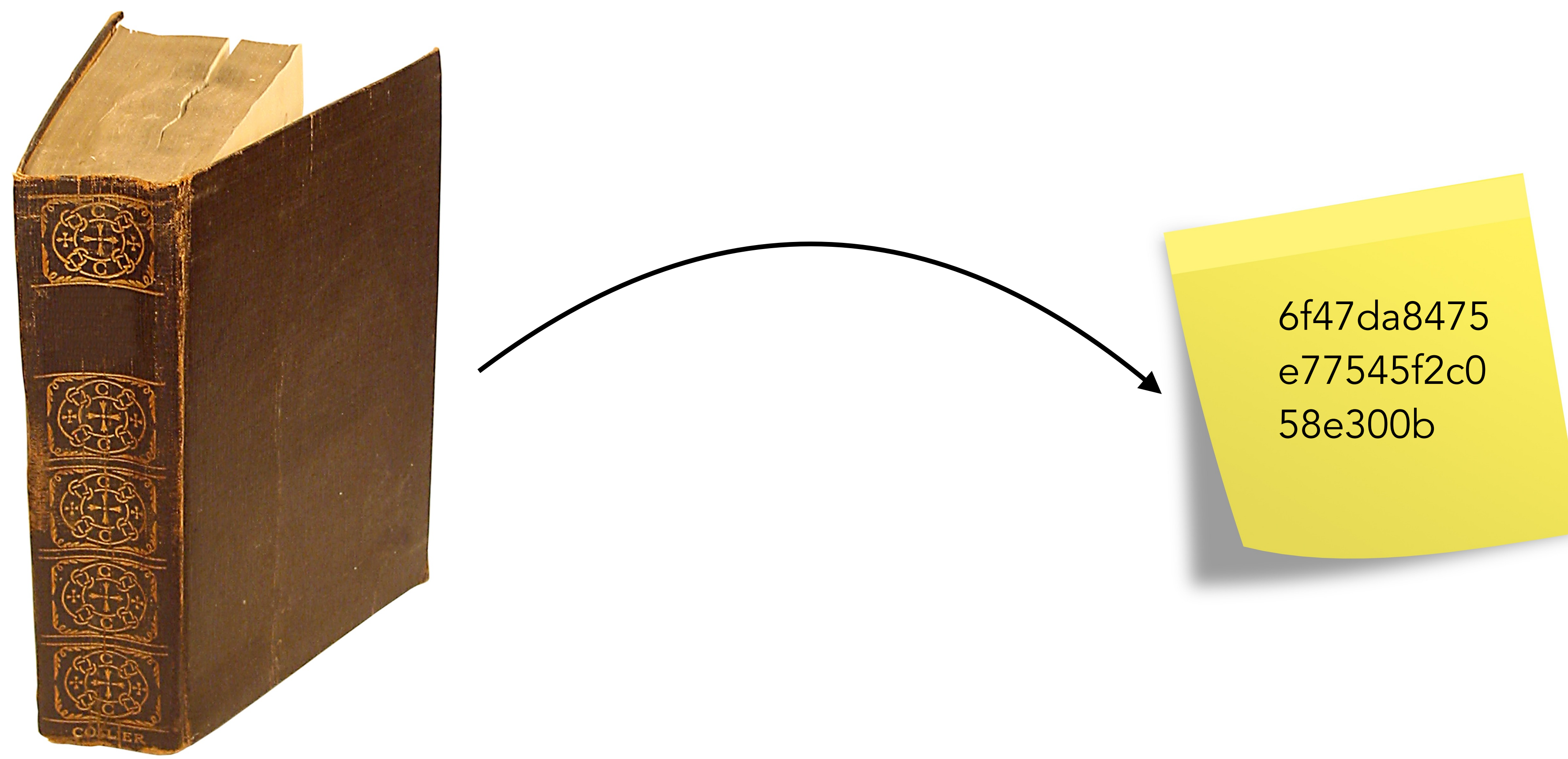
#cryptoisawesome?

What is a hash function?



Hash functions

Definition: Function (family) $H : \{0,1\}^* \rightarrow \{0,1\}^n$



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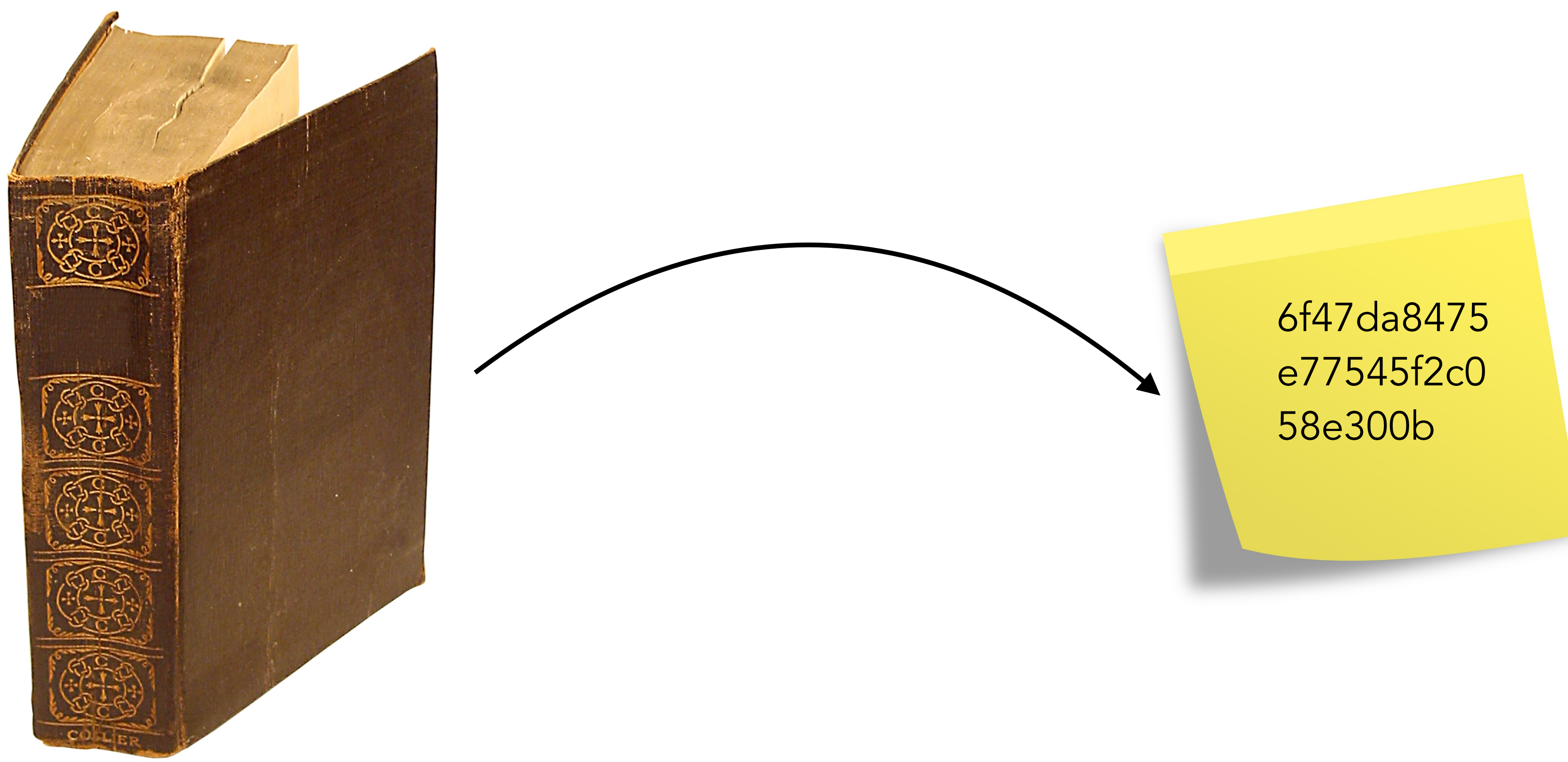
Defining intuition: Hash functions "look random"



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- Collision resistance
- Collapsingness
- Correlation intractability
- Bernoulli preservingness
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$\Longrightarrow$(Quantum) Random Oracle Model

Example application: Hash-and-sign

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Alice

Bob

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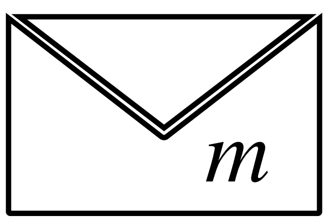

Bob

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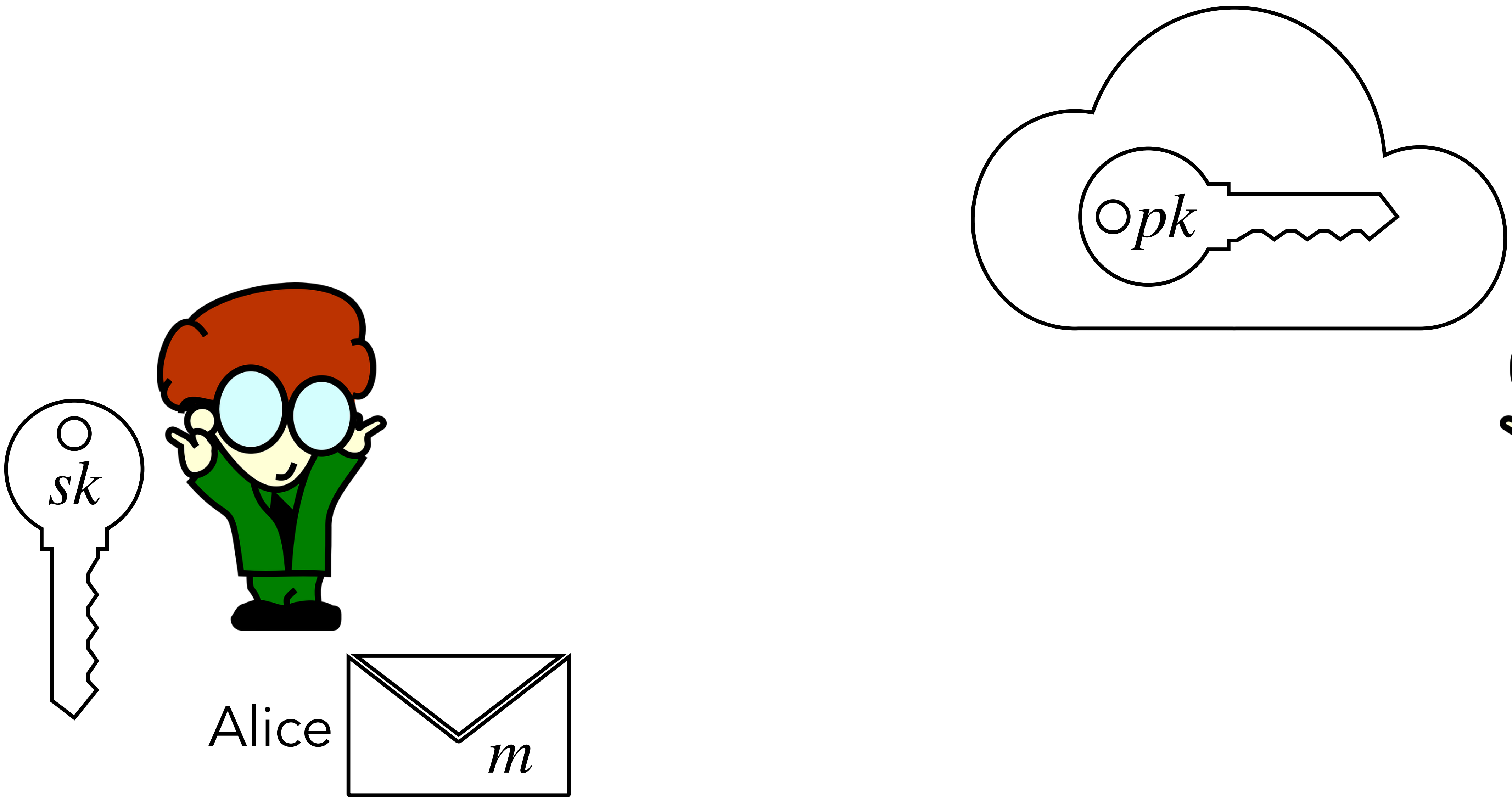

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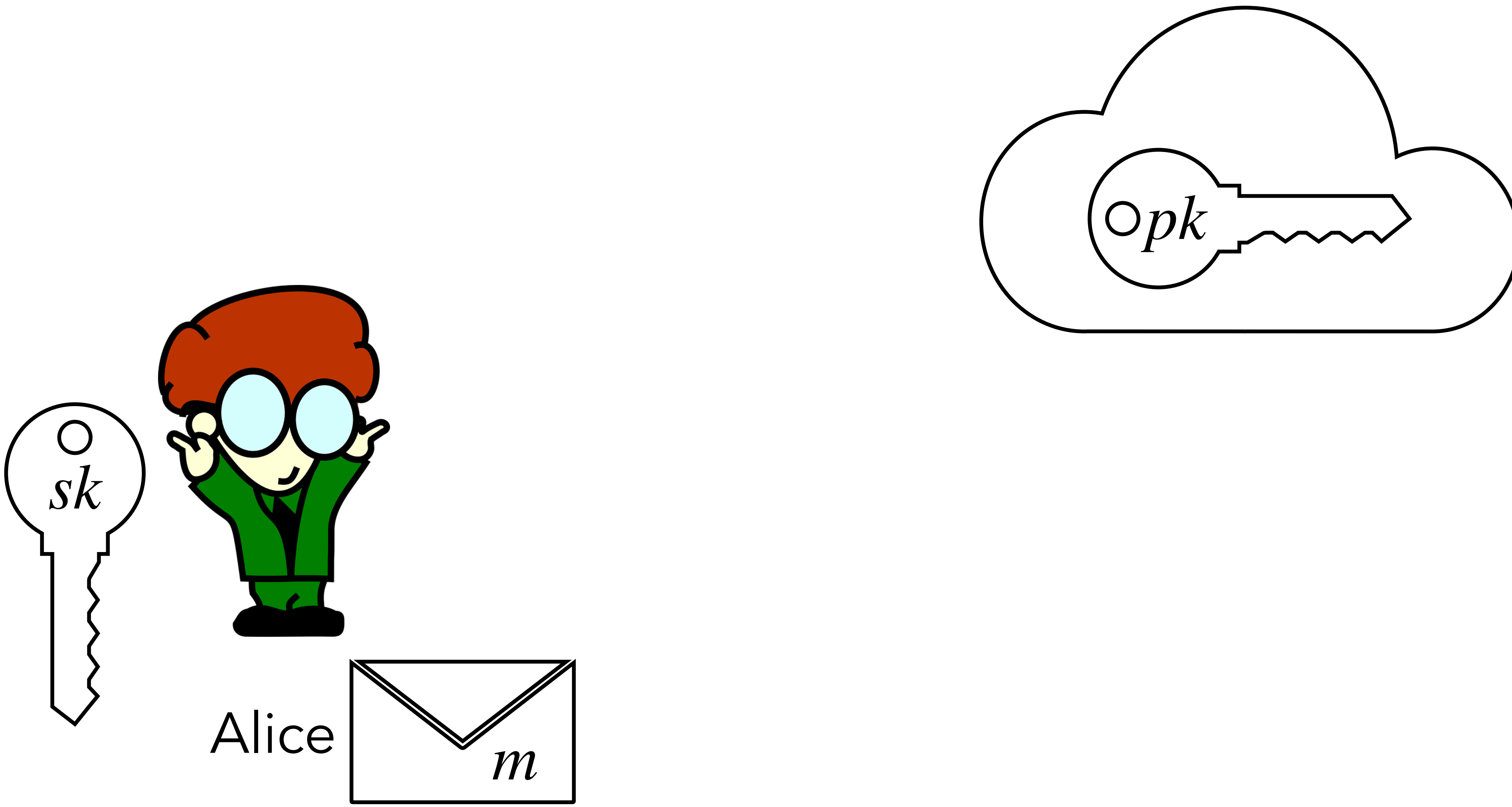

$$\sigma = \mathrm{Sign}_{sk}(m)$$

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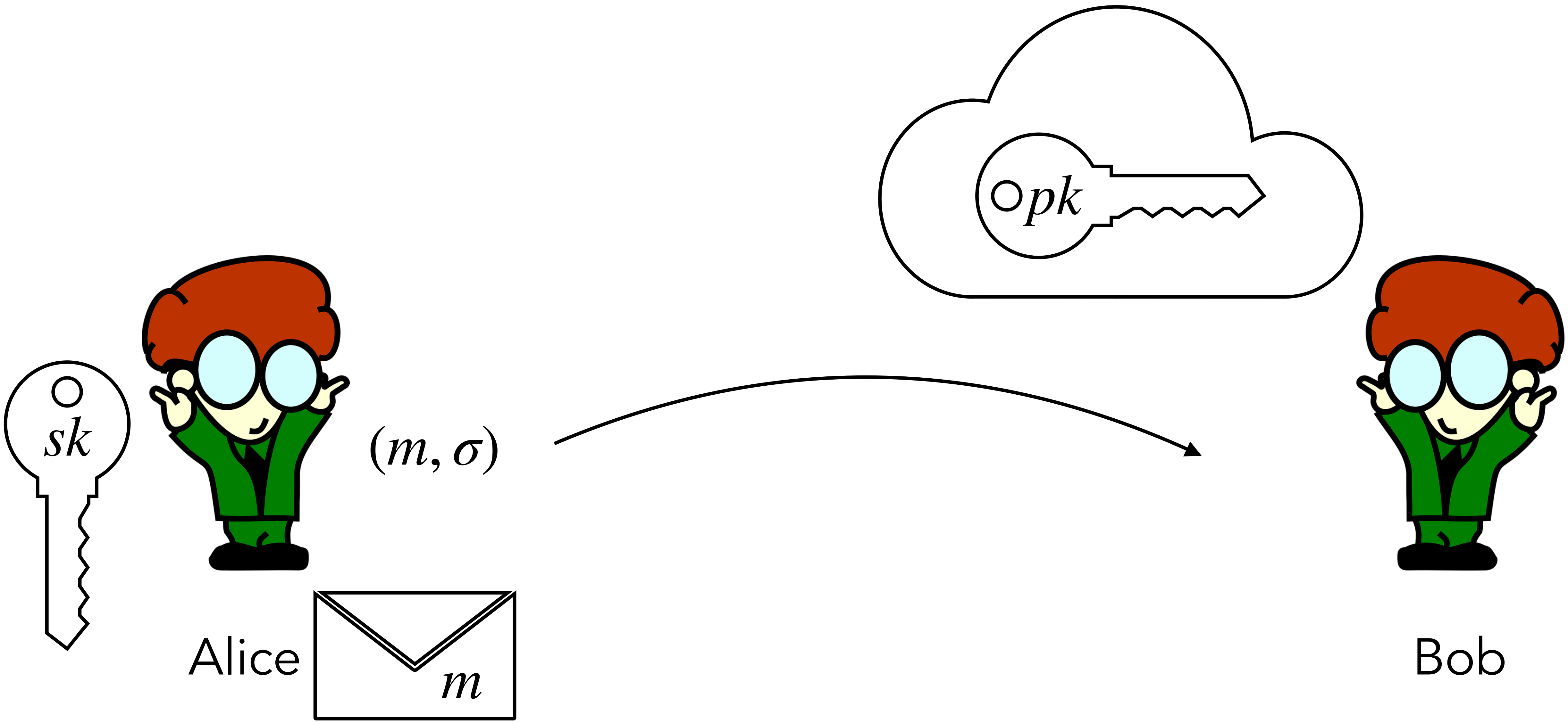

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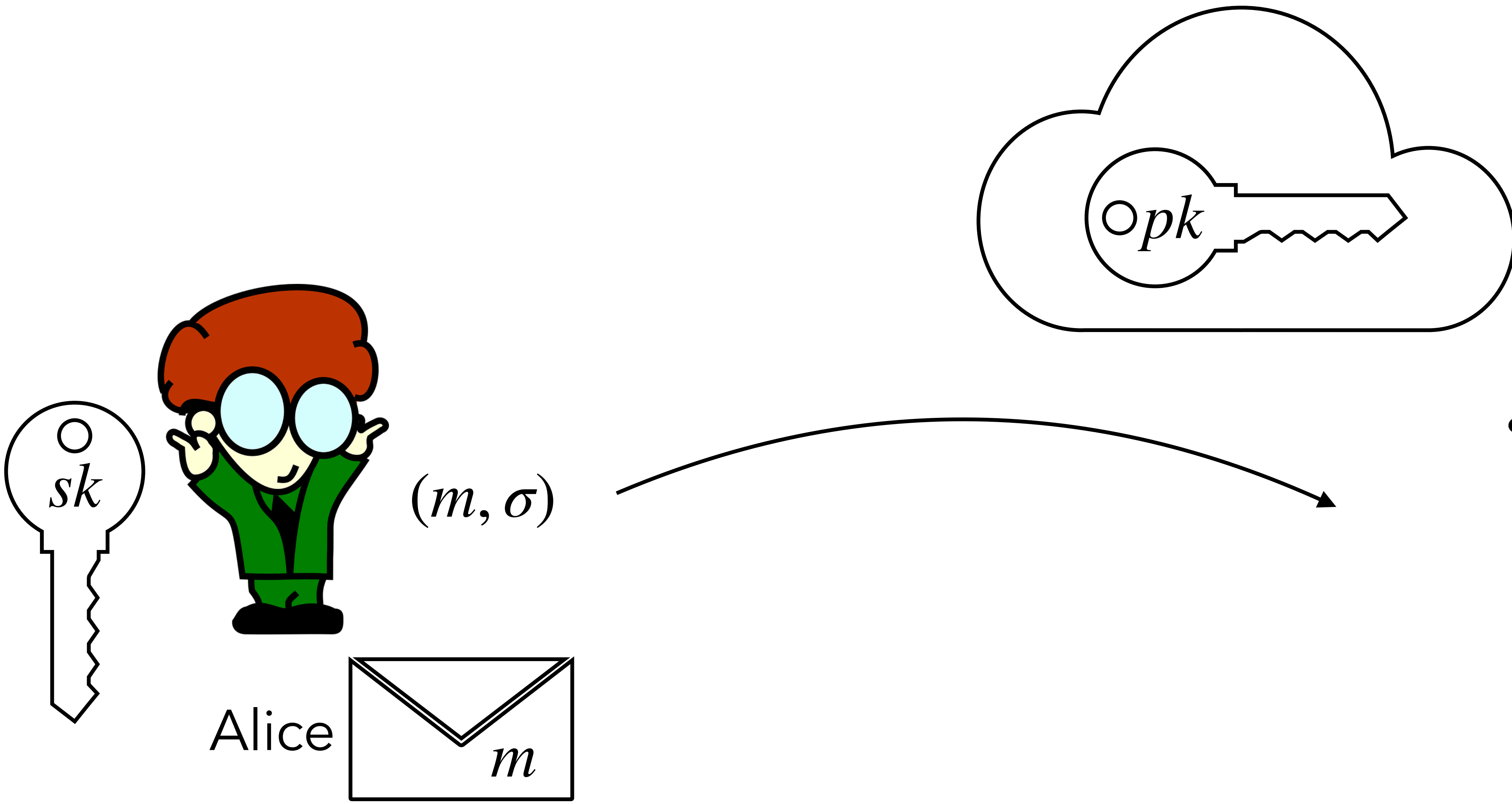

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- $\mathrm{Ver}_{pk}(m, \sigma) = \mathrm{accept}$

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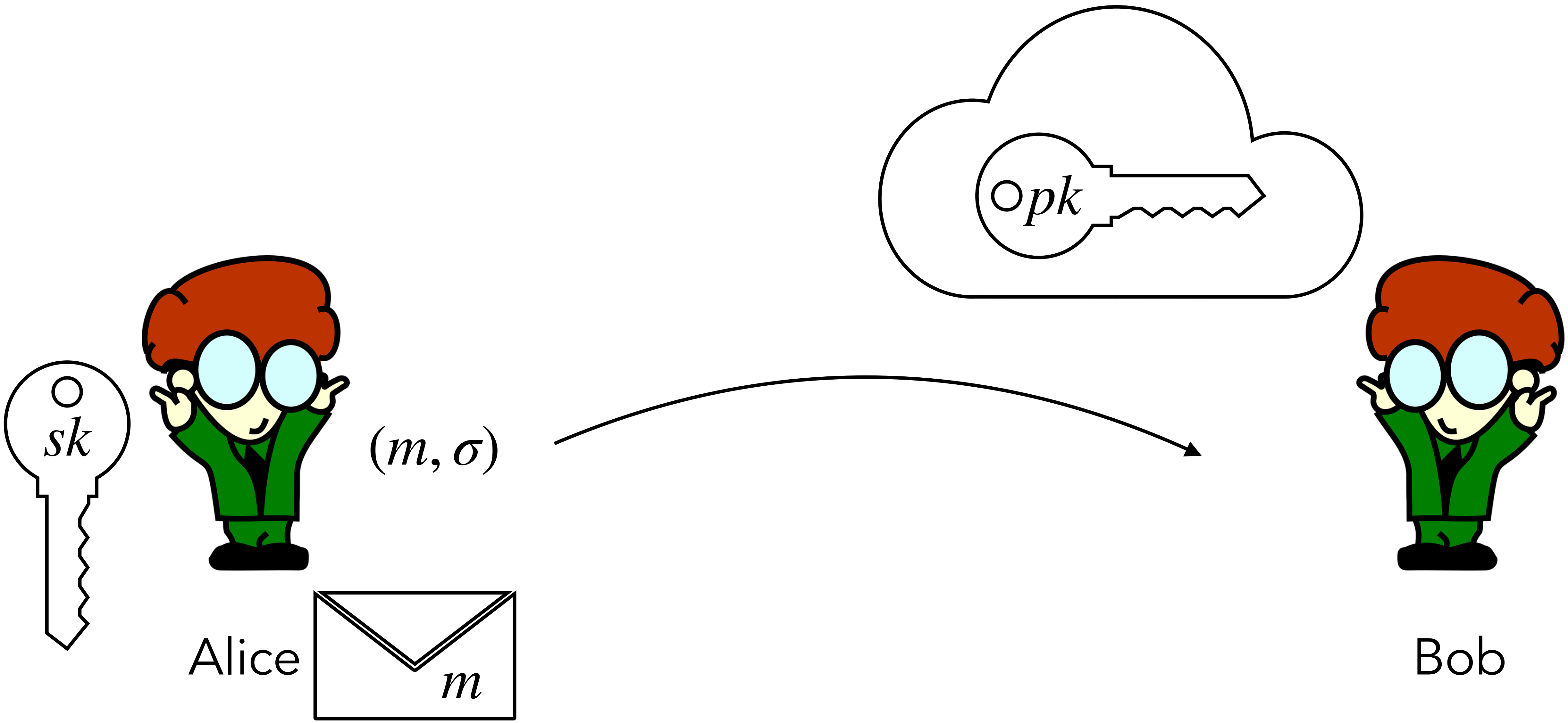

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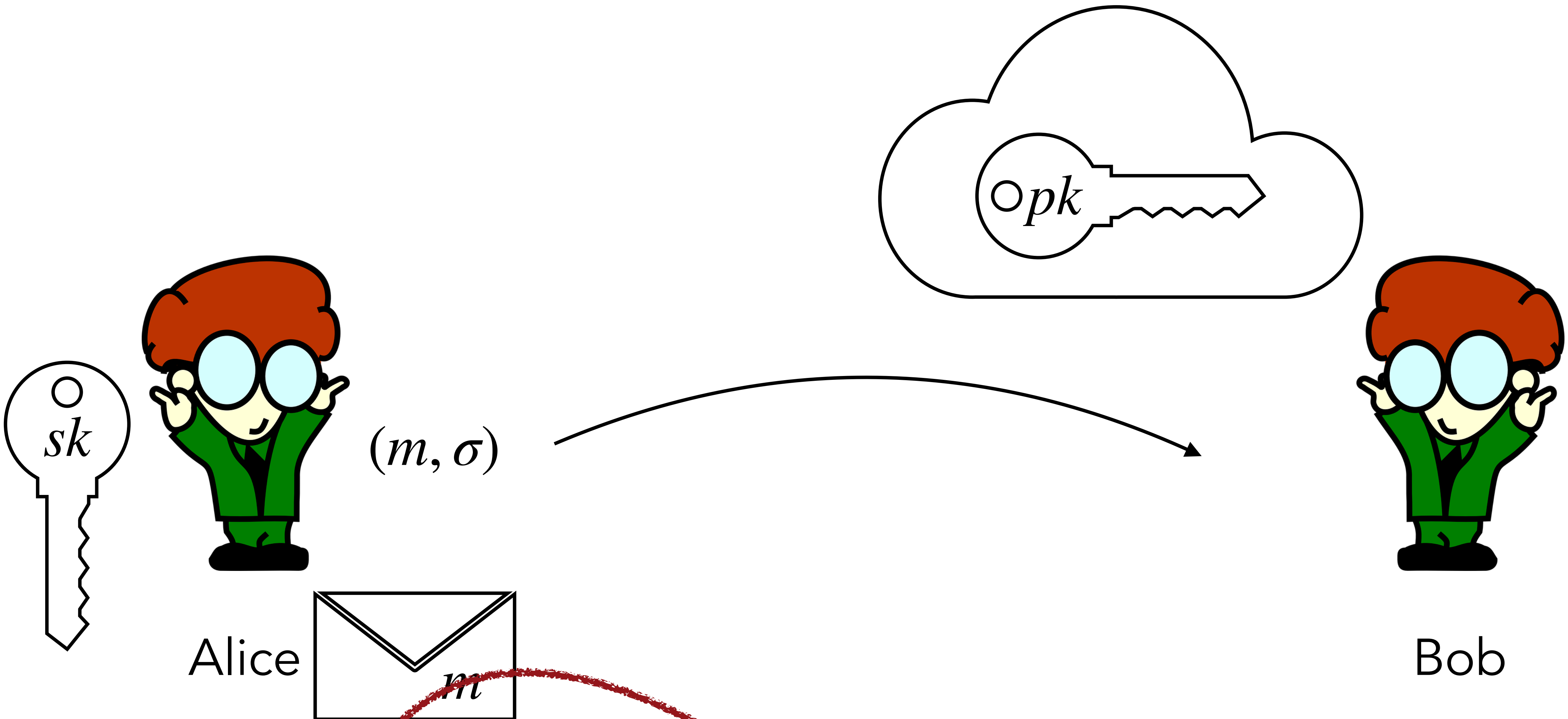

$\sigma = \mathrm{Sign}_{sk}(H(m))$

collision resistance suffices

- $\mathrm{Ver}_{pk}(m, \sigma) = \mathrm{accept}$

(Quantum) random oracle model

Model hash function as random function $H : \{0,1\}^* \to \{0,1\}^n$

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Allows public oracle access to $|x\rangle|y\rangle \mapsto |x\rangle|y \oplus H(x)\rangle$

+ Has enabled security proofs for more efficient cryptographic schemes
- It's not the real world!

Domain extension

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

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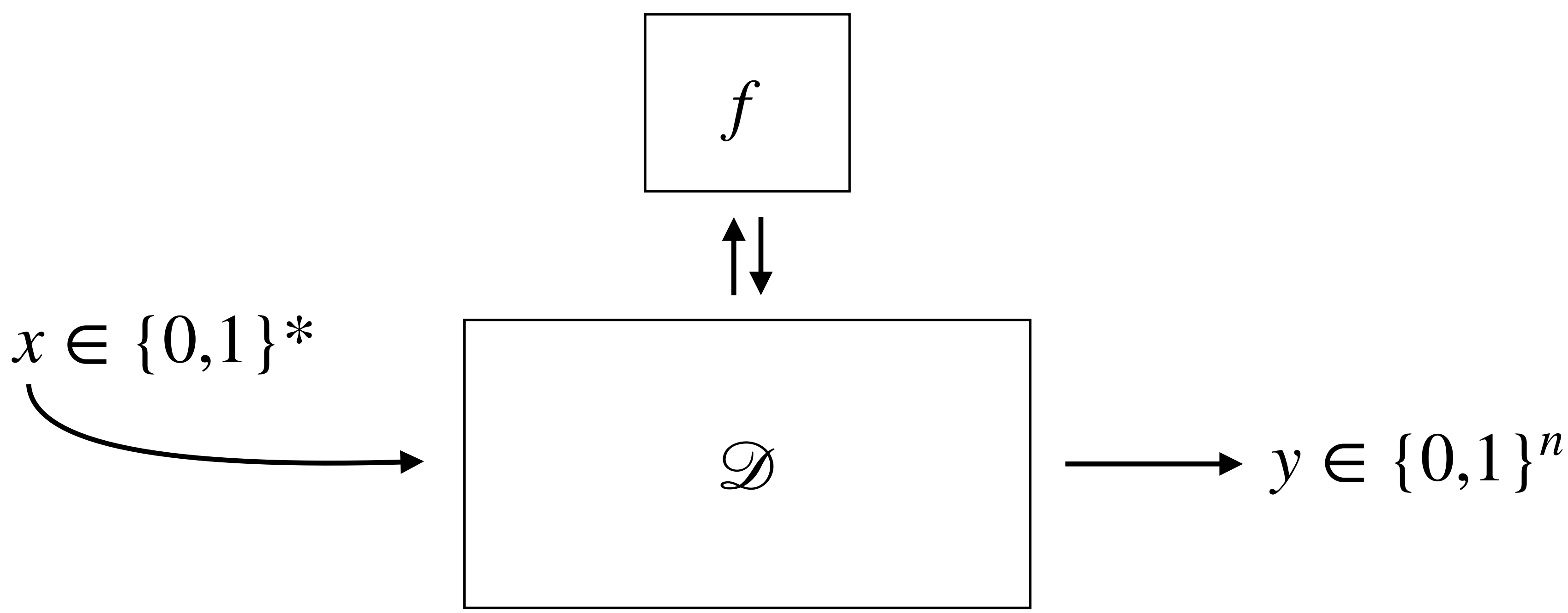

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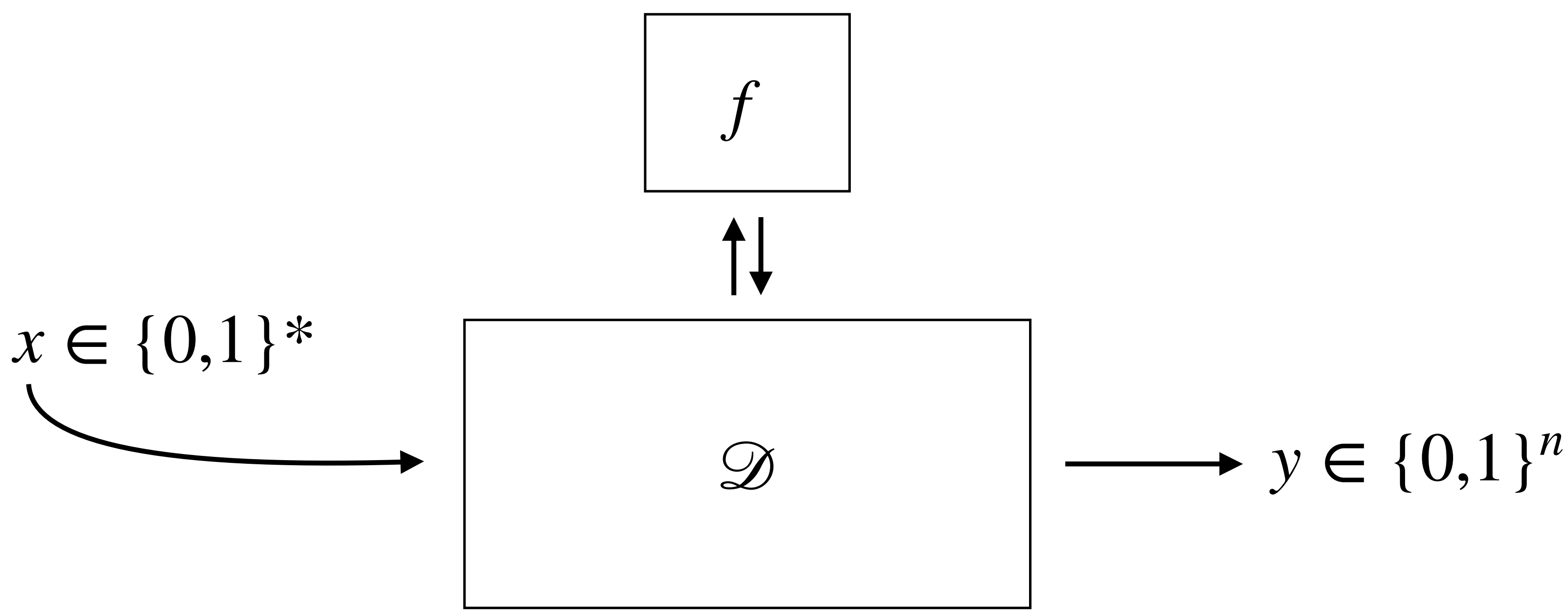

Such that H inherits the security properties of f

SHA-1 SHA-2, SHA-3 work like this.

Example: the sponge construction

A particular domain extension scheme used e.g. in SHA-3

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H: split input x into chunks $x_1, \ldots, x_k$ of r bits each

In SHA3-512:
$r = 576$

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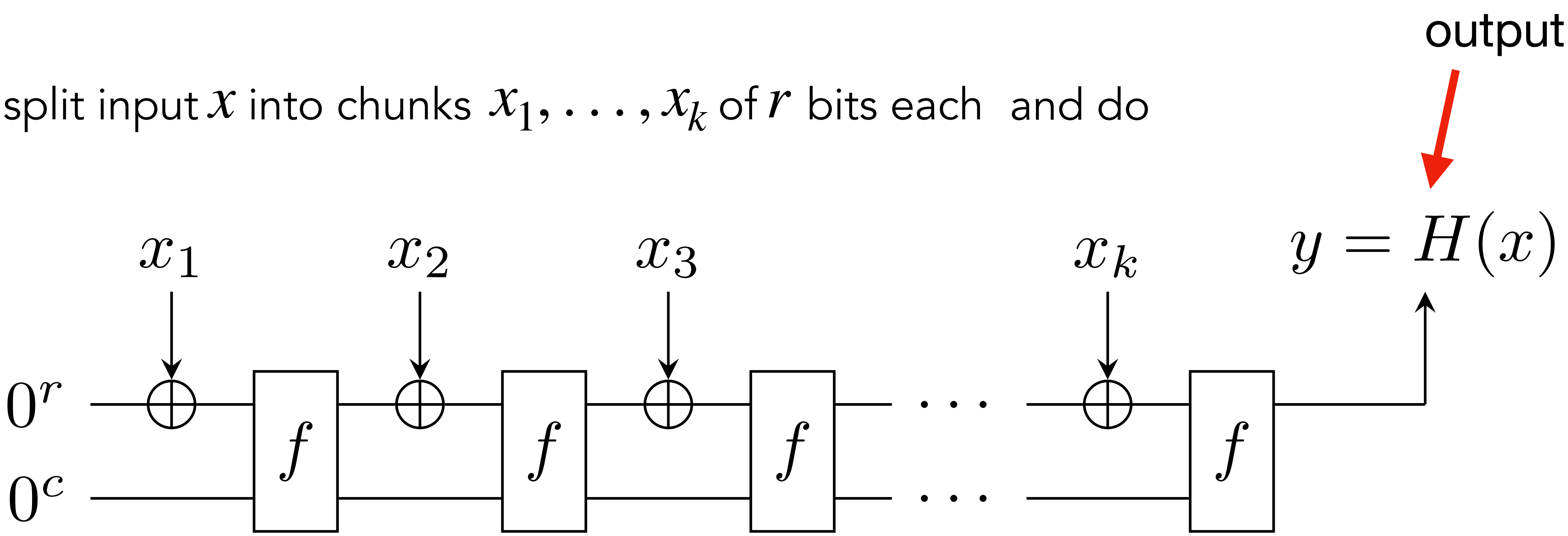

In SHA3-512:

$r = 576$

$c = 1024$

Hash functions in the NIST competition

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Digital signature schemes:

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- All: “hash and sign”.

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Key encapsulation schemes

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Points of attack

How to attack hash functions?

Fixed-length hash function

How to attack hash functions?

Domain Extension

↑

Fixed-length hash function

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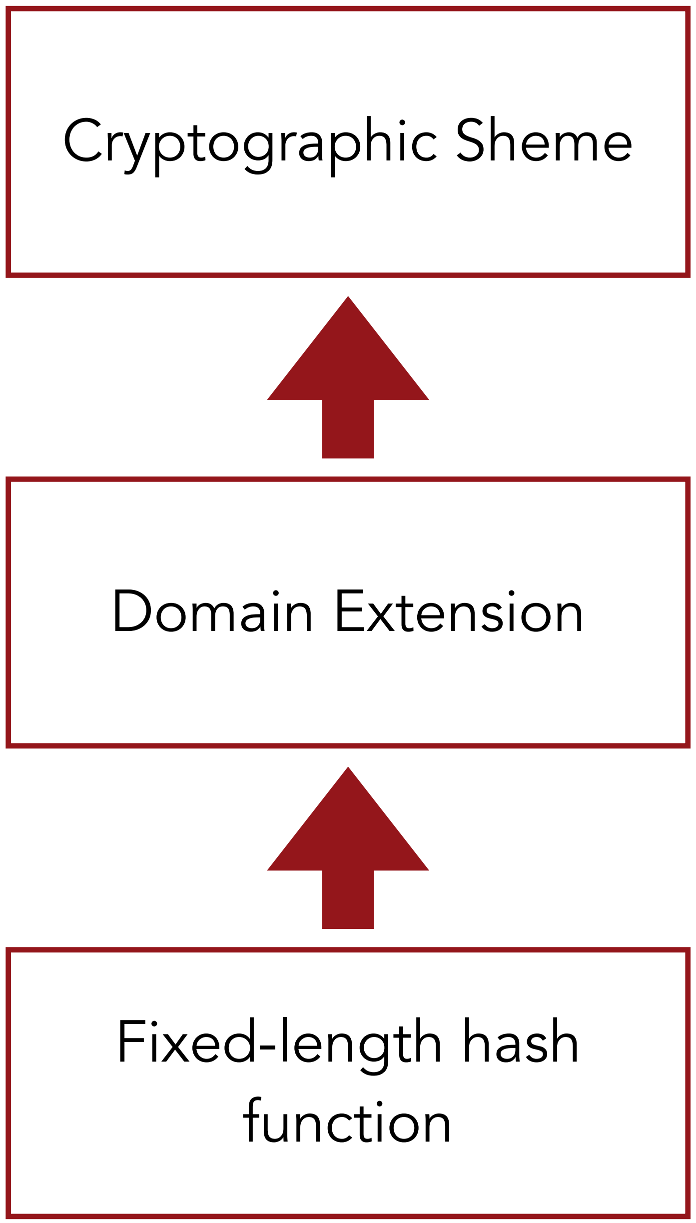


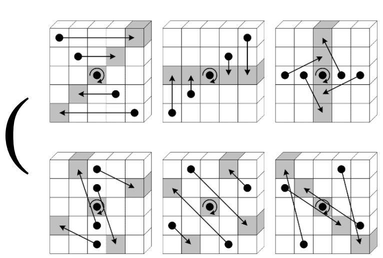
How to attack hash functions?

Cryptographic Sheme

Domain Extension

Fixed-length hash function

Attack using the structure of the fixed length hash function

“$H(x) = \mathscr{D}($  $)$“

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Attack the domain extension scheme

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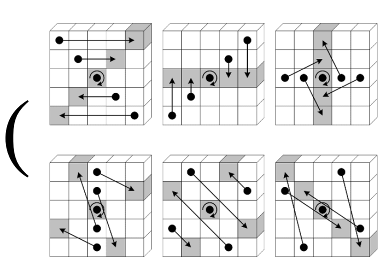
“$H(x) = \mathscr{D}($  $)$“

How to attack hash functions?

Cryptographic Sheme

Attack cryptographic scheme via its use of H

“$H = H$“

Domain Extension

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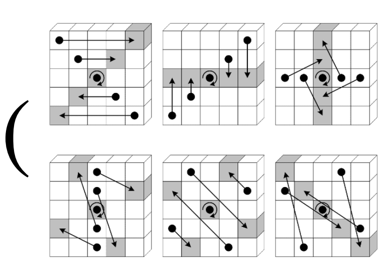
“$H(x) = \mathscr{D}($  $)$“

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Finding Hash Collisions with Quantum Computers by Using Differential Trails with Smaller Probability than Birthday Bound

Akinori Hosoyamada[1,2] and Yu Sasaki[1]

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{akinori.hosoyamada.bh,yu.sasaki.sk}@hco.ntt.co.jp
[2] Nagoya University, Nagoya, Japan, hosoyamada.akinori@nagoya-u.jp

Hosoyamada, A. And Sasaki, Y. “Finding Hash Collisions with Quantum Computers by Using Differential Trails with Smaller Probability than Birthday Bound”, EUROCRYPT 2020

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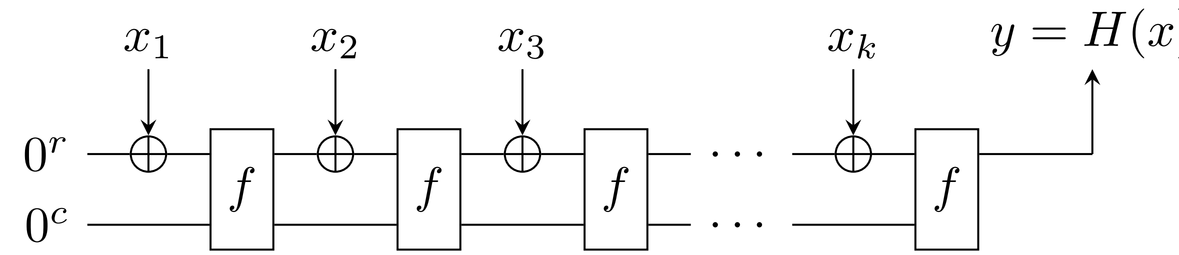
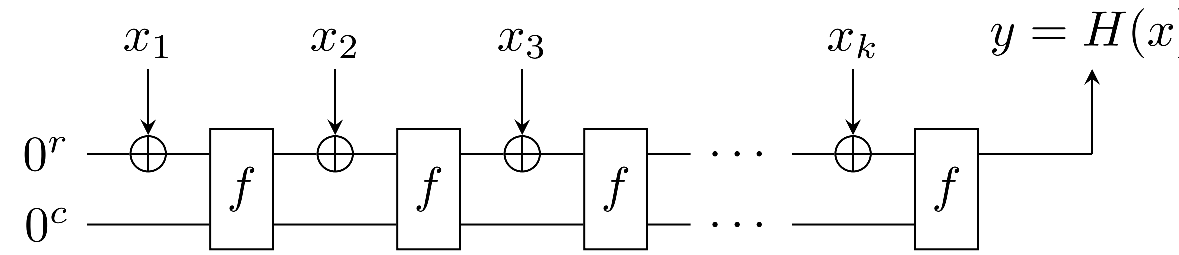


Theorem 16. *Let $\mathbf{S}_{c,r,\mathbf{f},pad,n}(m)$ be a sponge construction with arbitrary block function $\mathbf{f}$. There exists a quantum algorithm* COLL-RO *making at most $q_{\mathbf{f}}$ quantum queries to $\mathbf{f}$ and $q_{\mathcal{H}}$ quantum queries to a random oracle $\mathcal{H}$.* COLL-RO *outputs colliding messages $m \neq \hat{m}$ such that $\mathbf{S}_{c,r,\mathbf{f},pad,n}(m) = \mathbf{S}_{c,r,\mathbf{f},pad,n}(\hat{m})$ with probability at least $1/8$, where $q_{\mathbf{f}} := 2k_{\mathrm{Amb}} \cdot \min\{\frac{c+6+2r}{r} 2^{c/3}, \frac{2n+6+3r}{r} 2^{n/3}\}$, and $q_{\mathcal{H}} := 2k_{\mathrm{Amb}} \cdot \min\{2^{c/3}, 2^{n/3}\} + 2$, where k_{Amb} is the constant from Theorem 14 and pad is any padding function which appends at most $2r$ bits.*

Czajkowski, J., Bruinderink, L. G., Hülsing, A., Schaffner, C., & Unruh, D. “Post-quantum security of the sponge construction”, PQCrypto 2018

How to attack hash functions?

Attack the domain extension scheme



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Finds collision for sponge
by finding collision of f

Czajkowski, J., Bruinderink, L. G., Hülsing, A., Schaffner, C., & Unruh, D. "Post-quantum security of the sponge construction", PQCrypto 2018

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Attack cryptographic scheme
via its use of H

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Remainder of this talk:
2 Examples

Fiat-Shamir and Fujisaki-Okamoto

Sigma-protocols

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Prover

Sigma-protocols

Prover

Verifier

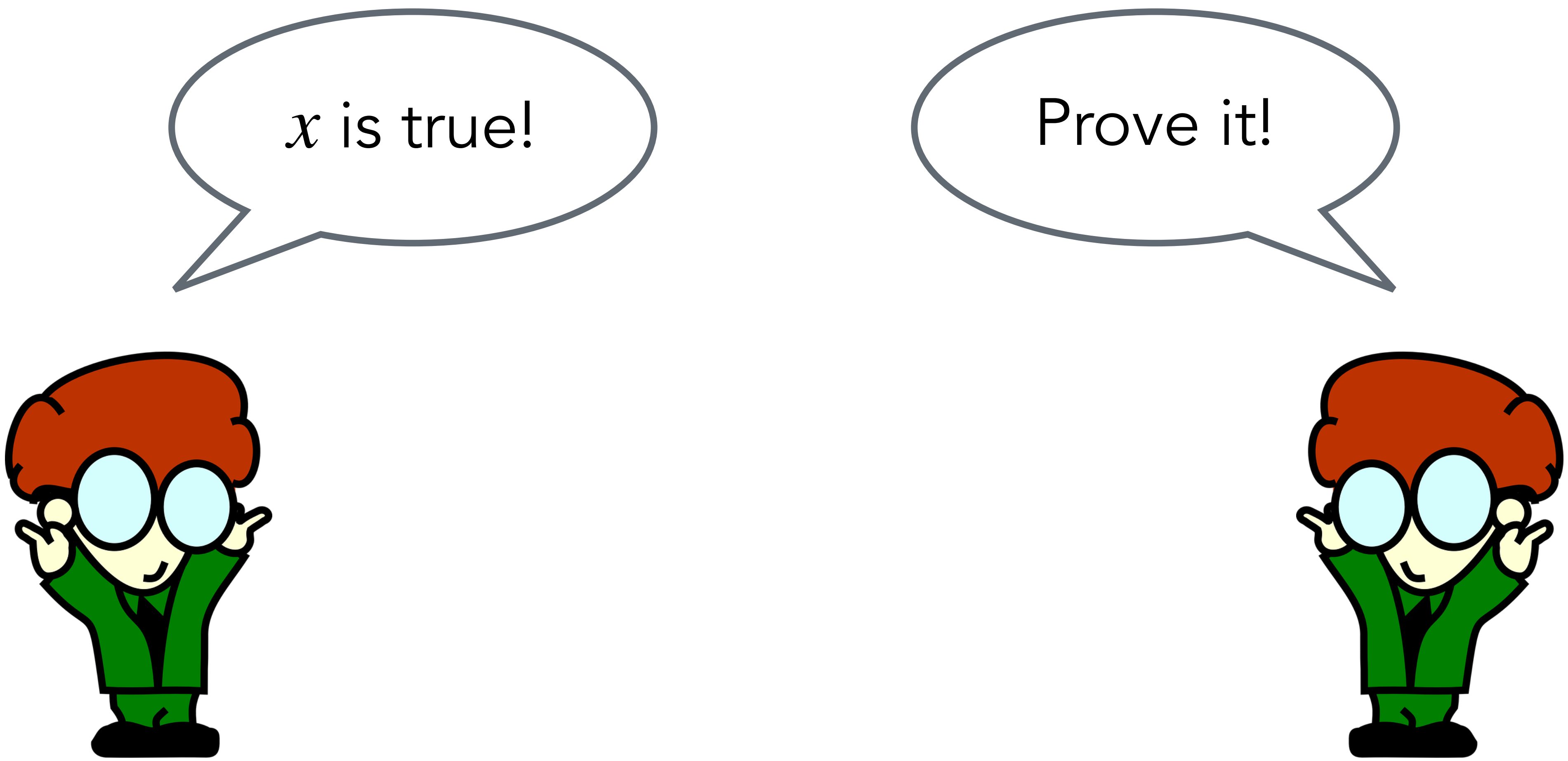
Sigma-protocols

x is true!

Prover

Verifier

Sigma-protocols



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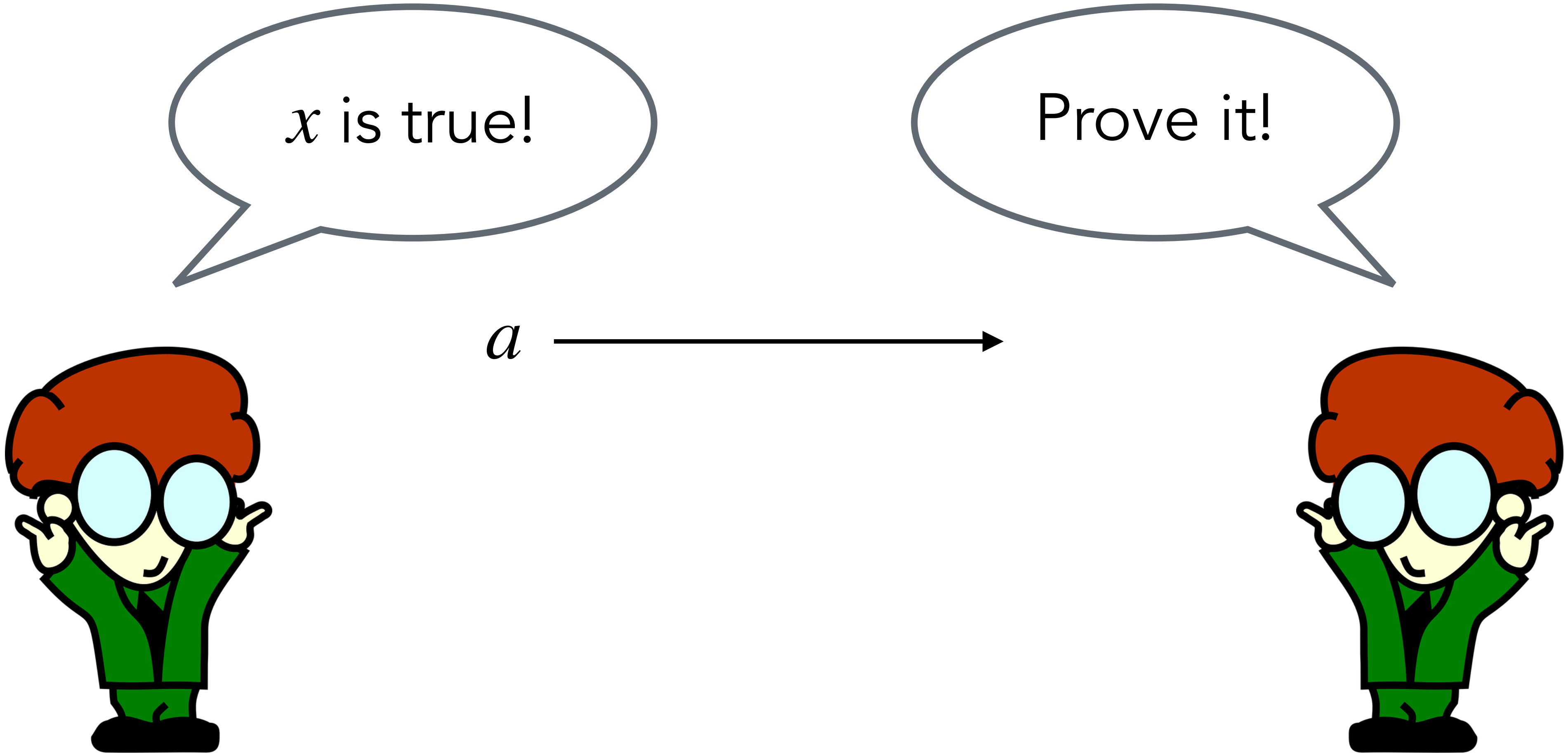

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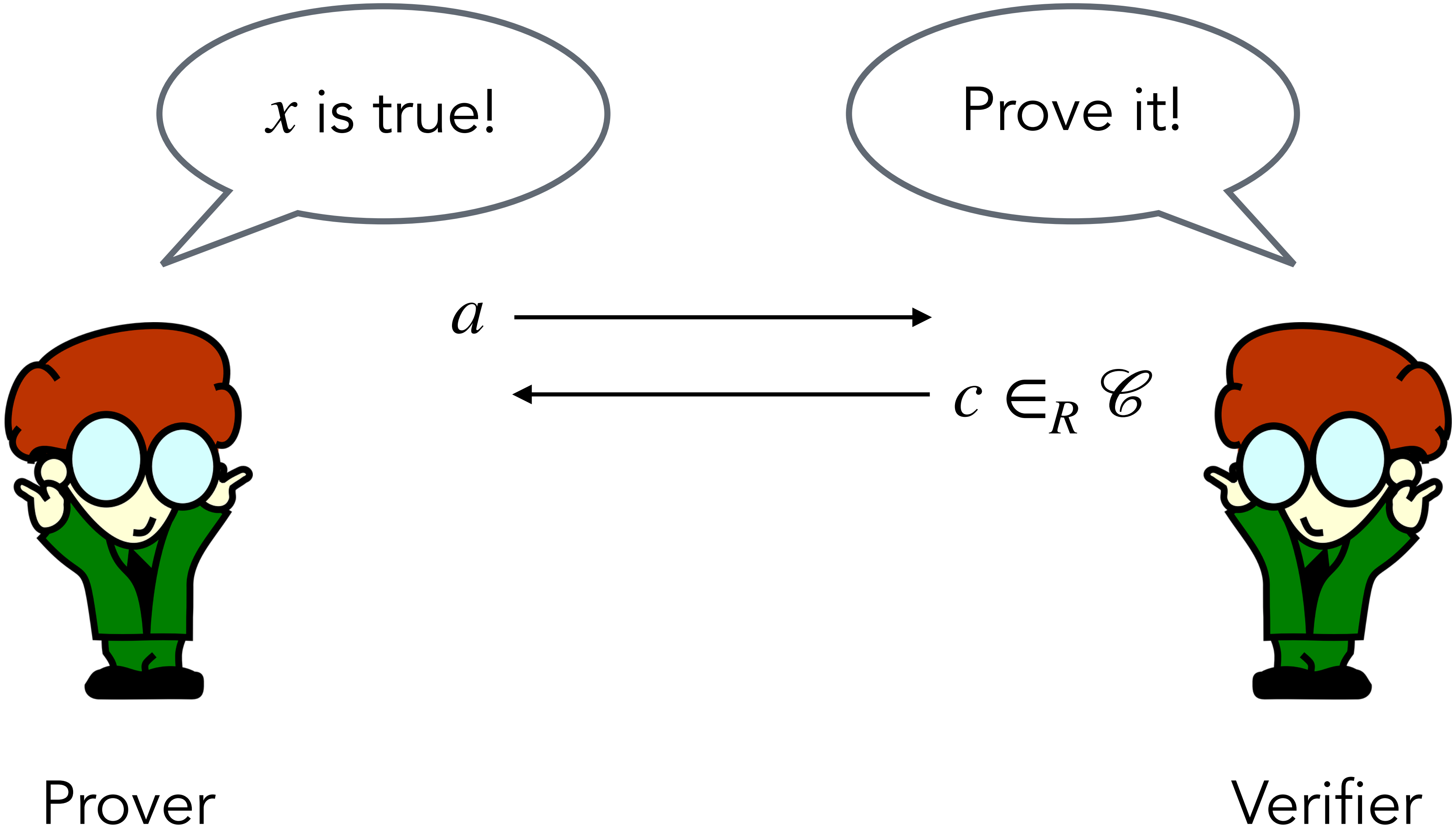

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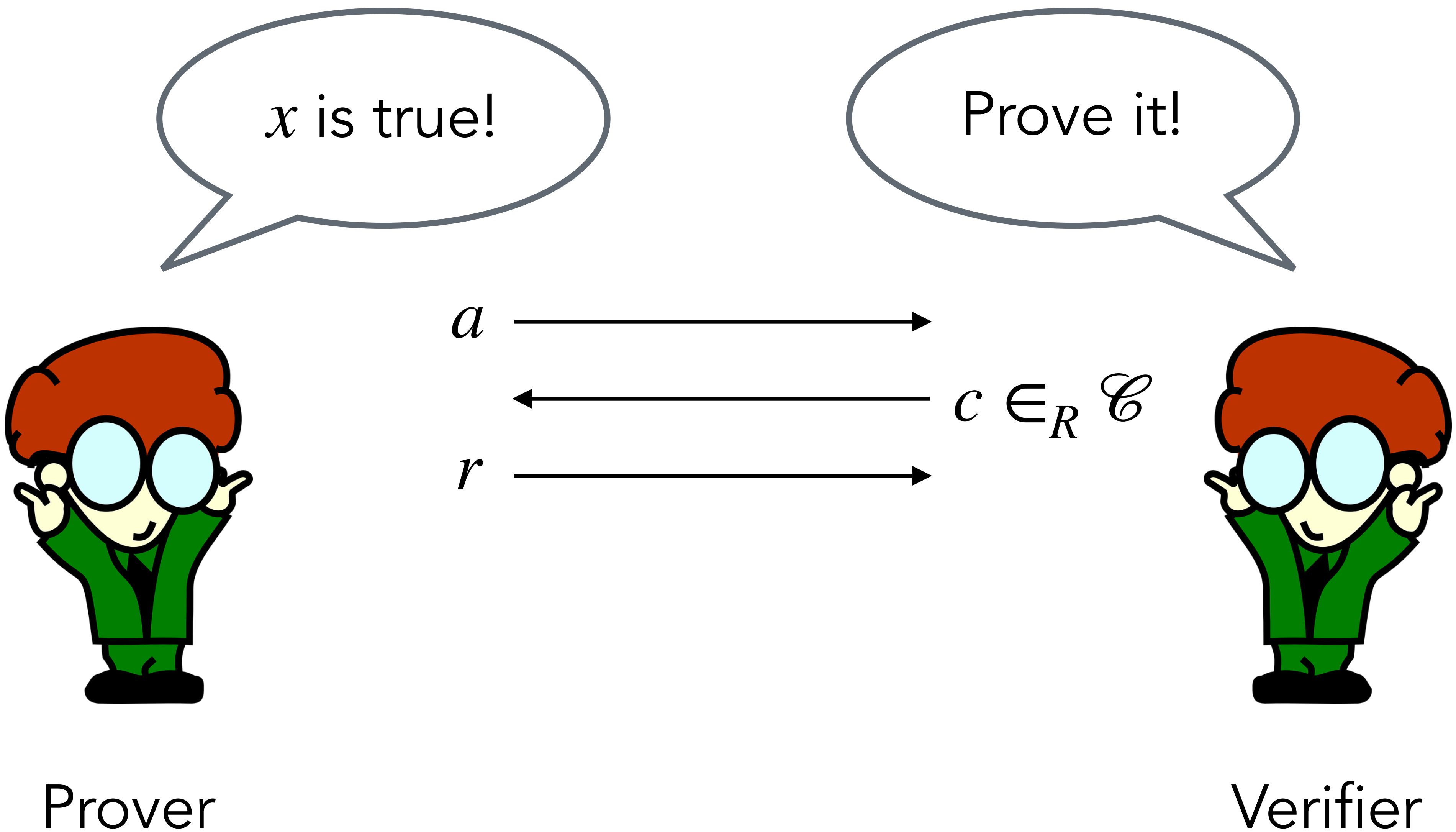

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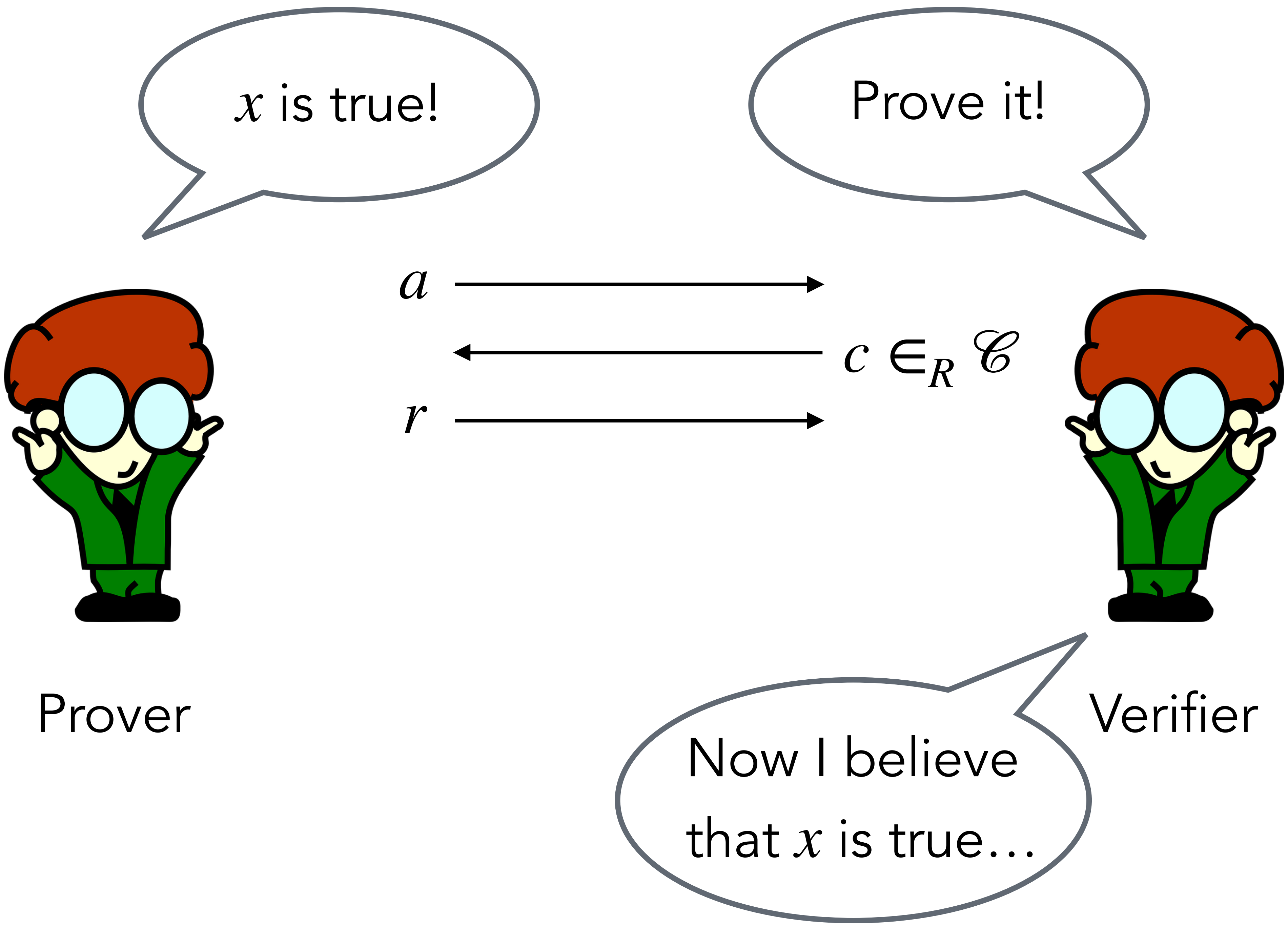

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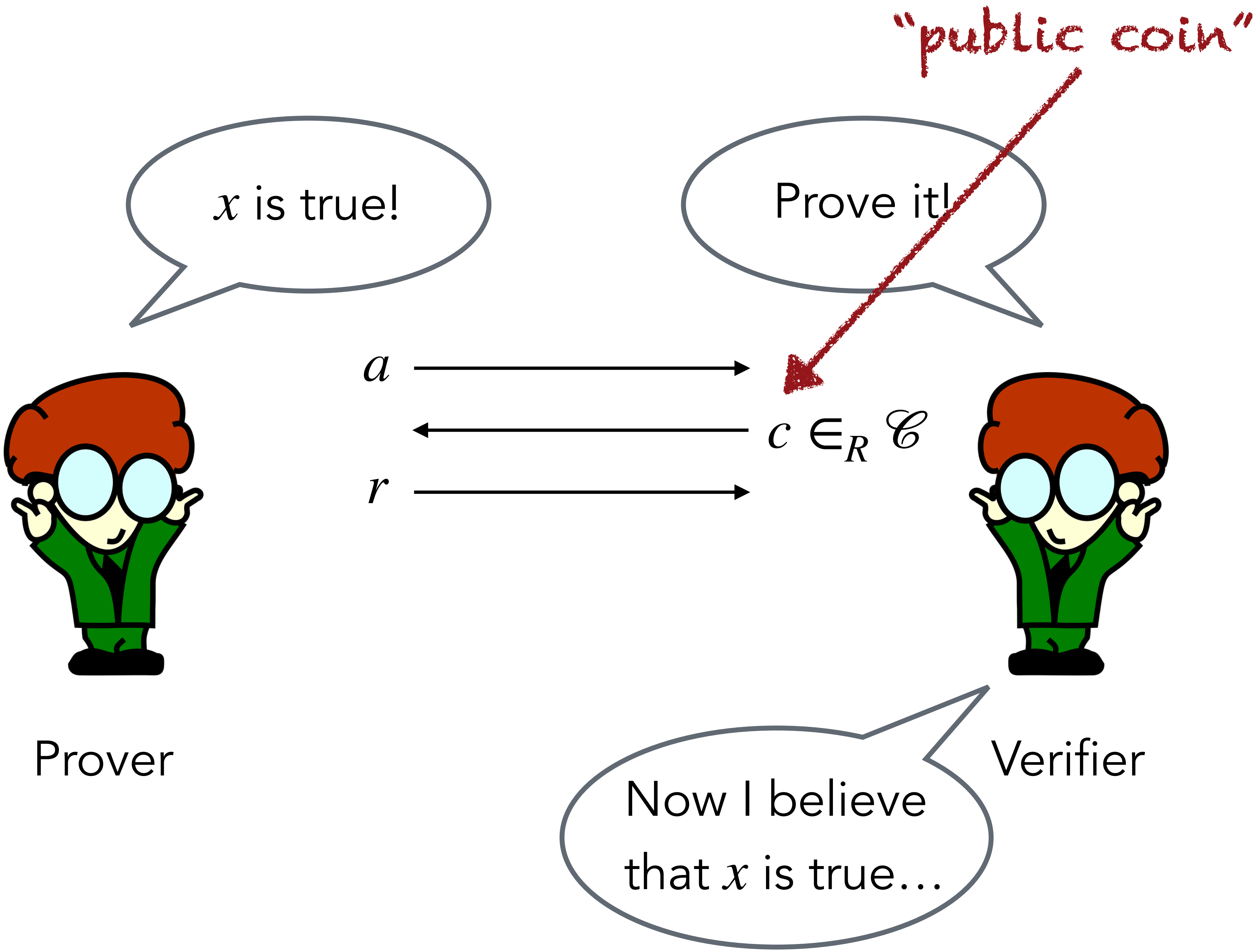

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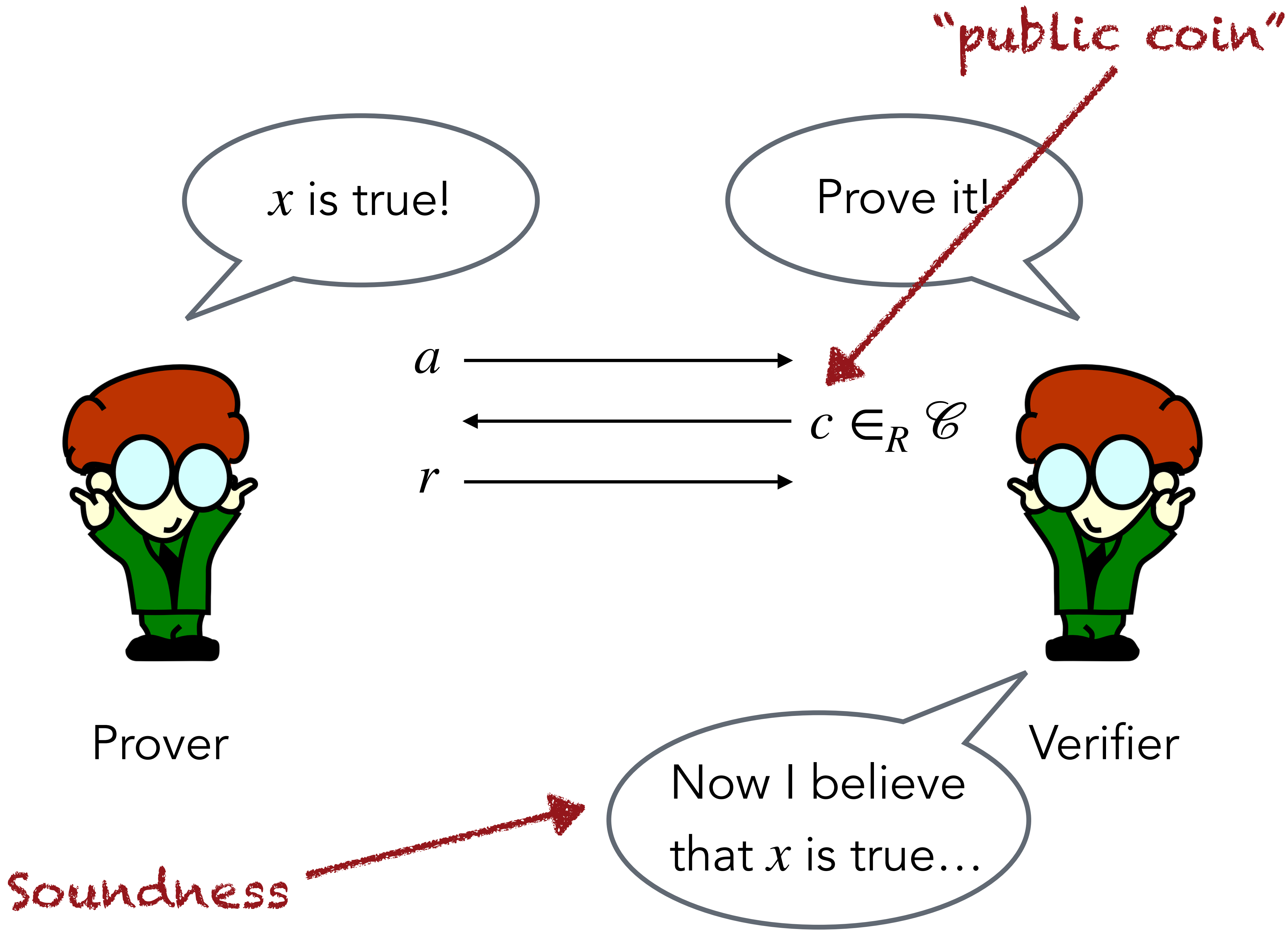
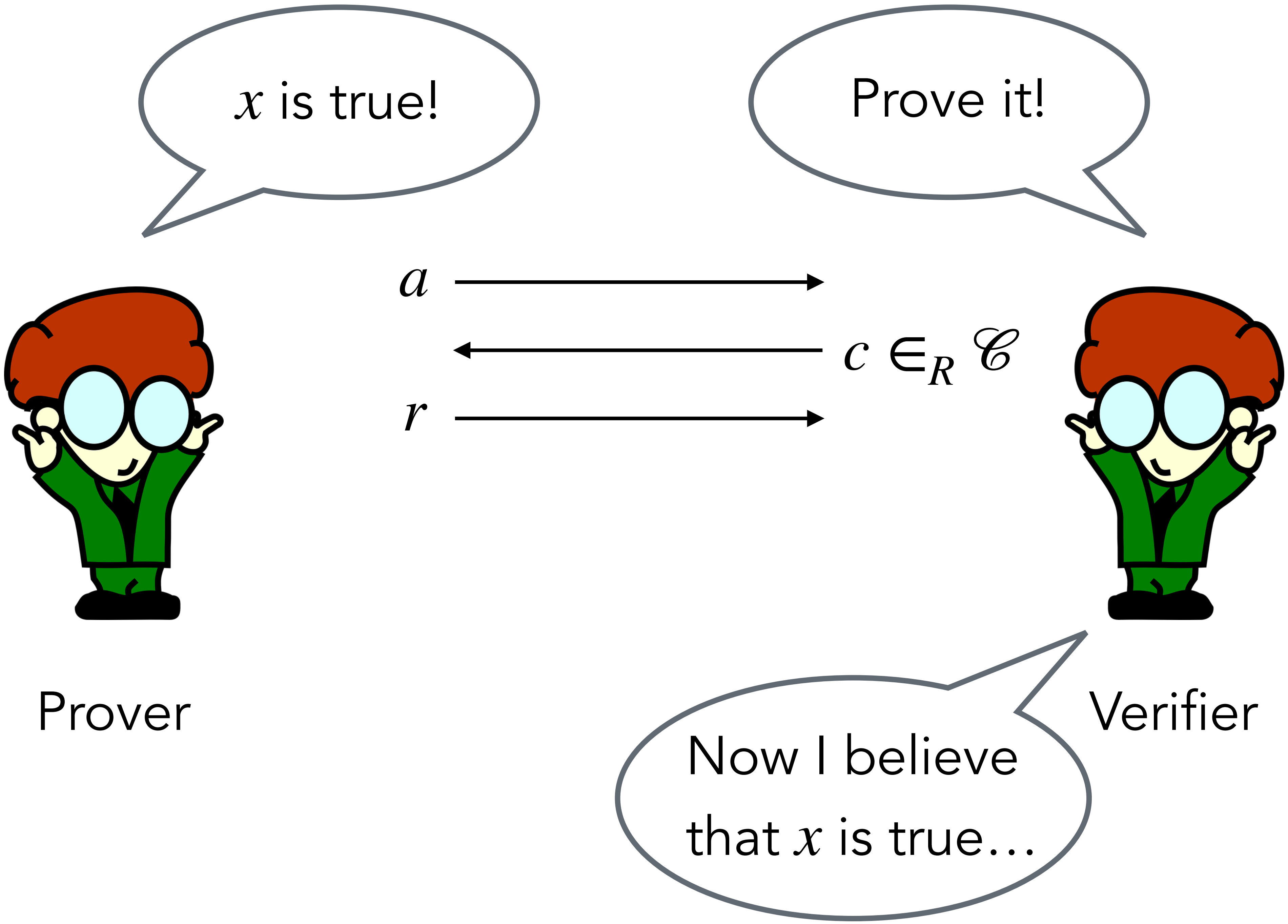


Fiat-Shamir transformation



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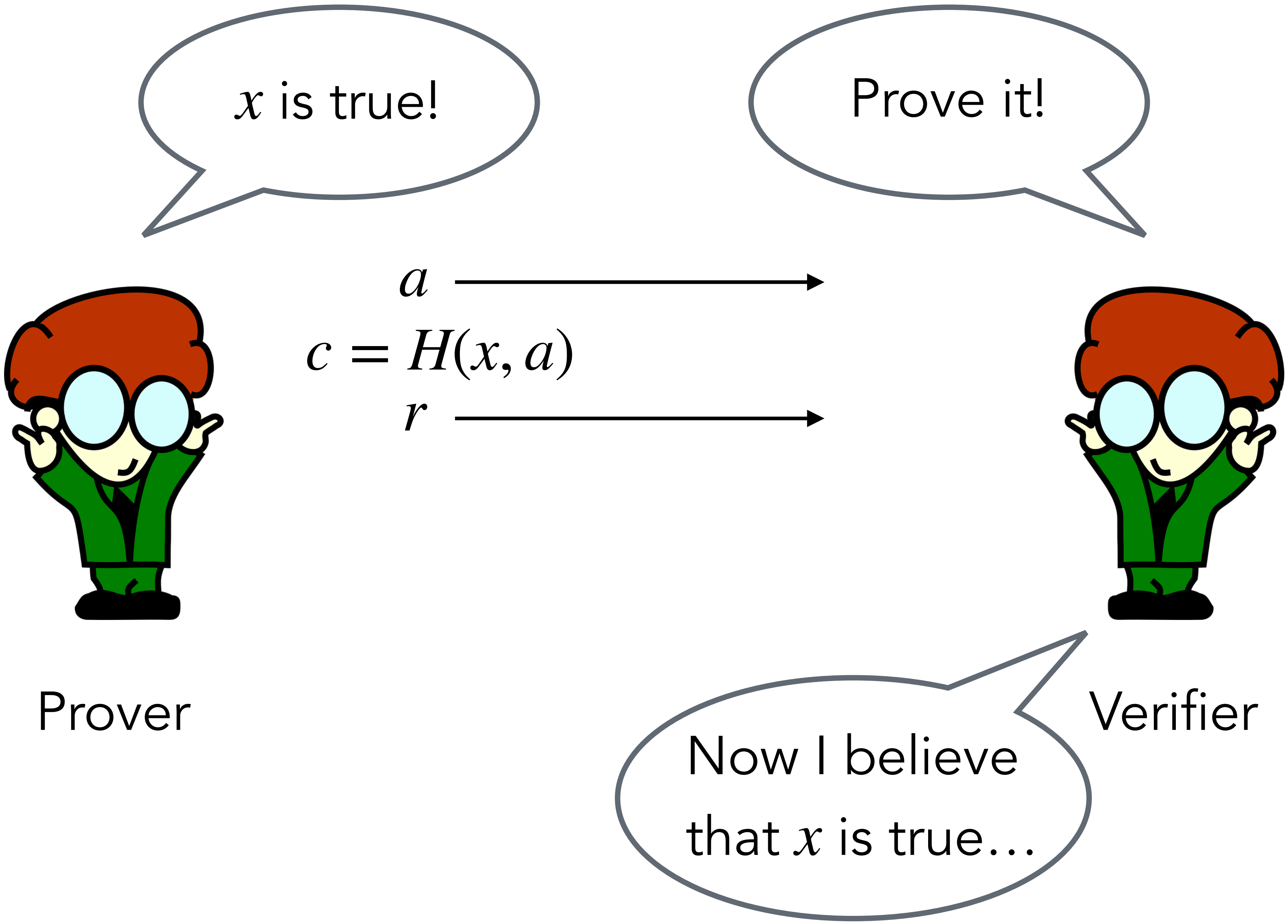

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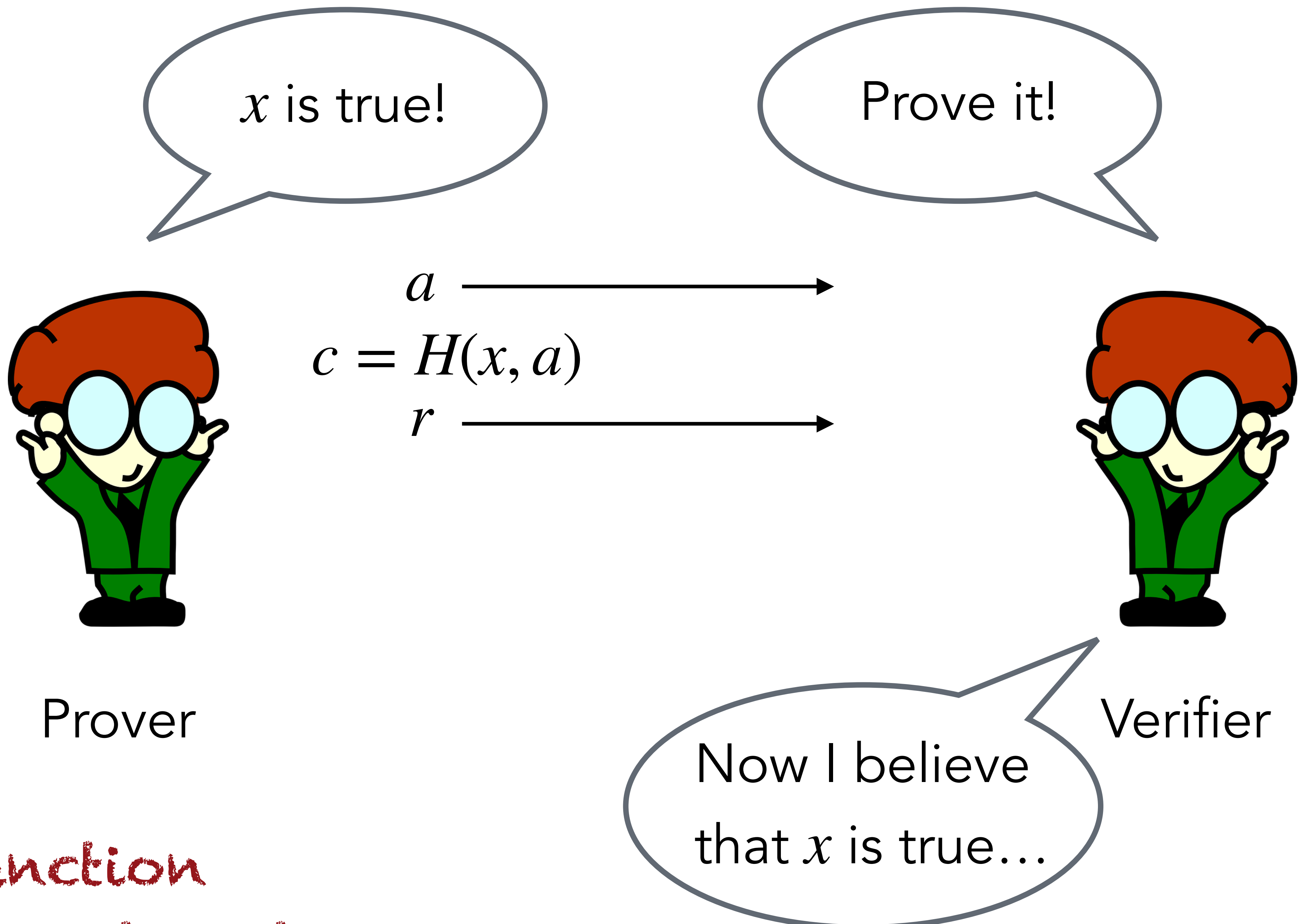
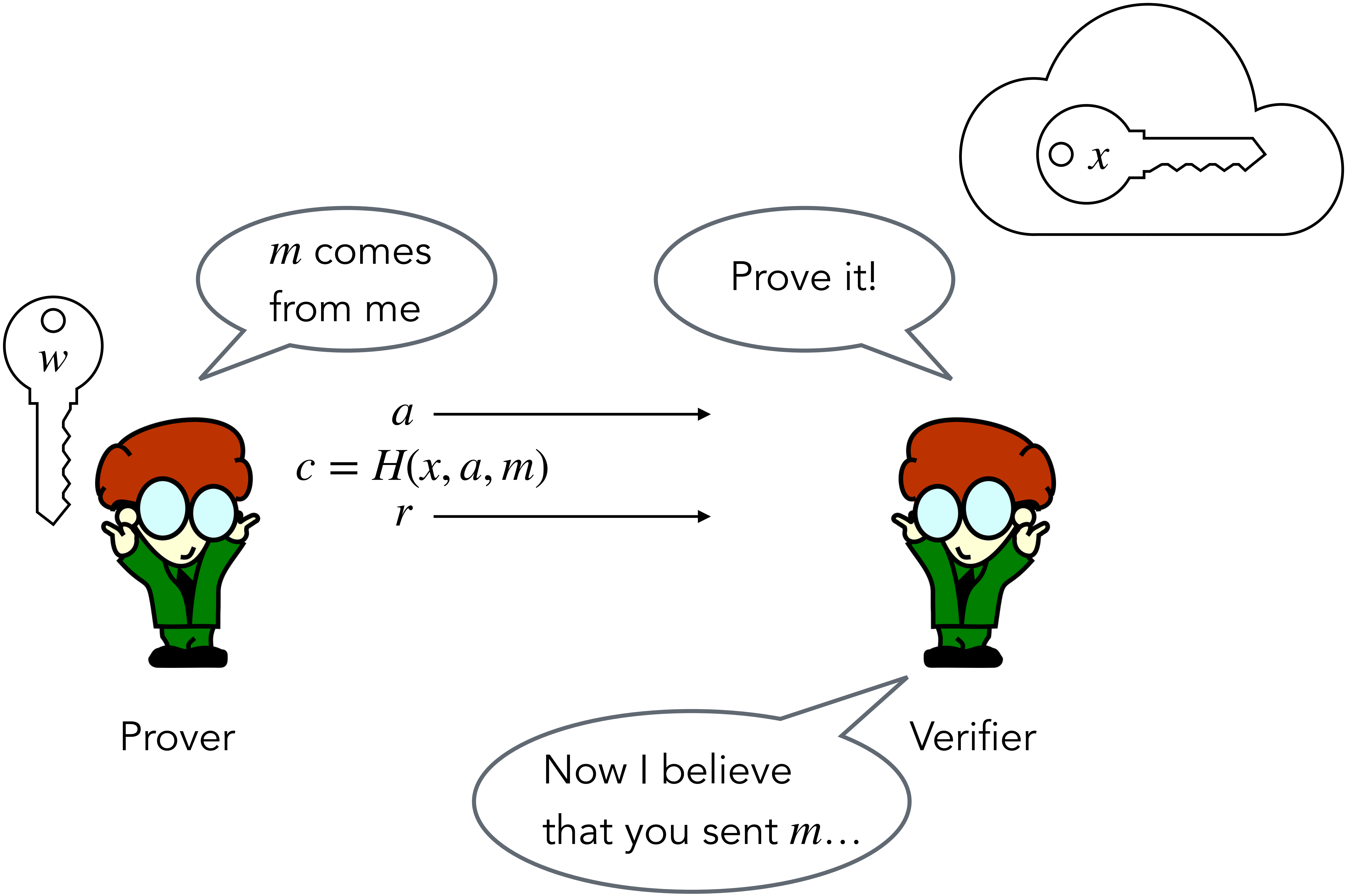


Hash function
replaces interaction

Fiat-Shamir signature scheme



Fujisaki-Okamoto transformation

Upgrades weak security to chosen-ciphertext security for key encapsulation

“Derandomize, Hash&reincrypt”

Fujisaki-Okamoto transformation

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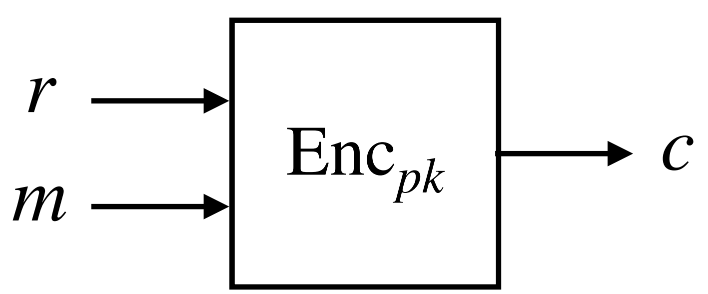

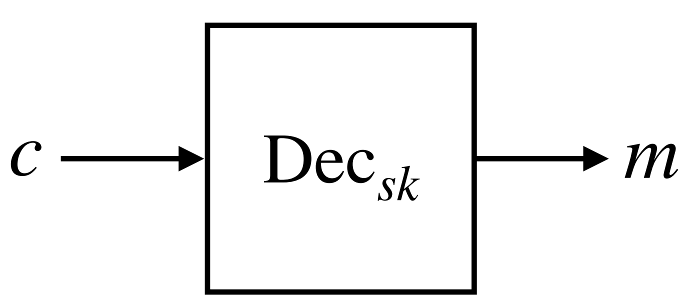

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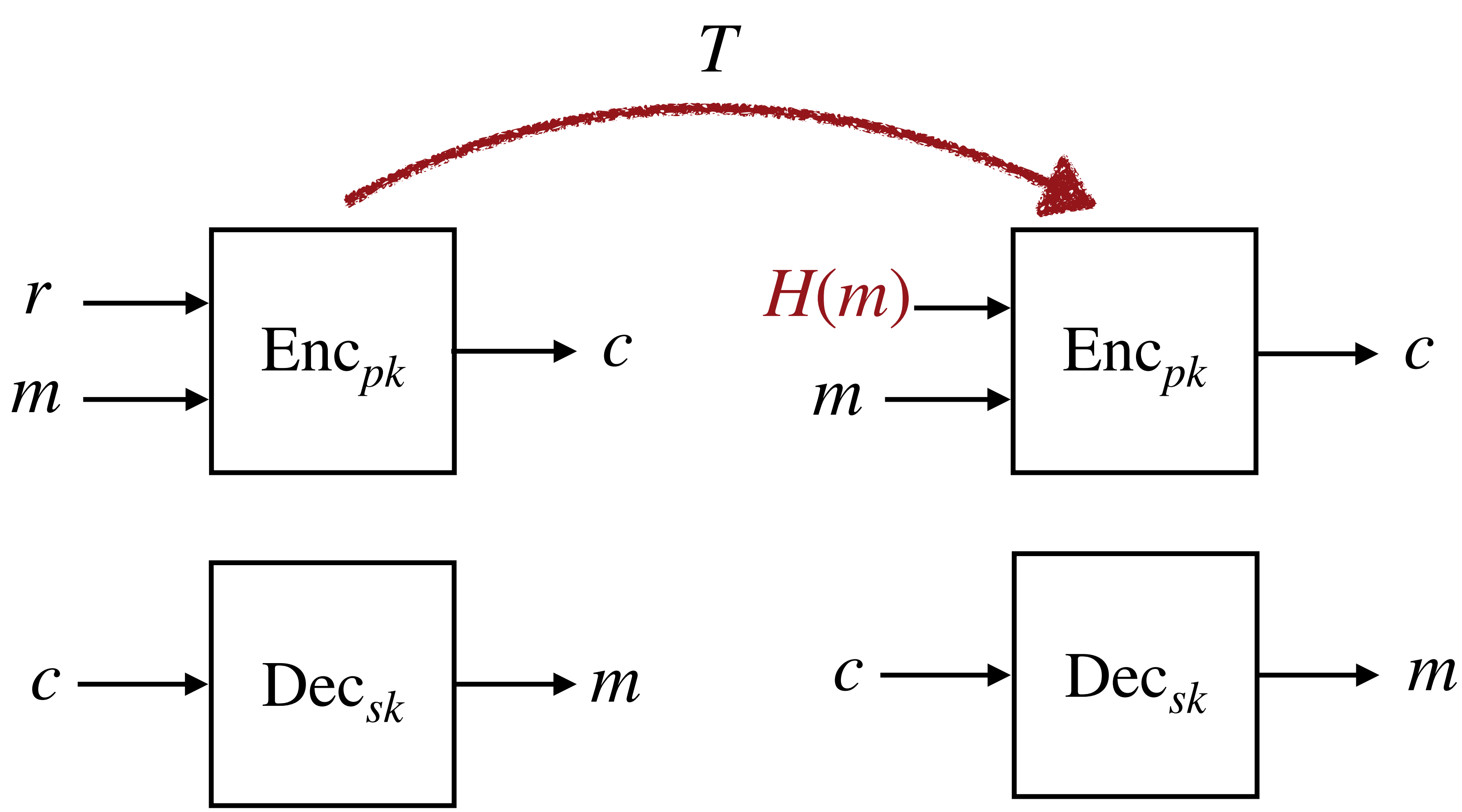
"Derandomize"



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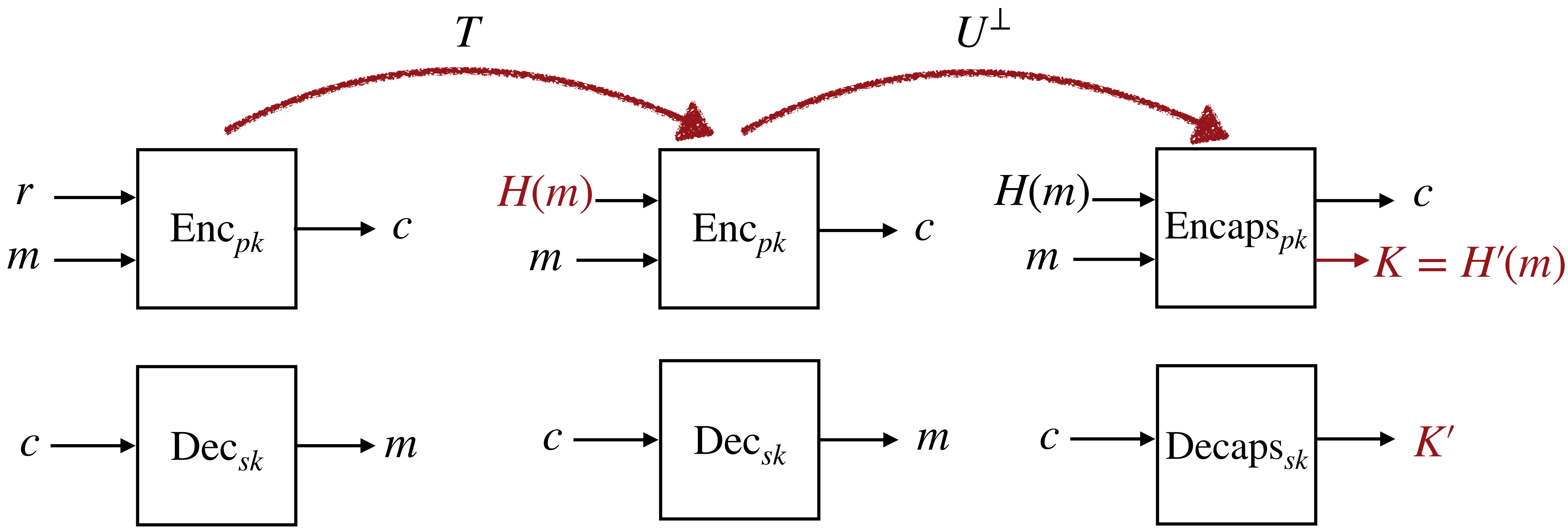
"Derandomize, Hash&reincrypt"

"Derandomize" "Hash&reincrypt"



$$K' = \begin{cases} H'(m) & c = \mathrm{Enc}_{pk}(m, H(m)) \\ \perp & \text{else} \end{cases}$$

Attacks and attack approaches

Fiat-Shamir transformation in the QROM

Theorem (Don, Fehr, M, Schaffner '19):

An dishonest prover making q quantum queries to the random oracle can prove a wrong statement in the Fiat-Shamir Transformation $\mathsf{FS}(\Sigma)$ of a sigma protocol Σ with probability at most

$$\varepsilon_{\mathsf{FS}(\Sigma)}(q) \leq (2q+1)^2 \varepsilon_\Sigma,$$

Where ε_Σ is the soundness error of Σ.

Don, J., Fehr, S., Majenz, C., & Schaffner, C., "Security of the Fiat-Shamir transformation in the quantum random-oracle model", Crypto 2019

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(Independent work: Liu&Zhandry, Crypto 2019, less tight…)

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Can we find a matching attack?

(Independent work: Liu&Zhandry, Crypto 2019, less tight…)

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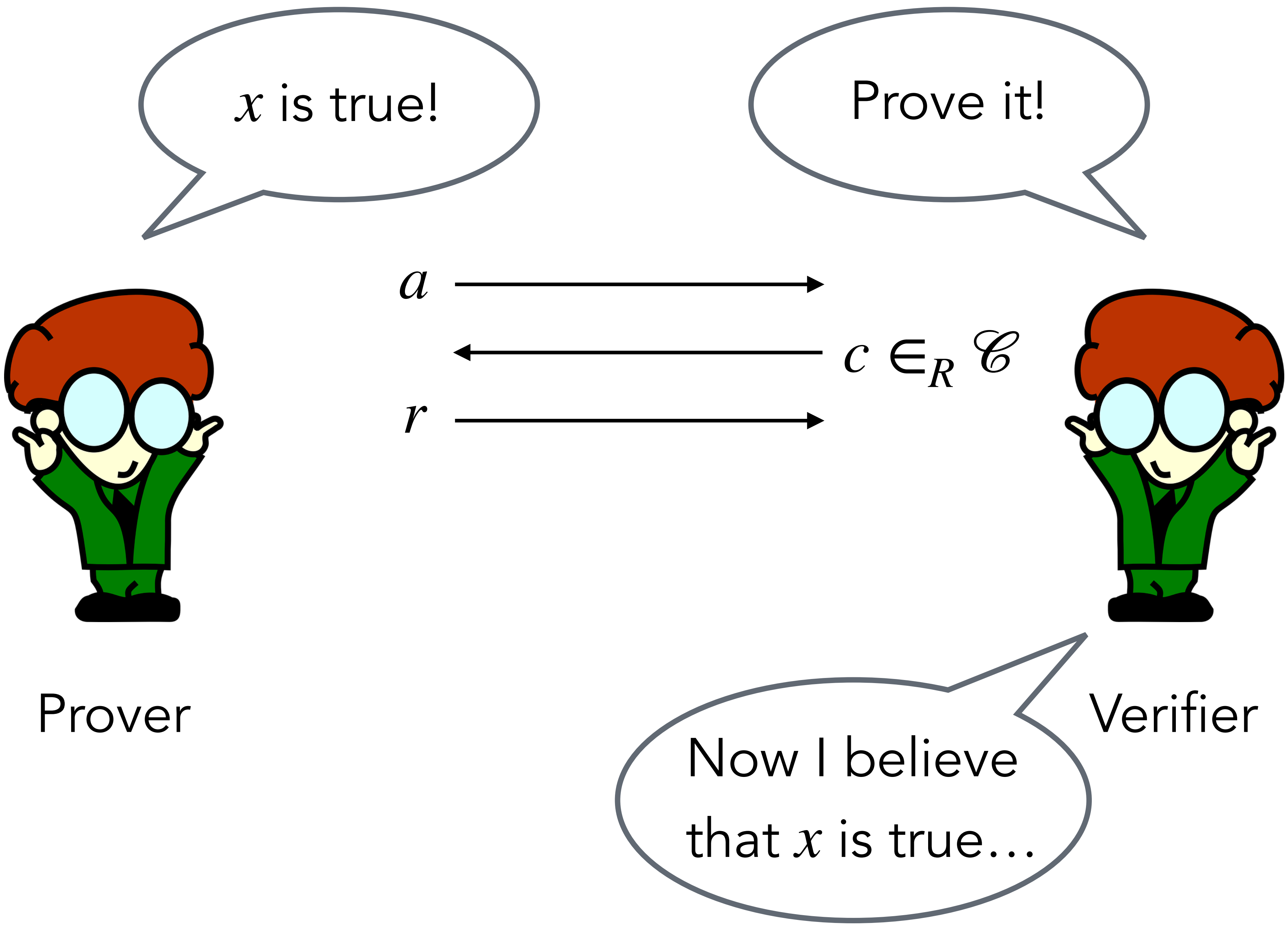
Liu, Q. and Zhandry, M., "Revisiting Post-Quantum Fiat-Shamir", Crypto 2019

Zero knowledge



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Formally: (a, c, r) can be *simulated*

Definition (Honest-verifier zero knowledge, informal):
A sigma protocol Σ is honest-verifier zero knowledge (HVZK) if there exists a simulator $\mathcal{S}$ such that for all true statements x, $(a, c, r) \leftarrow \mathcal{S}(x)$ is indistinguishable from a transcript from the protocol.

Attack

How can $\mathcal{S}$ even exist for Σ with soundness?

$\mathcal{S}(x)$ can choose (a, c, r) in any order!

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$$f_x^H(\rho) = \begin{cases} 1 & \text{if } \mathcal{S}(x;\rho) = (a, c, r) \text{ such that } H(x, a) = c \\ 0 & \text{else} \end{cases}$$

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Theorem (informal; Don, Fehr, M '20):

Let Σ be a sigma protocol that is perfectly HVZK and has special soundness + some mild additional properties. Then there exists a quantum polynomial-time attacker making q queries to H that succeeds with probability $\varepsilon_{\mathsf{FS}(\Sigma)}(q) \geq q^2 \varepsilon_\Sigma$.

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How relevant is the attack?

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How relevant is the attack?

Sigma protocols for Fiat-Shamir signatures

- are HVZK
- Have special soundness or similar

The QROM is uninstantiable

Did we figure out Fiat-Shamir?

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Theorem (Canetti, Goldreich, Halevi '98):

There exists a digital signature scheme Π^H using a hash function H, such that

i) Π^H is secure in the ROM

ii) Π^H is insecure for any efficient H

Canetti, R., Goldreich, O., Halevi, S., "The random oracle methodology, revisited", STOC 1998

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The digital signature scheme Π^H from above is secure in the QROM.

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Theorem (Eaton and Song '19):
The digital signature scheme Π^H from above is secure in the QROM.

Better attacks possible, but likely using structure of H.

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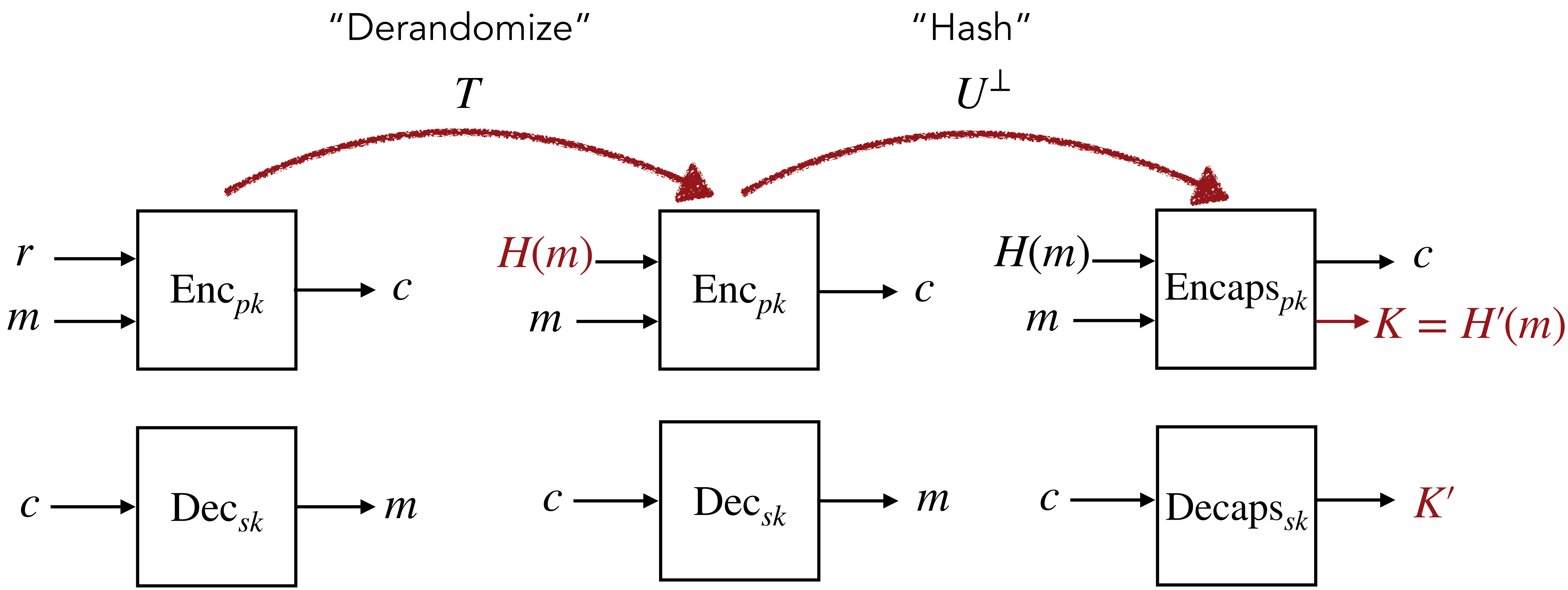
Fujisaki-Okamoto transformation

Upgrades weak security to chosen-ciphertext security for key encapsulation

“Derandomize, then Hash”



$$K' = \begin{cases} m & K = \mathrm{Enc}_{pk}(m, H(m)) \\ \perp & \text{else} \end{cases}$$

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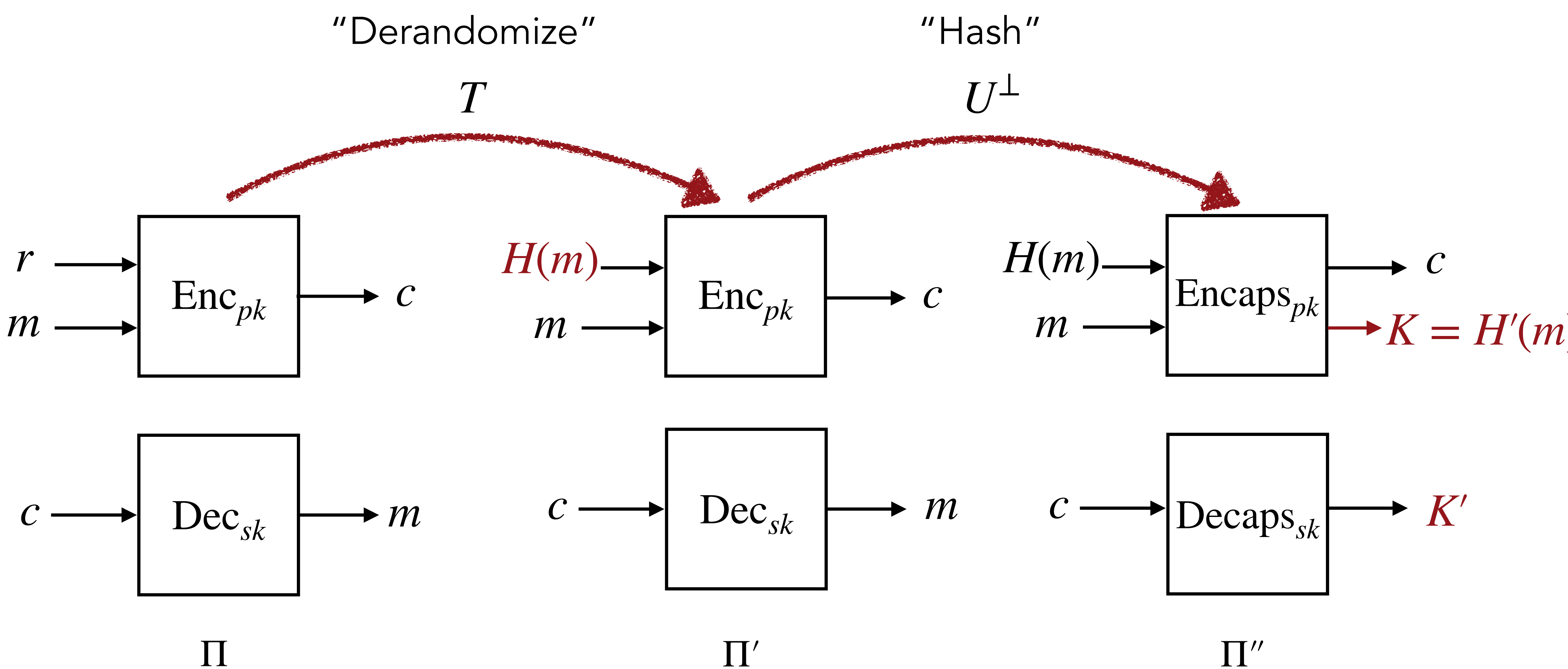

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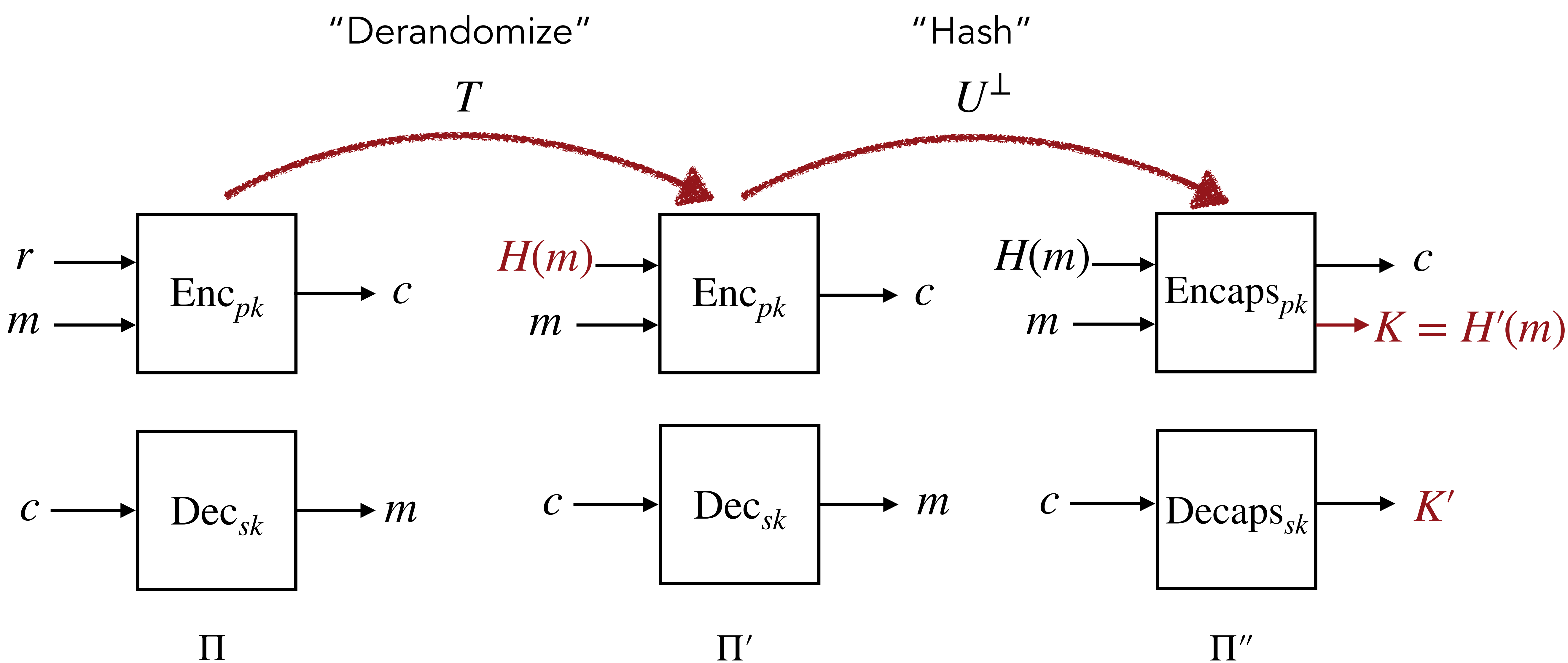

For proving post-quantum security, model H, H' as random oracles (QROM)

Fujisaki-Okamoto transformation in the QROM

Π IND-CPA Π' OW-CPA Π'' IND-CCA

Fujisaki-Okamoto transformation in the QROM

Π IND-CPA

Π' OW-CPA $\xrightarrow[\text{Tight reduction}]{U^{\not\perp}}$ Π'' IND-CCA

Bindel, N., Hamburg, M., Hövelmanns, K., Hülsing, A., & Persichetti, E. “Tighter proofs of CCA security in the quantum random oracle model” TCC 2019

Fujisaki-Okamoto transformation in the QROM

$$\Pi \text{ IND-CPA} \xrightarrow[\text{Lossy reduction}]{T} \Pi' \text{ OW-CPA} \xrightarrow[\text{Tight reduction}]{U^{\not\perp}} \Pi'' \text{ IND-CCA}$$

Multiplicative loss q

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Tight in the classical ROM!

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No attack known that exploits this gap

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Fujisaki-Okamoto transformation in the QROM

$$\begin{tikzcd} \Pi \text{ IND-CPA} \arrow[r, dashed, "T", "\text{Lossy reduction}"'] & \Pi' \text{ OW-CPA} \arrow[r, "U^{\not\perp}", "\text{Tight reduction}"'] & \Pi'' \text{ IND-CCA} \end{tikzcd}$$

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Vanilla approach (Grover)?

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$$\Pi\ \text{IND-CPA} \overset{T}{\dashrightarrow} \Pi'\ \text{OW-CPA} \xrightarrow{U^{\not\perp}} \Pi''\ \text{IND-CCA}$$

Lossy reduction

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Vanilla approach (Grover)? Probably not…

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Other algorithms?

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T: Lossy reduction

Multiplicative loss q

$U^{\not\perp}$: Tight reduction

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(This is the question from Dan's email)

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Lossy reduction

Multiplicative loss q

Tight reduction

Reductions in the QROM

No attack known that exploits this gap

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Lossy reduction

Multiplicative loss q

Tight reduction

Reductions in the QROM
⇒ same insufficiency as for FS

No attack known that exploits this gap

Vanilla approach (Grover)? Probably not…

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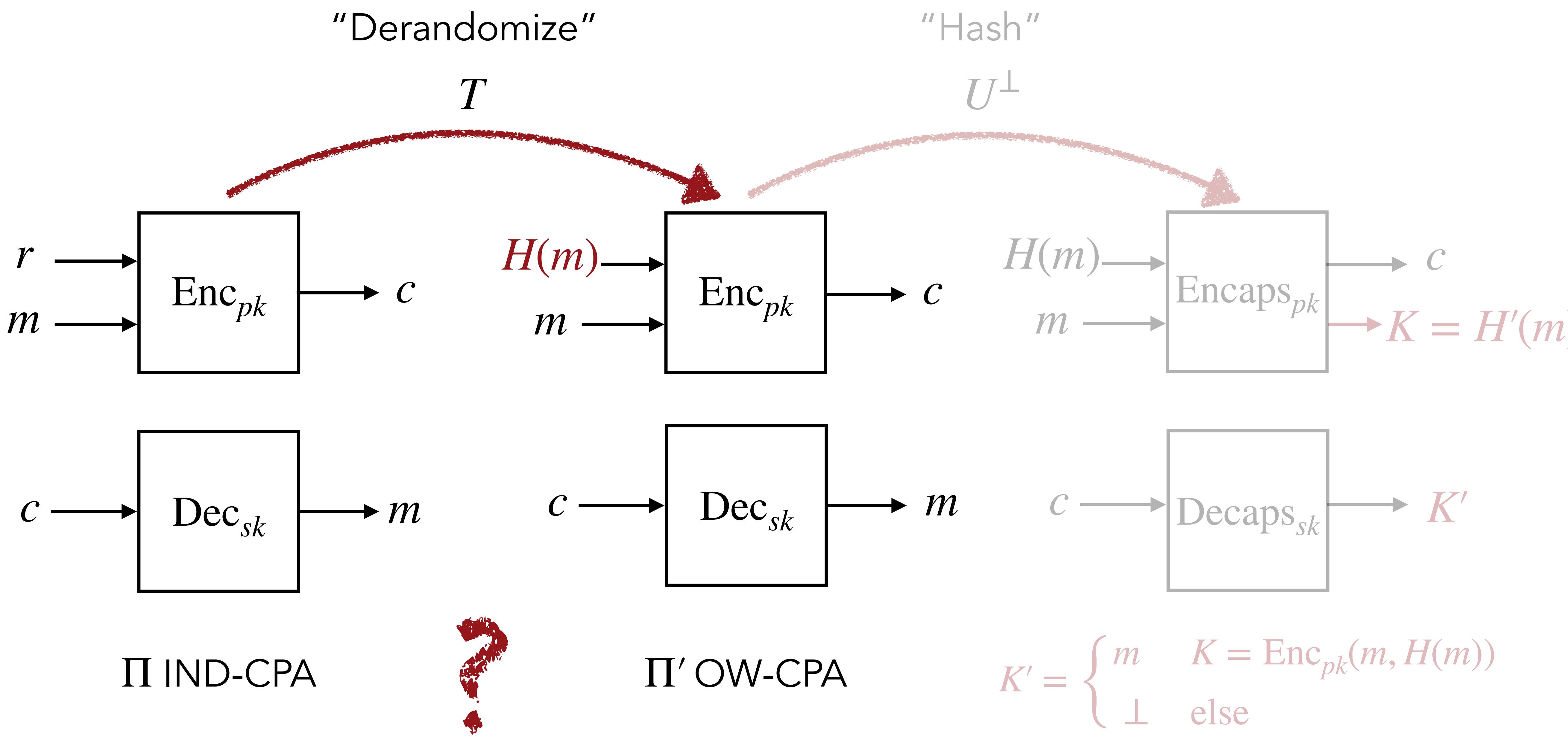

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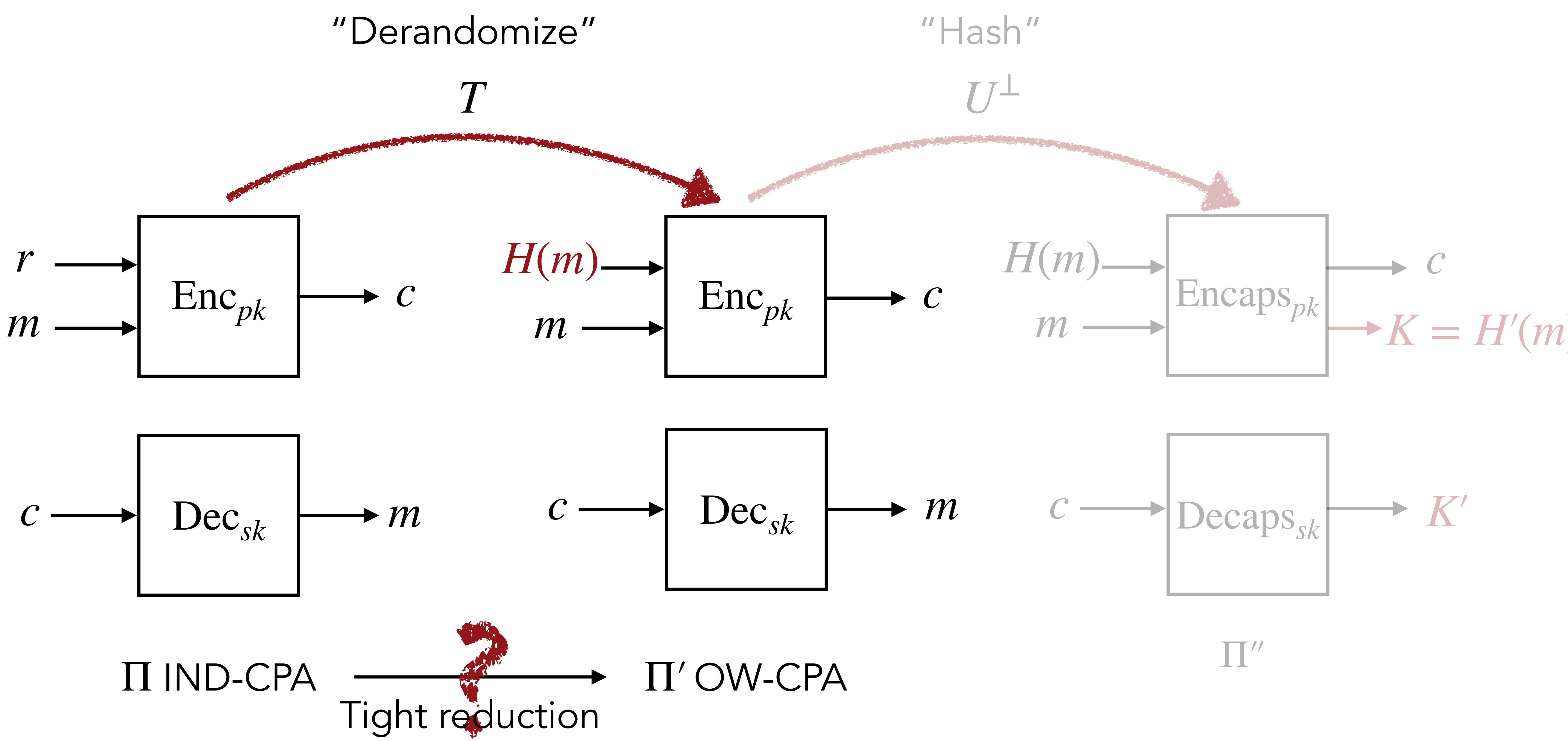


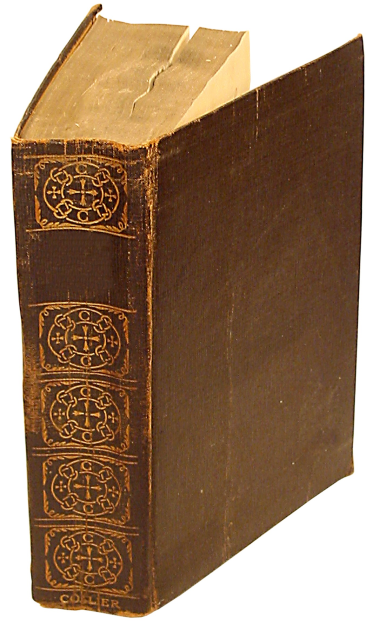
Summary

Hash functions are used everywhere. ⇒We need to subject them to quantum cryptanalysis!

Attacks possible at different levels

Hash function application in schemes: some open questions regarding attacks

Polynomial improvements over trivial, but: important for parameter choice



Thanks!