zkSNARKs in the ROM with Unconditional UC-Security

TL;DR Micali and BCS are UC-secure in the GROM

Giacomo Fenzi @ EPFL

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Joint work with Alessandro Chiesa

EPFL

Motivation

zkSNARKs are deployed in the real world

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zkSNARKs are ZKPs where verification is **exponentially** faster than execution.

zkSNARKs are deployed in the real world

E.g.: proof based rollups to improve scalability

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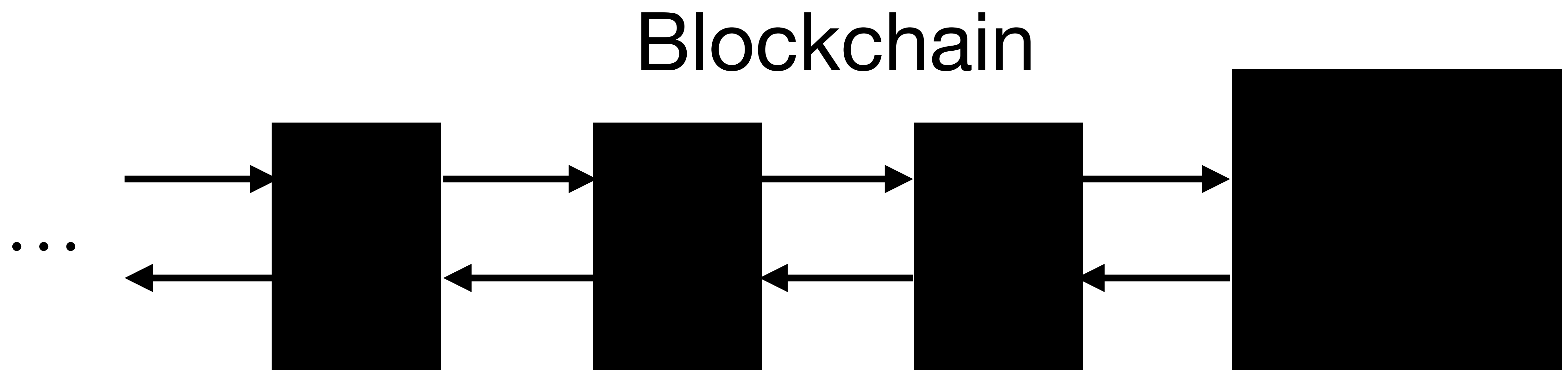
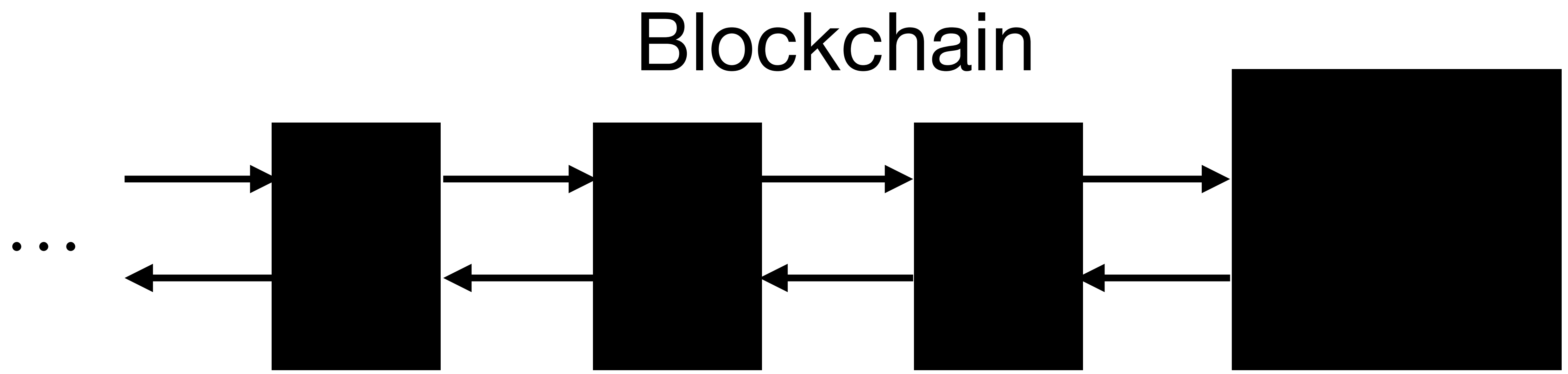
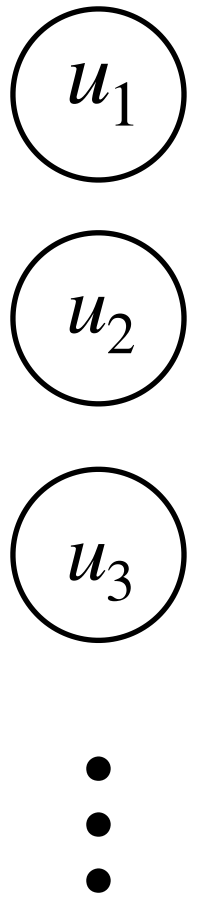


zkSNARKs are deployed in the real world

E.g.: proof based rollups to improve scalability

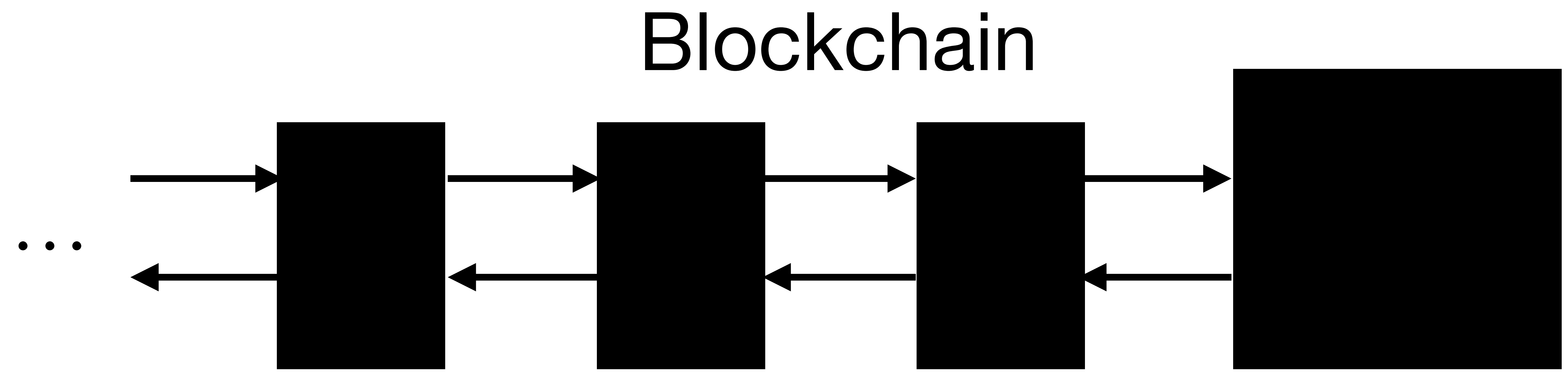


Rollup Users



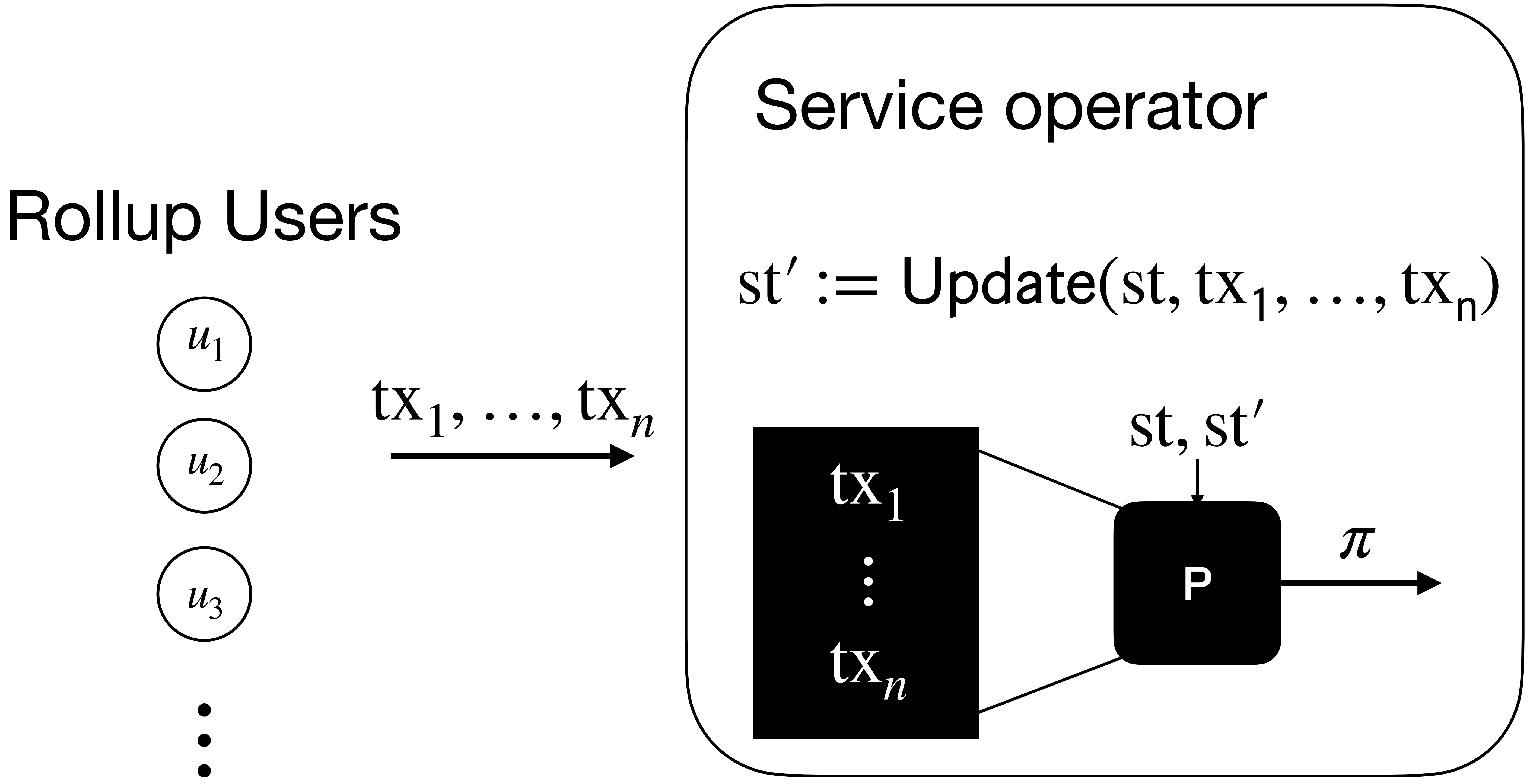
zkSNARKs are deployed in the real world

E.g.: proof based rollups to improve scalability



Blockchain

…



Service operator

Rollup Users

$\mathrm{st}' := \mathsf{Update}(\mathrm{st}, \mathrm{tx}_1, \ldots, \mathrm{tx}_n)$

u_1

u_2

u_3

$\mathrm{tx}_1, \ldots, \mathrm{tx}_n$

tx_1

⋮

tx_n

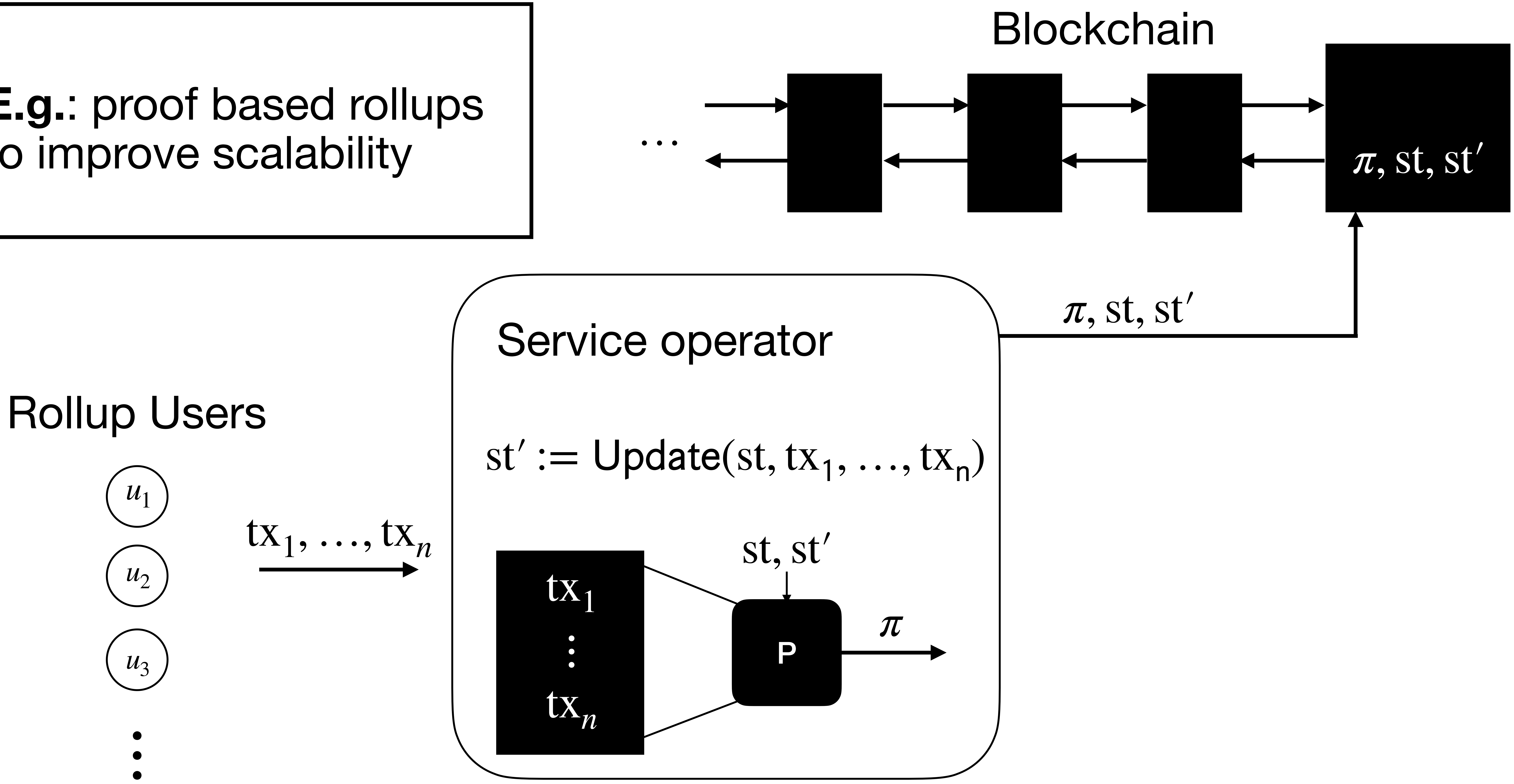
$\mathrm{st}, \mathrm{st}'$

P

π

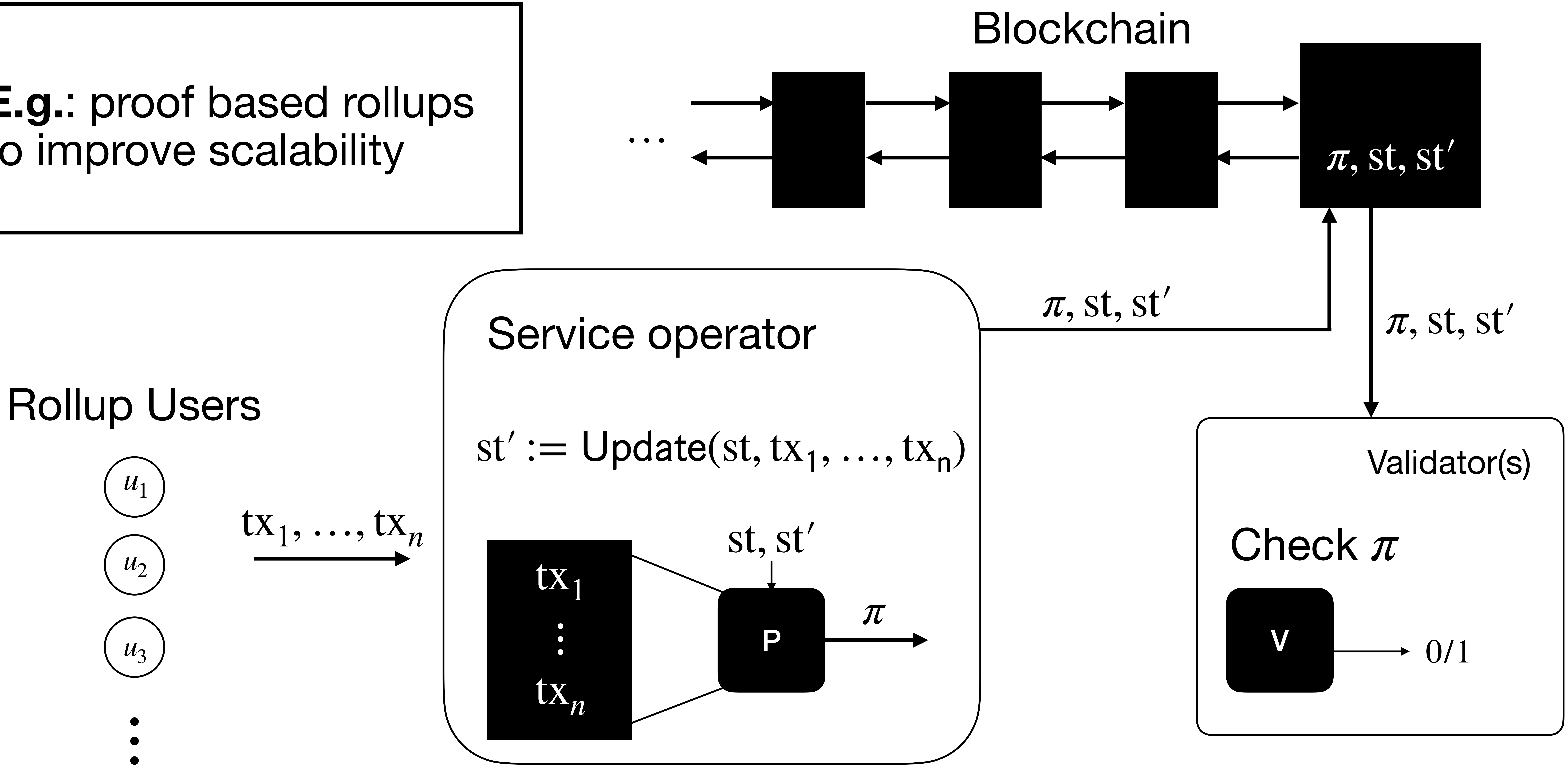
zkSNARKs are deployed in the real world

E.g.: proof based rollups to improve scalability



zkSNARKs are deployed in the real world

E.g.: proof based rollups to improve scalability



Blockchain

…

π, st, st$'$

Service operator

$\mathrm{st}' :=$ Update(st, $\mathrm{tx}_1, \ldots, \mathrm{tx}_\mathrm{n}$)

tx_1 ⋮ tx_n

st, st$'$

P

π

π, st, st$'$

π, st, st$'$

Rollup Users

u_1

u_2

u_3

⋮

$\mathrm{tx}_1, \ldots, \mathrm{tx}_n$

Validator(s)

Check π

V

0/1

Goal: Modular Security Analysis

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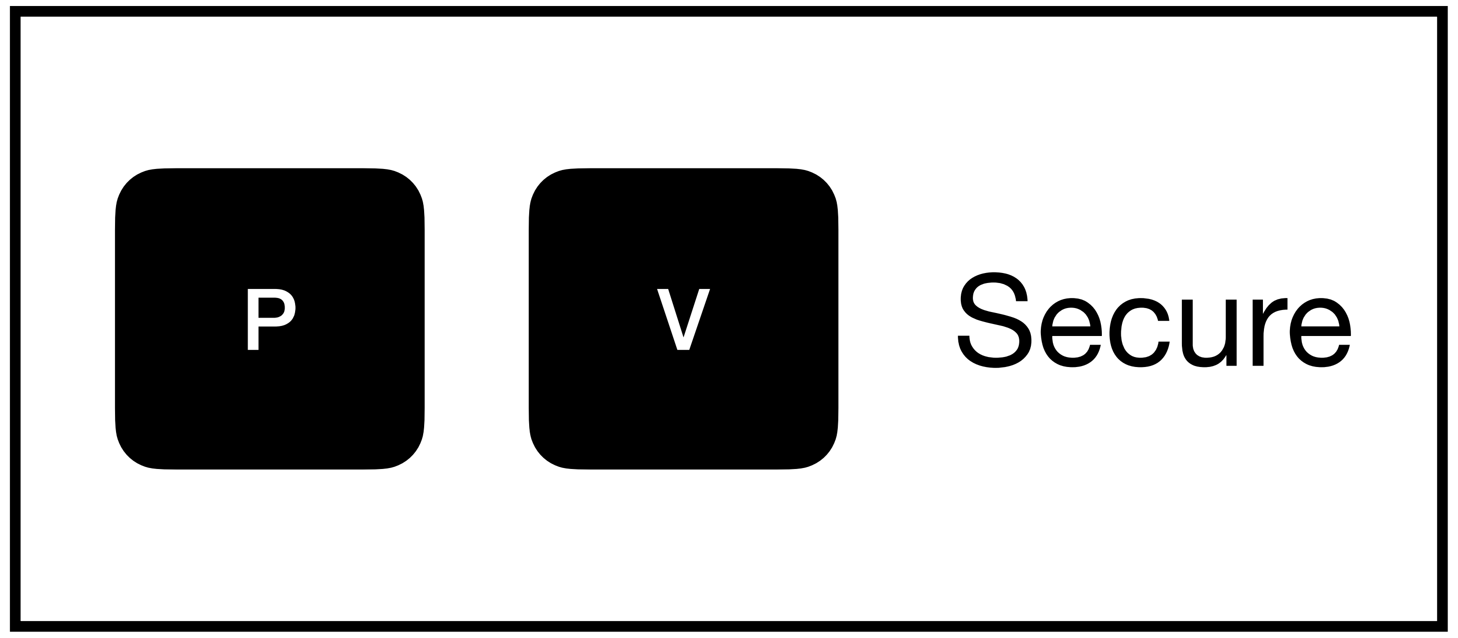
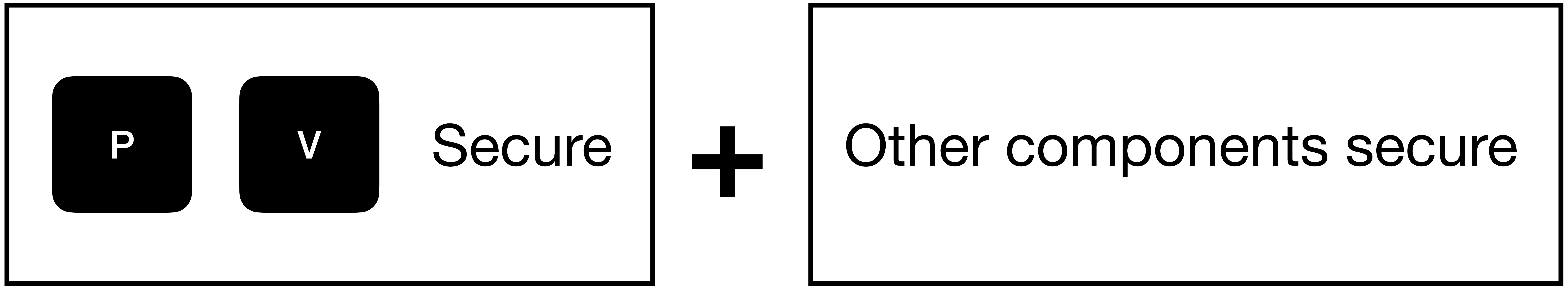


P

V

Secure

Goal: Modular Security Analysis



Secure + Other components secure

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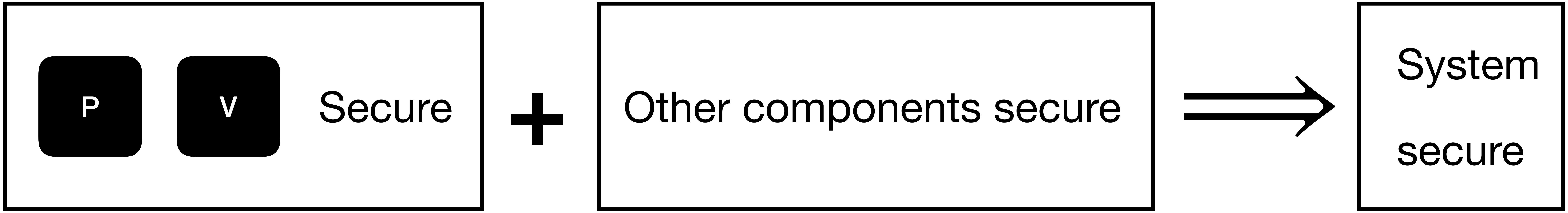
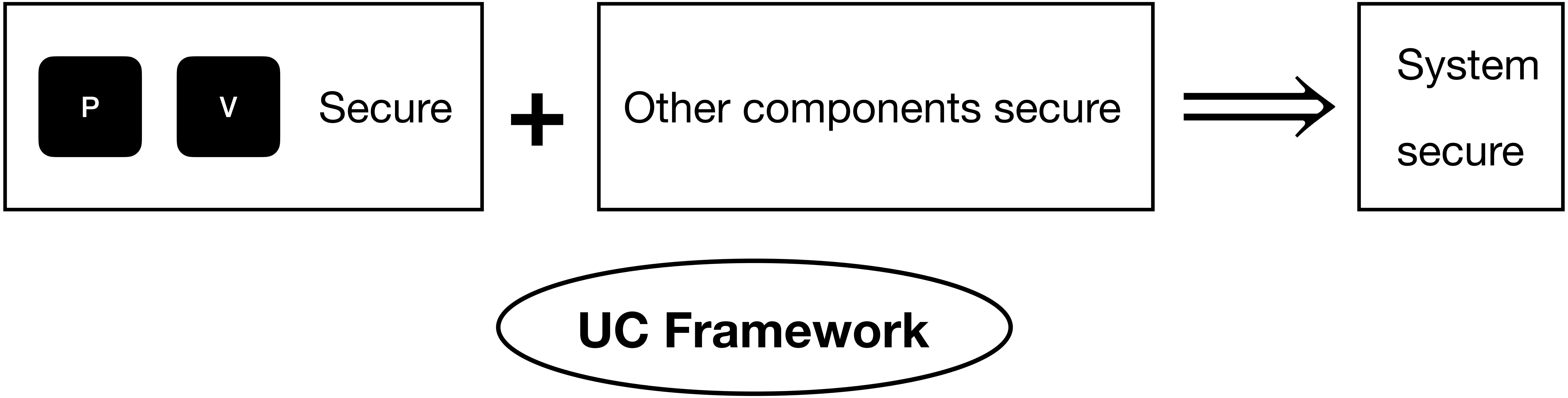


Secure + Other components secure ⟹ System secure

Goal: Modular Security Analysis



P

V

Secure

+

Other components secure

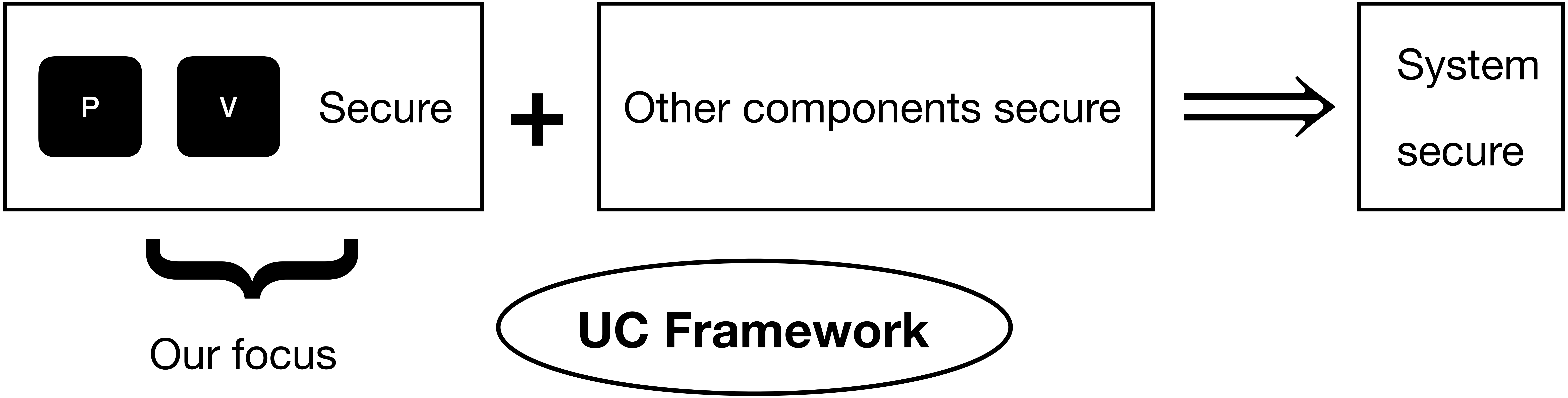
⟹

System

secure

UC Framework

Goal: Modular Security Analysis



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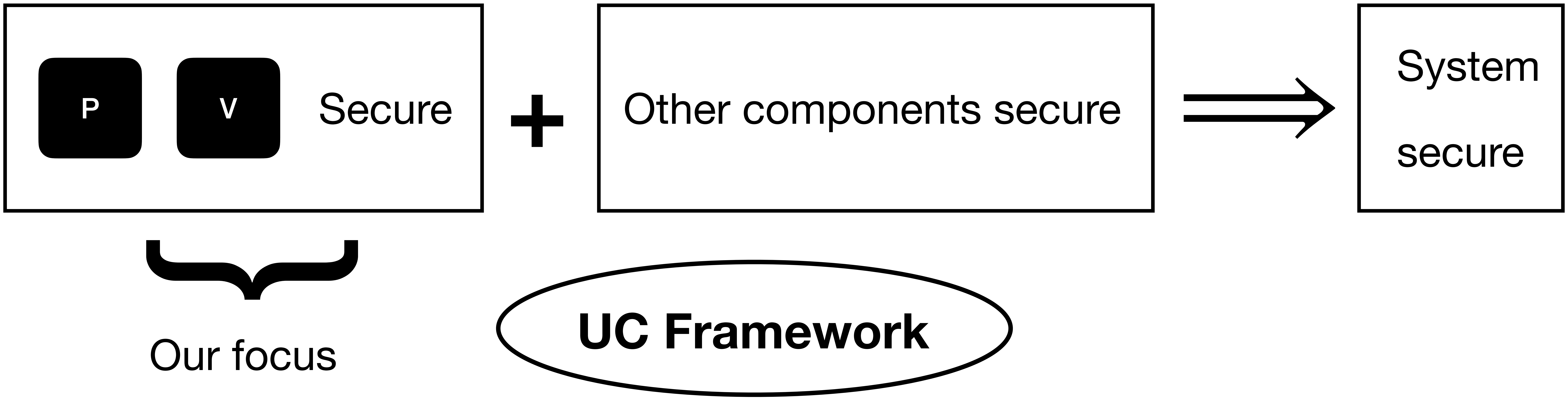
System secure

Our focus

UC Framework

Goal: Modular Security Analysis



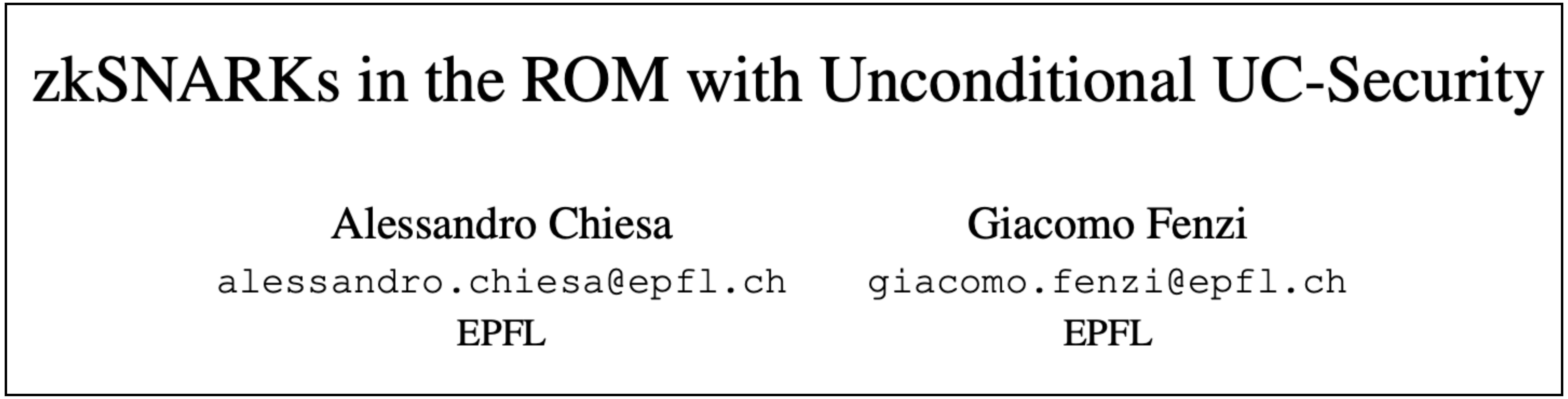
P V Secure + Other components secure ⟹ System secure

Our focus

UC Framework

Which zkSNARKs are UC-secure?

This work



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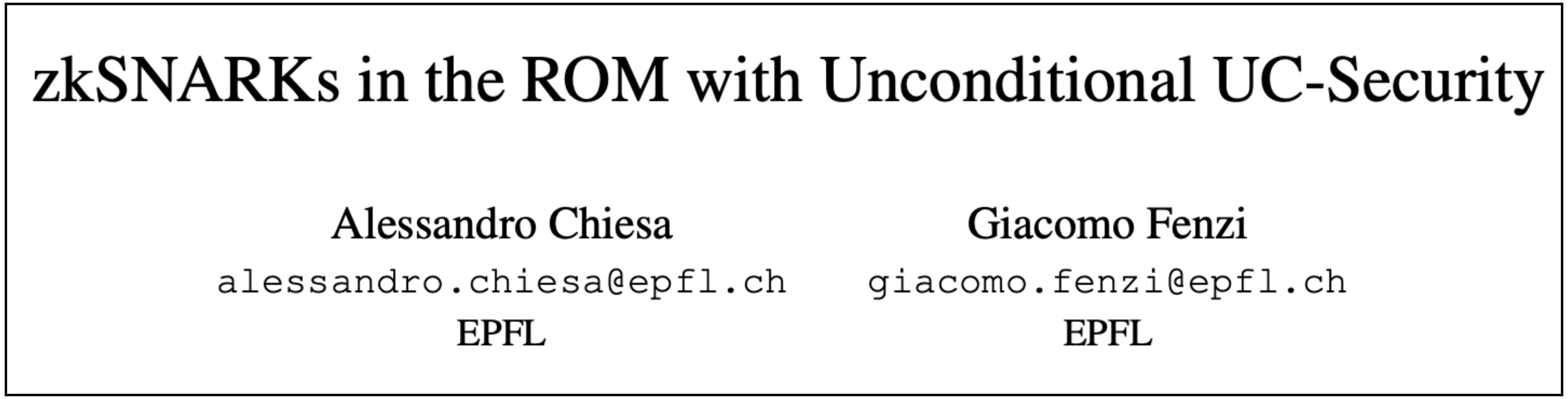

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Show **existing** zkSNARKs are UC-secure
(including deployed ones)

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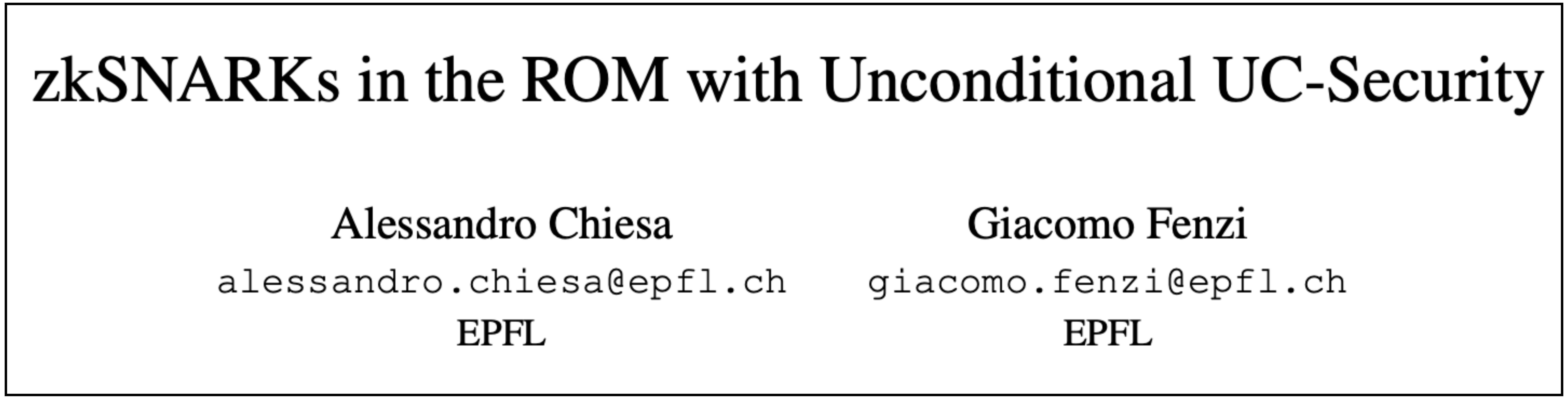

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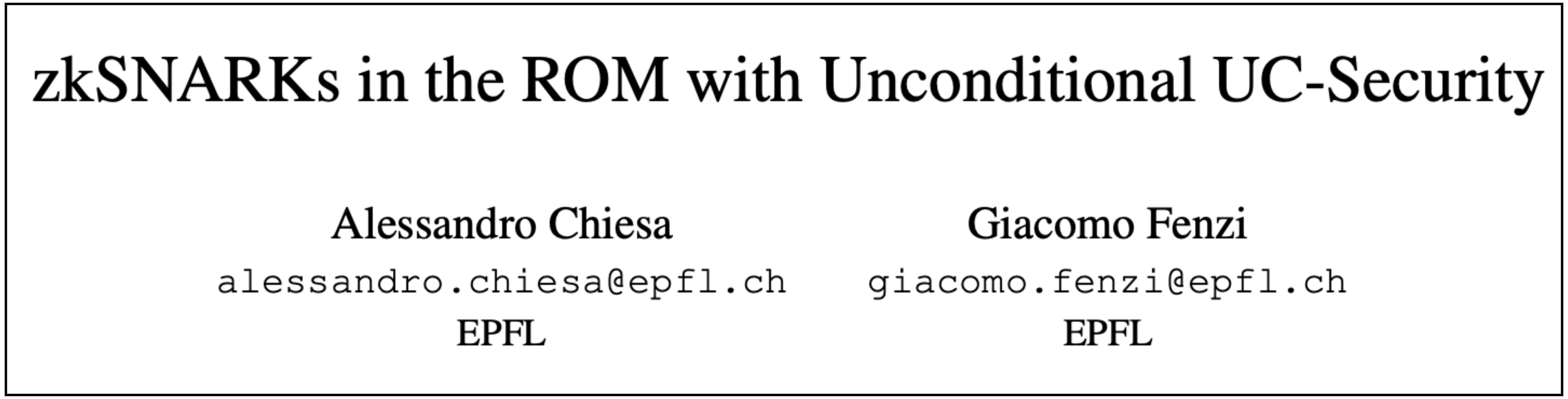

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ROM **only**: transparent, post-quantum,
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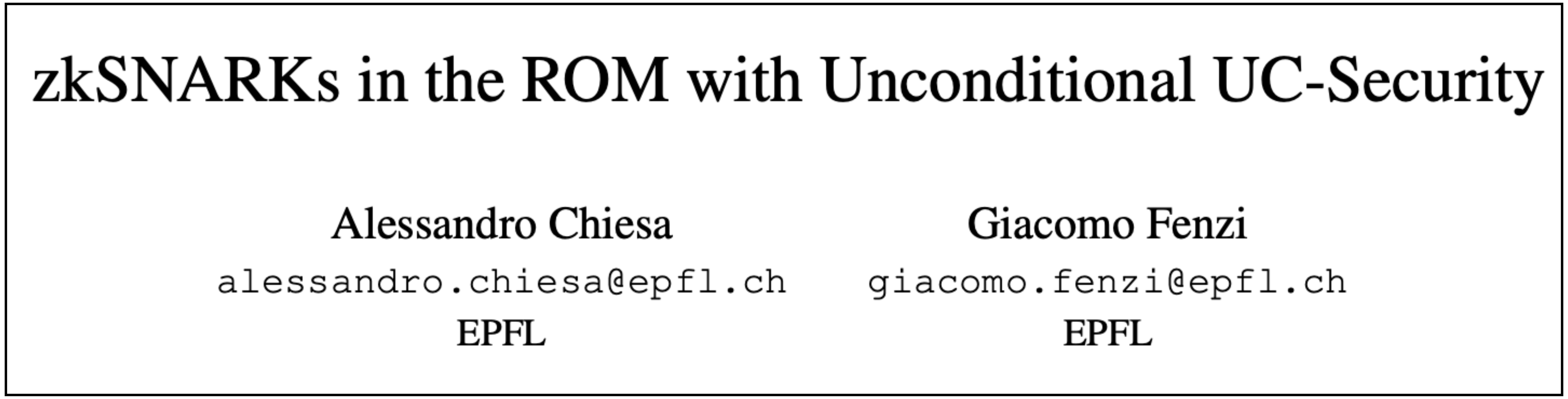

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Show **existing** zkSNARKs are UC-secure (including deployed ones)

Succinct

ROM **only**: transparent, post-quantum, unconditional security

Concrete security bounds: useful for practitioners

Our results

Main Thm.

There exists a zkSNARK that is unconditionally UC-secure in the GROM

Lemma

Let ARG *be a "UC-friendly" argument in the ROM.*

Then, $\Pi[\mathsf{ARG}]$ *is UC-secure in the GROM*

Theorem

The Micali construction is "UC-friendly" in the ROM, provided that the underlying PCP is honest-verifier zero knowledge and knowledge sound.

Corollary

The Micali construction is UC-secure in the GROM, when instantiated as above.

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The Micali construction is "UC-friendly" in the ROM, provided that the underlying PCP is honest-verifier zero knowledge and knowledge sound.

Same conditions required for KS of Micali in the ROM

Corollary

The Micali construction is UC-secure in the GROM, when instantiated as above.

Theorem

The ***BCS*** *construction is "UC-friendly" in the ROM, provided that the underlying* ***IOP*** *is honest-verifier zero knowledge and* ***(state-restoration)*** *knowledge sound.*

Corollary

The ***BCS*** *construction is UC-secure in the GROM, when instantiated as above.*

Theorem

*The **BCS** construction is "UC-friendly" in the ROM, provided that the underlying **IOP** is honest-verifier zero knowledge and **(state-restoration)** knowledge sound.*

Same conditions required for KS of BCS in the ROM

Corollary

*The **BCS** construction is UC-secure in the GROM, when instantiated as above.*

Techniques

GROM

[CDGLN18]

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Goal: ROM-like interface shared by **all** parties in the security experiment

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[CDGLN18]

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Flavor: **r**estricted **p**rogrammable and **o**bservable **g**lobal **r**andom **o**racle

GROM

[CDGLN18]

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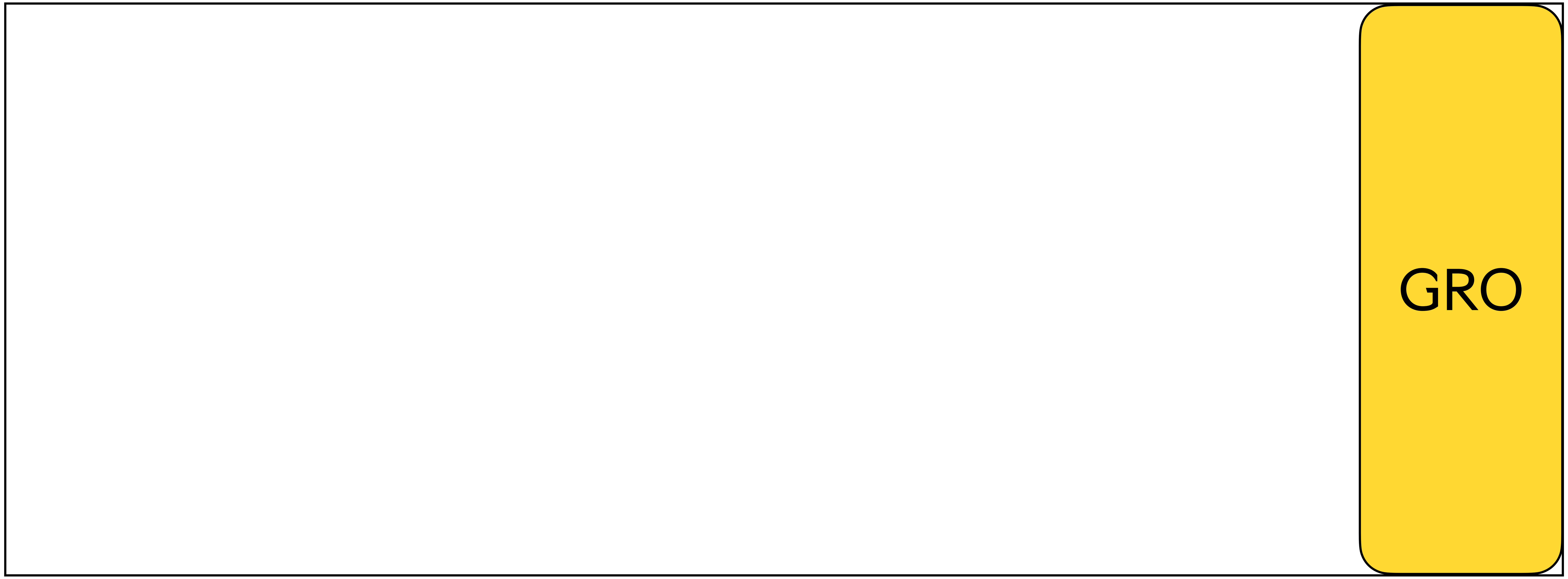

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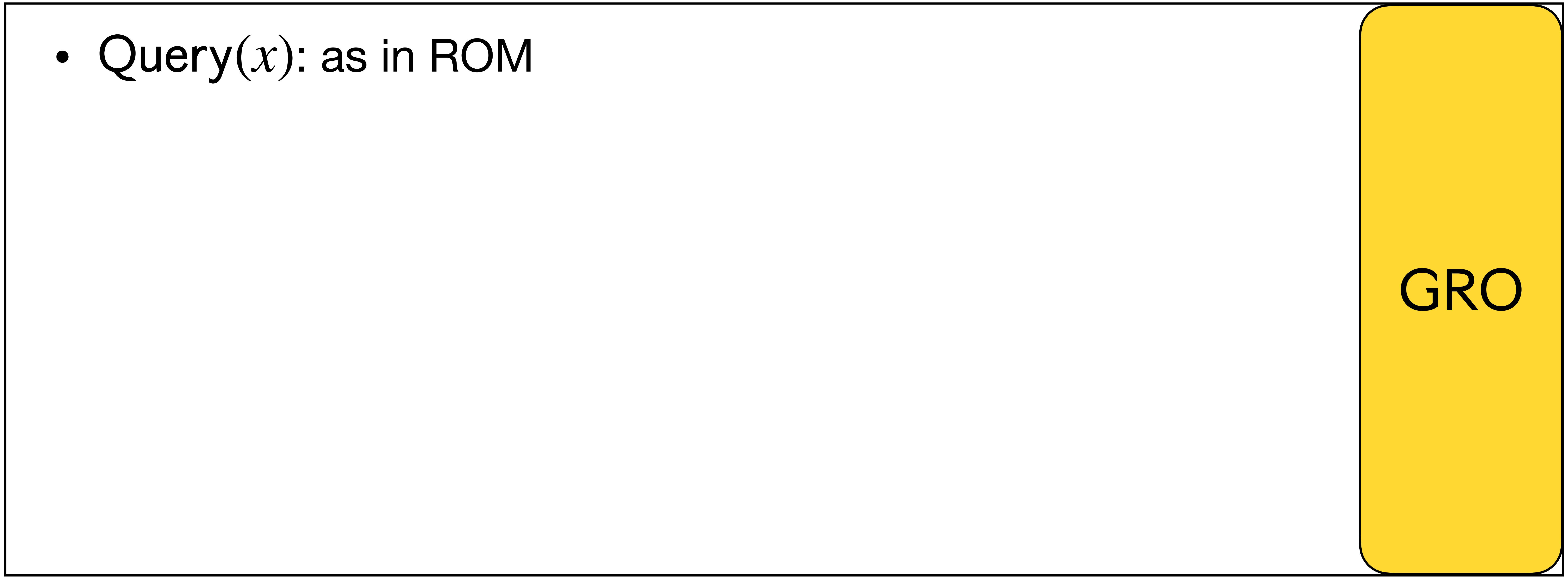

- Query(x): as in ROM

GROM

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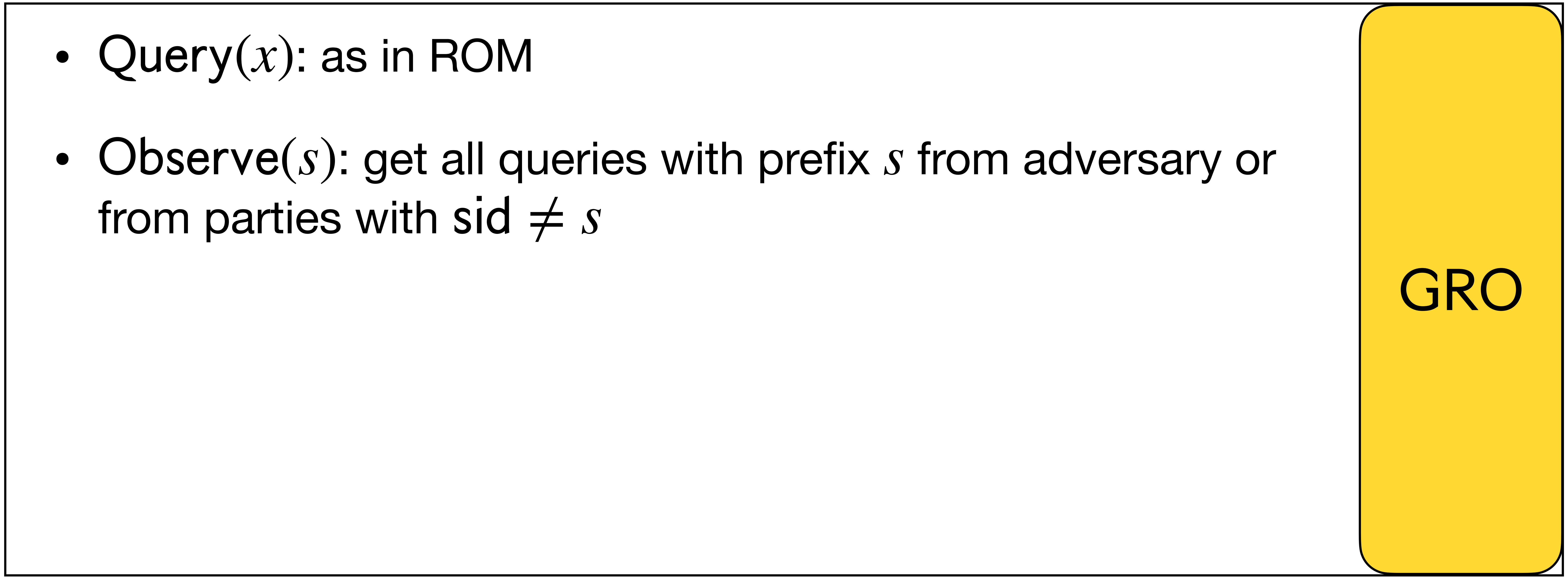

- Query(x): as in ROM
- Observe(s): get all queries with prefix s from adversary or from parties with sid $\neq s$

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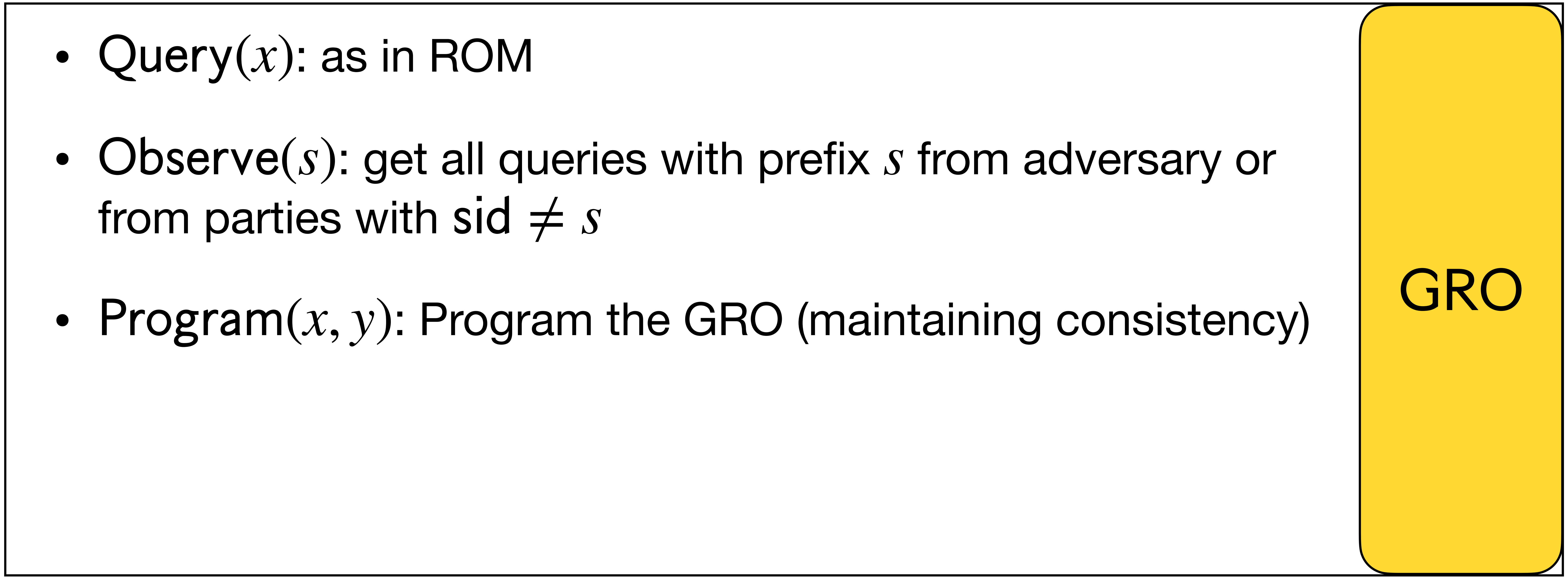

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- Program(x, y): Program the GRO (maintaining consistency)

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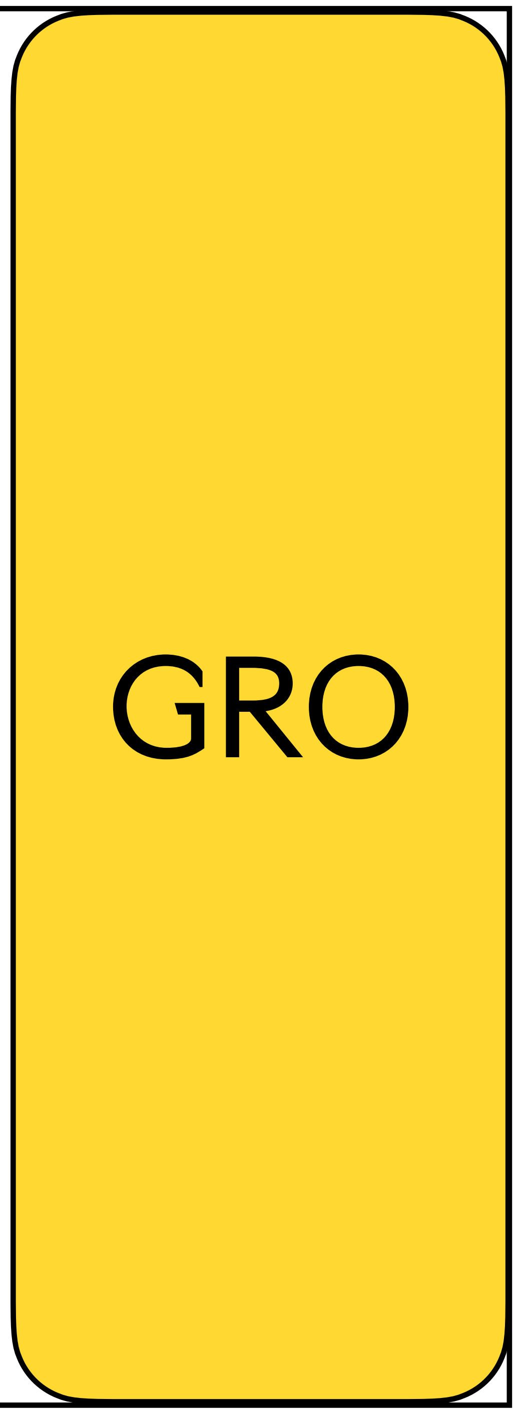
- $\mathsf{Program}(x, y)$: Program the GRO (maintaining consistency)
- $\mathsf{IsProgrammed}(x)$: allows parties in session sid to check if a $x = \mathsf{sid} \circ x'$ has been programmed



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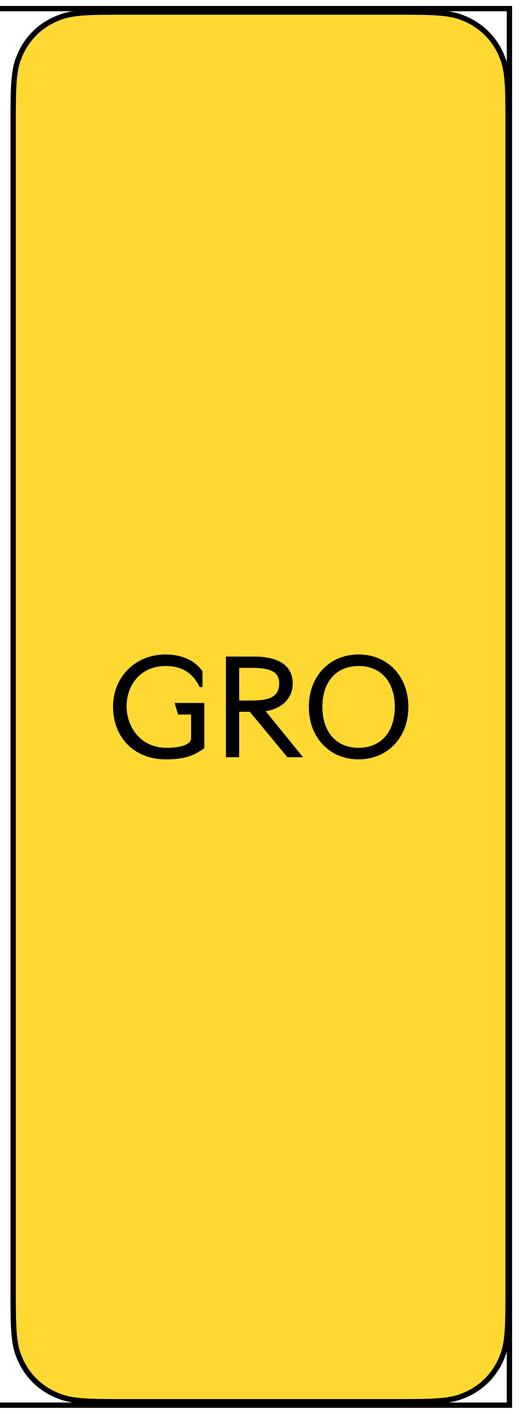

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- Program(x, y): Program the GRO (maintaining consistency)
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GRO

Crucial: Simulator can program points without being detected!

UC with Budgets

Plain UC only models adversaries that are **computationally** bounded using import

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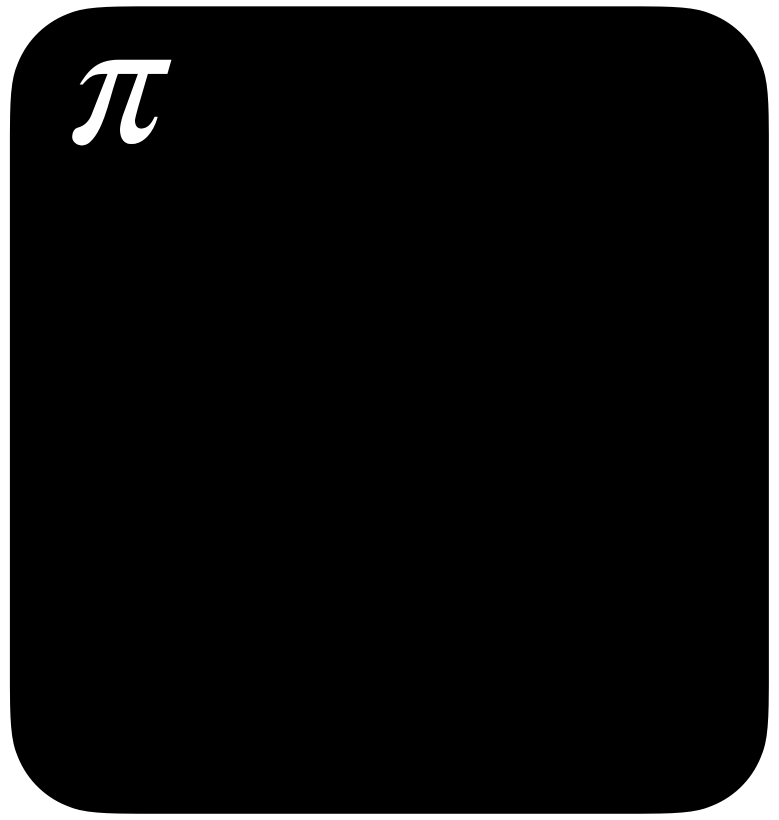

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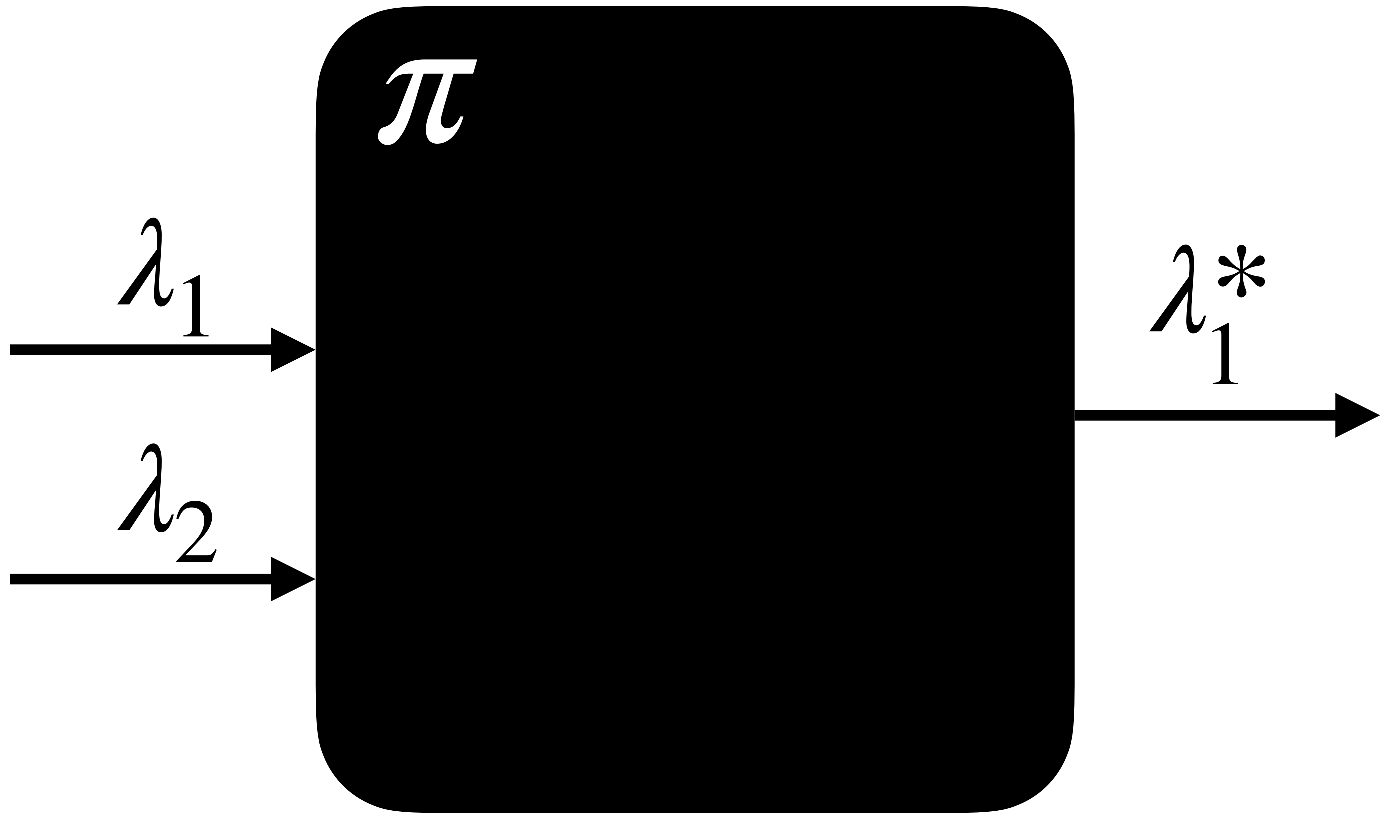

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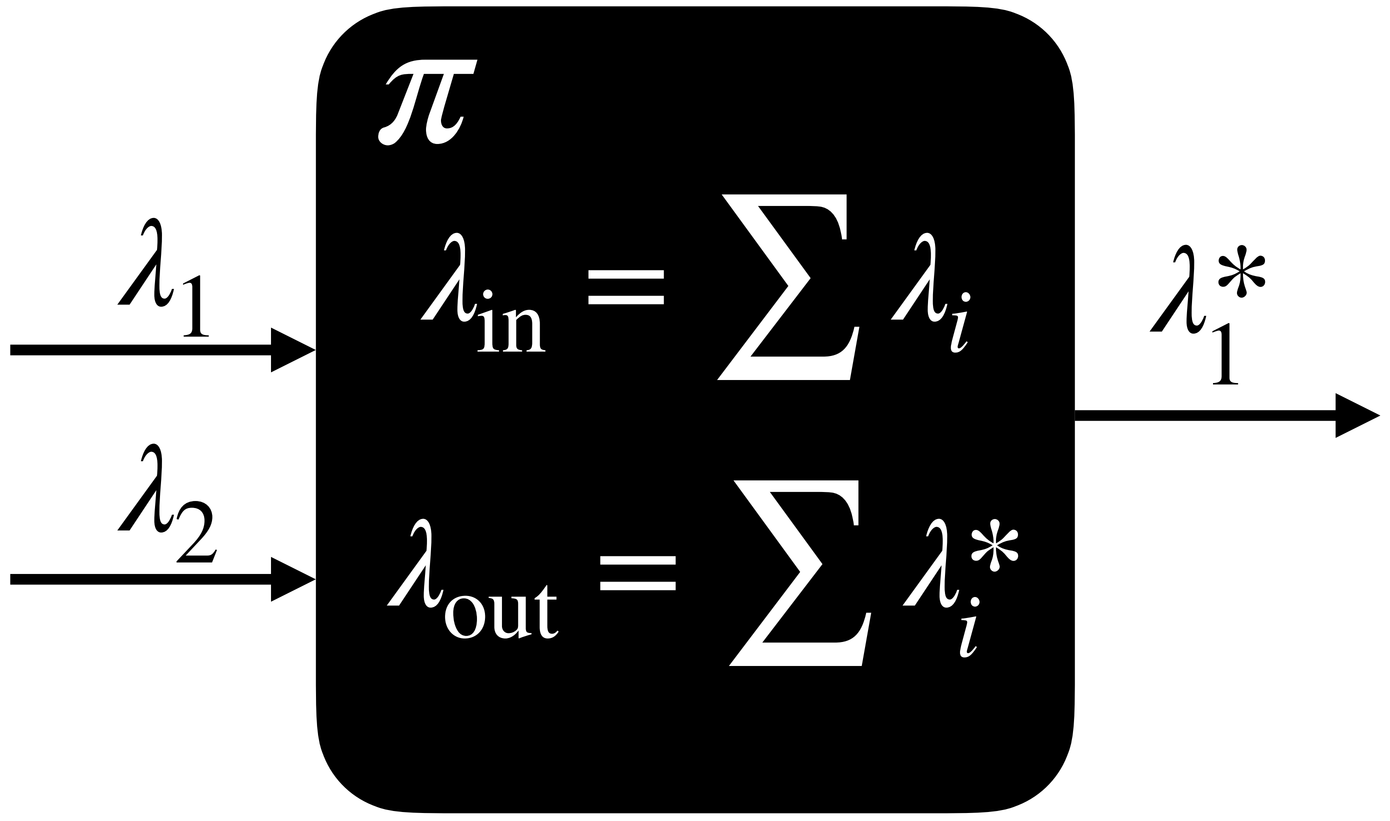

π
λ_1
λ_2
$\lambda_{\text{in}} = \sum \lambda_i$
$\lambda_{\text{out}} = \sum \lambda_i^*$
λ_1^*

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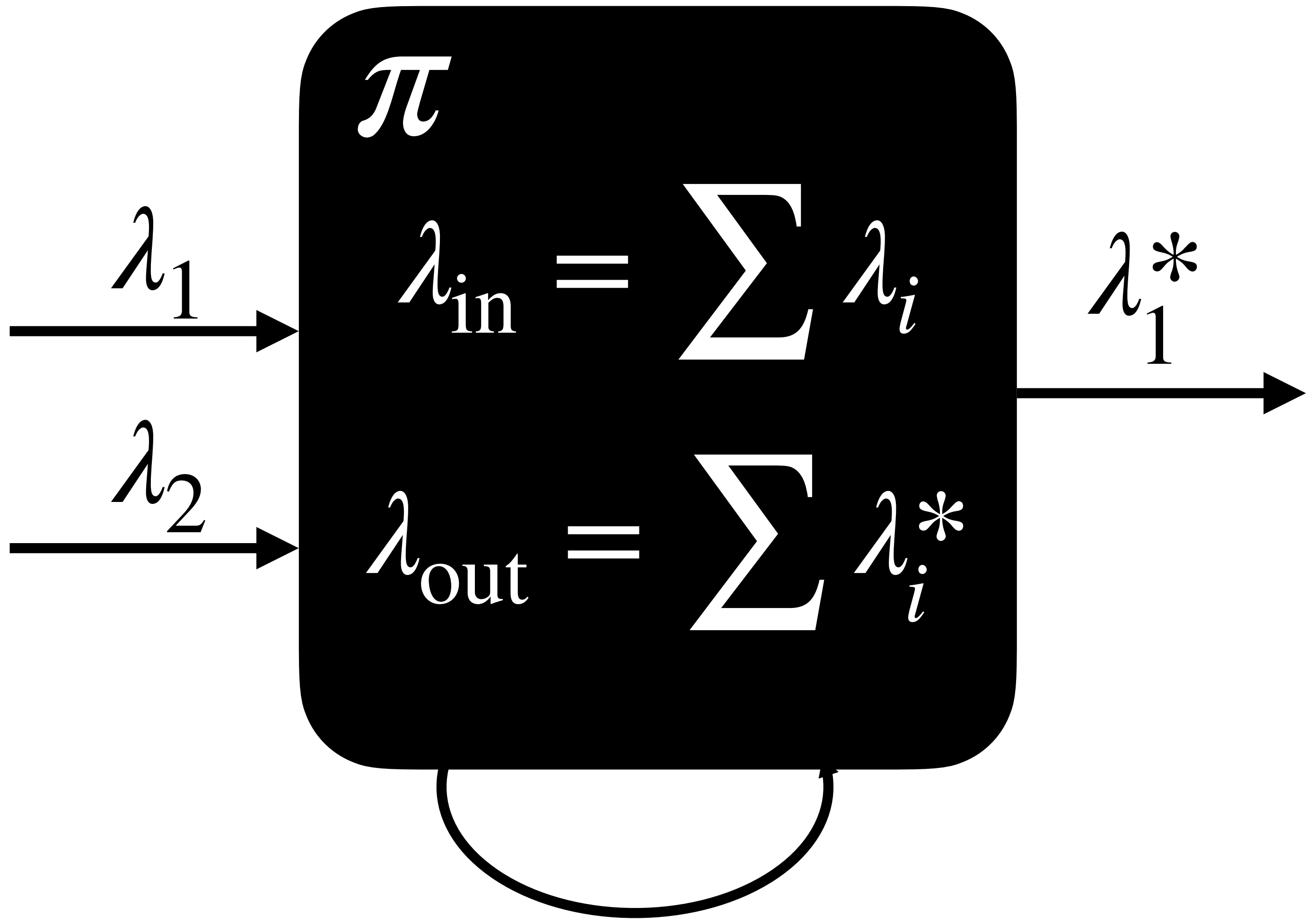

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$\lambda_{\text{in}} = \sum \lambda_i$

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time$(\pi) \leq p(\lambda_{\text{in}} - \lambda_{\text{out}})$

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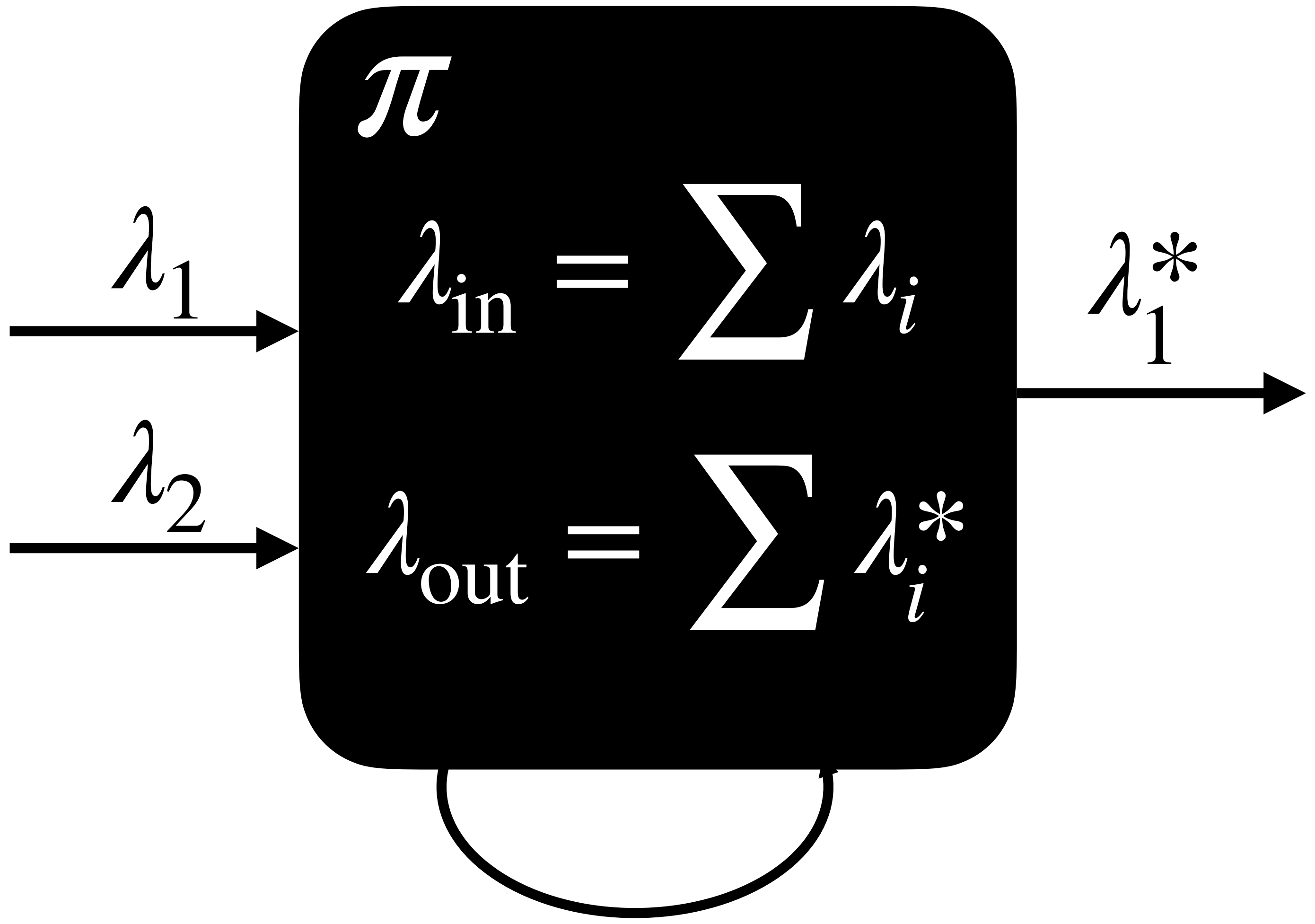
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We consider adversaries that are **resource** bounded and computationally **unbounded.** We model this introducing budgets

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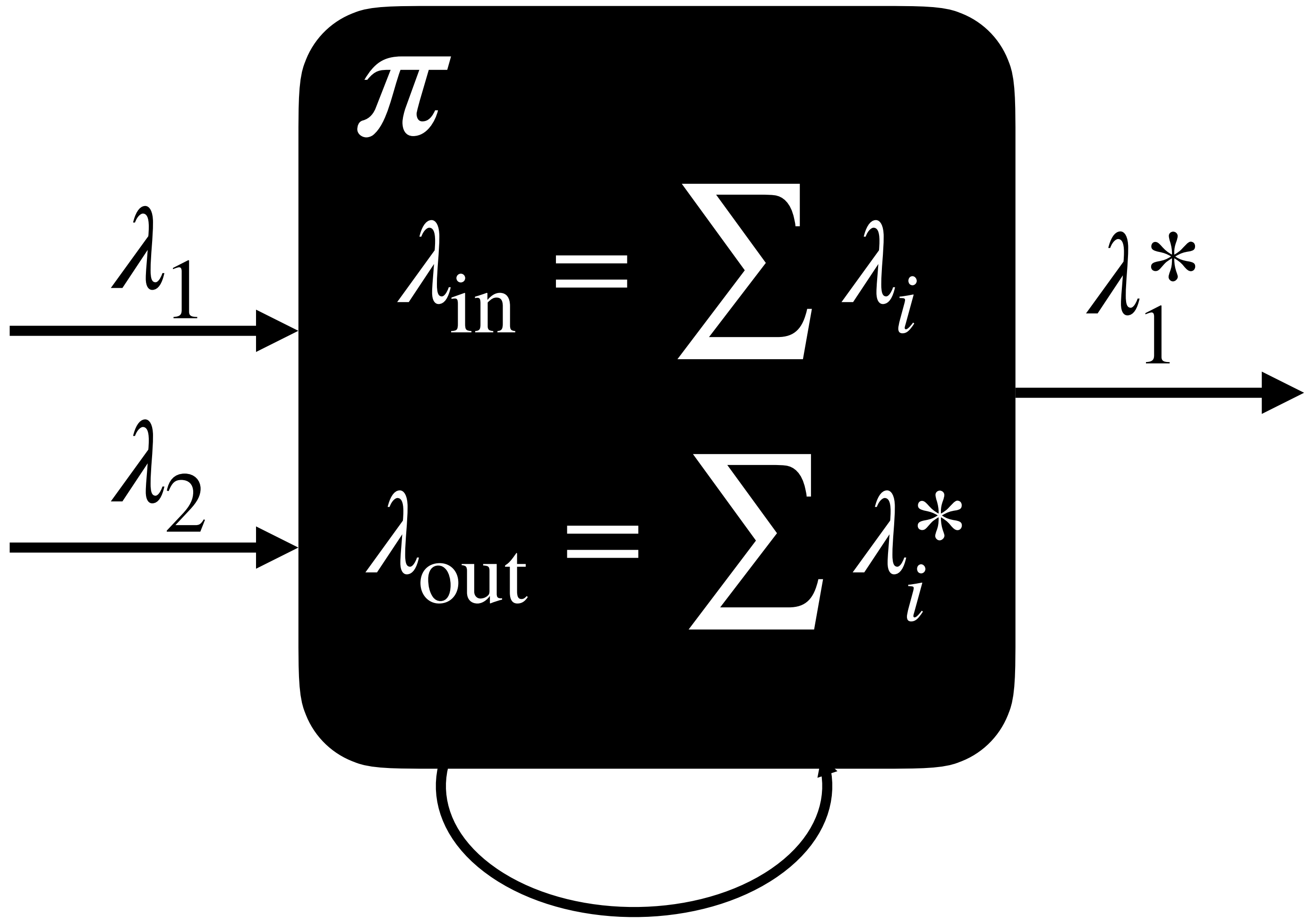
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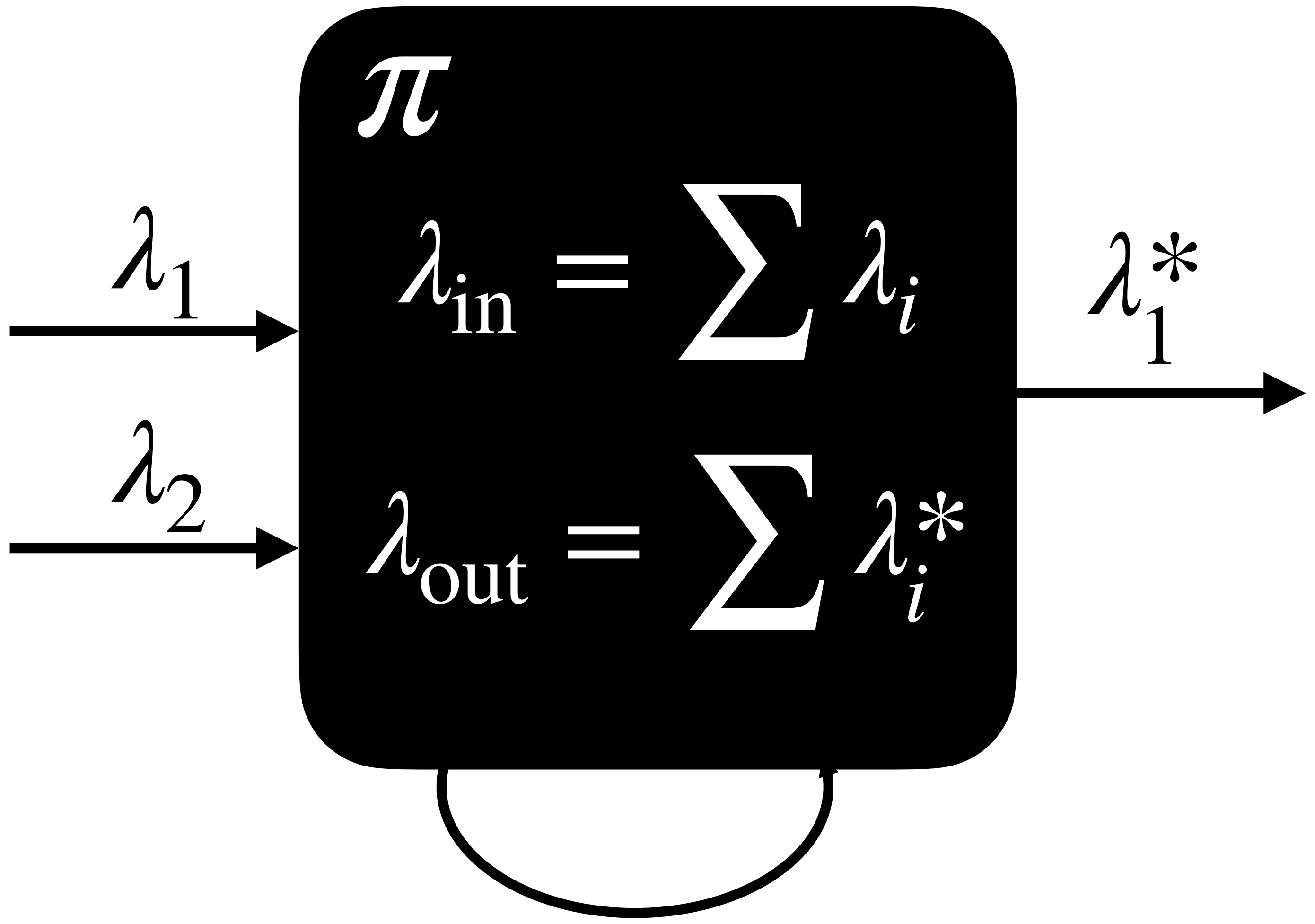

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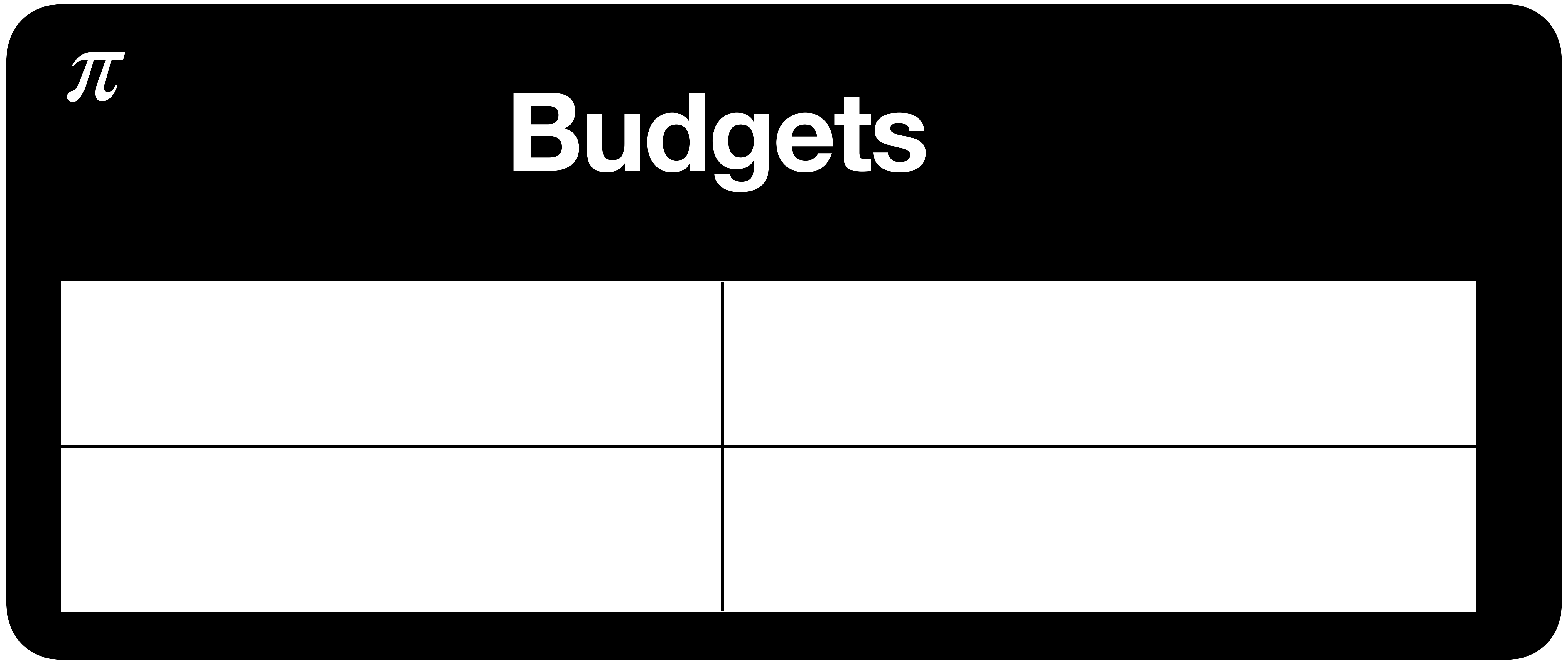

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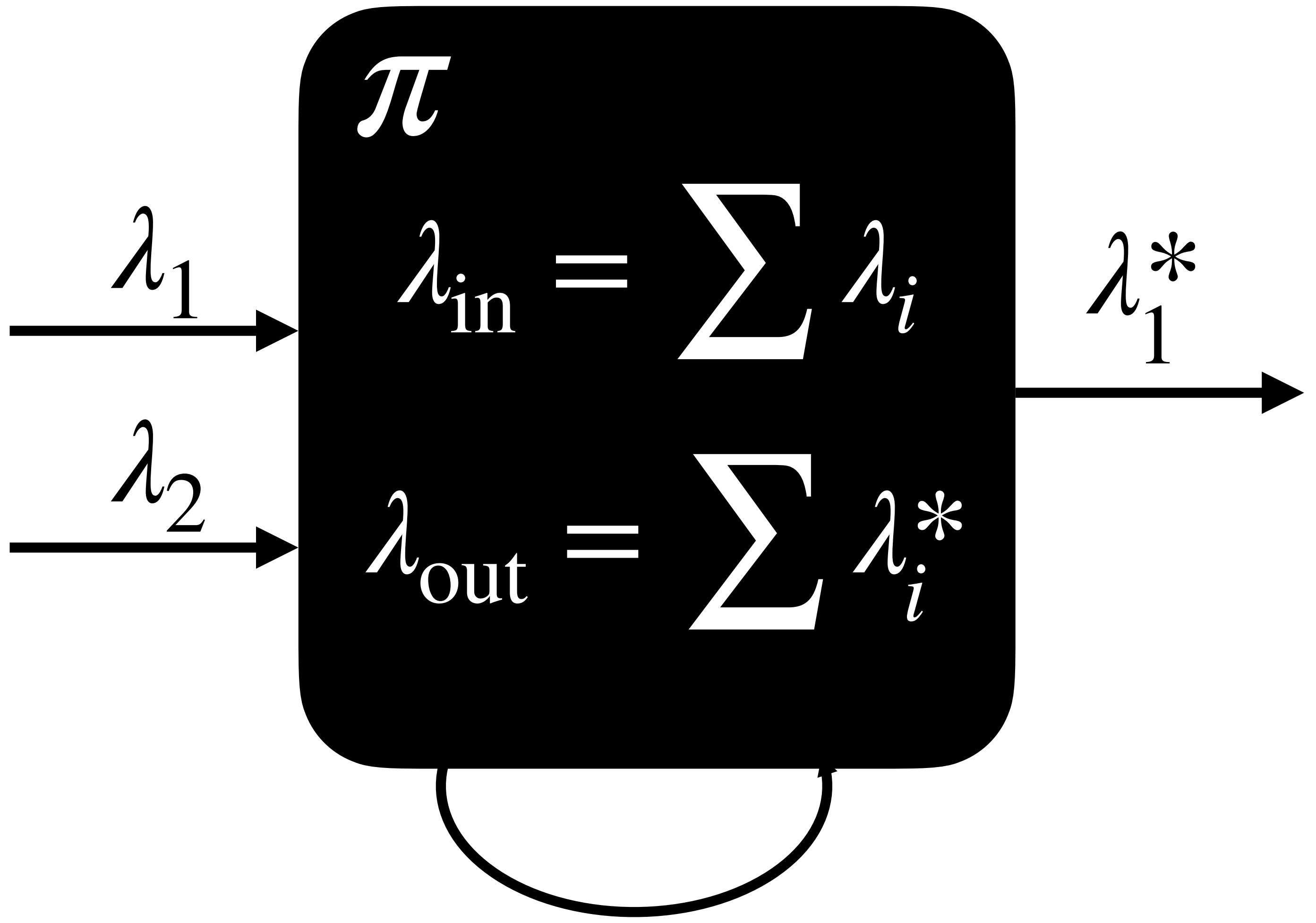
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Budgets

t_q query	

UC with Budgets

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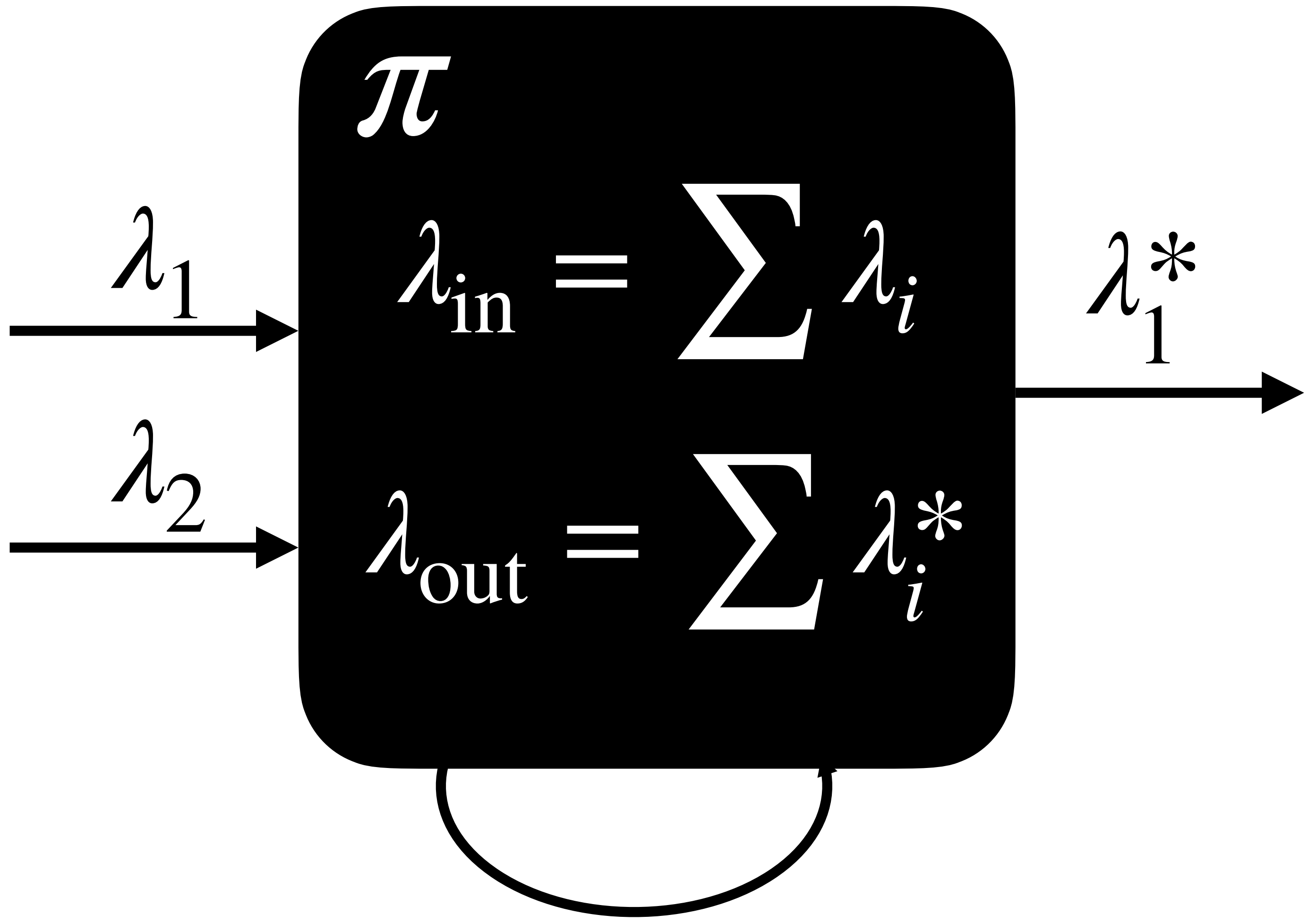
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Budgets

t_{q} query	
t_{p} programming	

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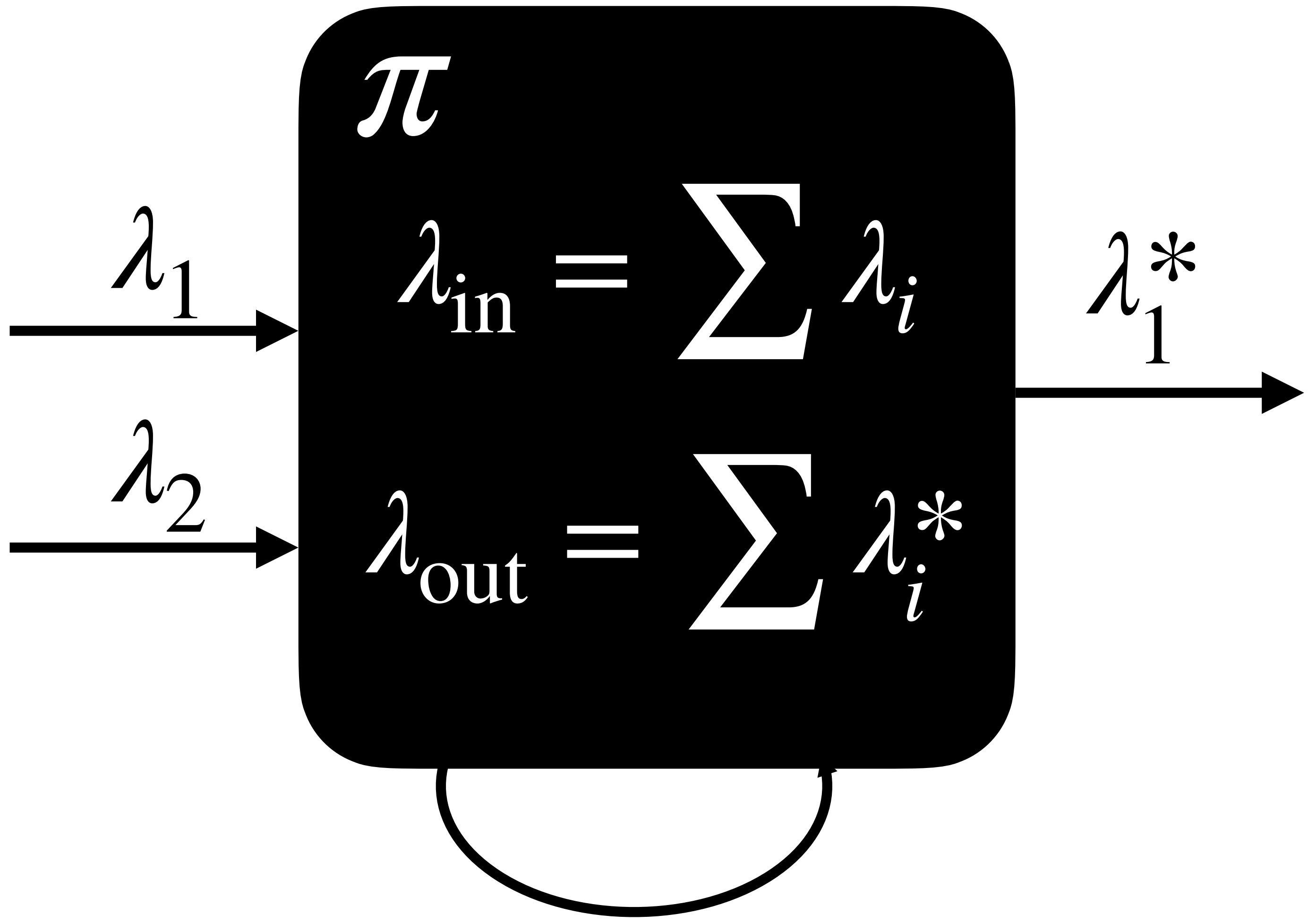

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Budgets

t_{q} query	ℓ_{p} proving
t_{p} programming	

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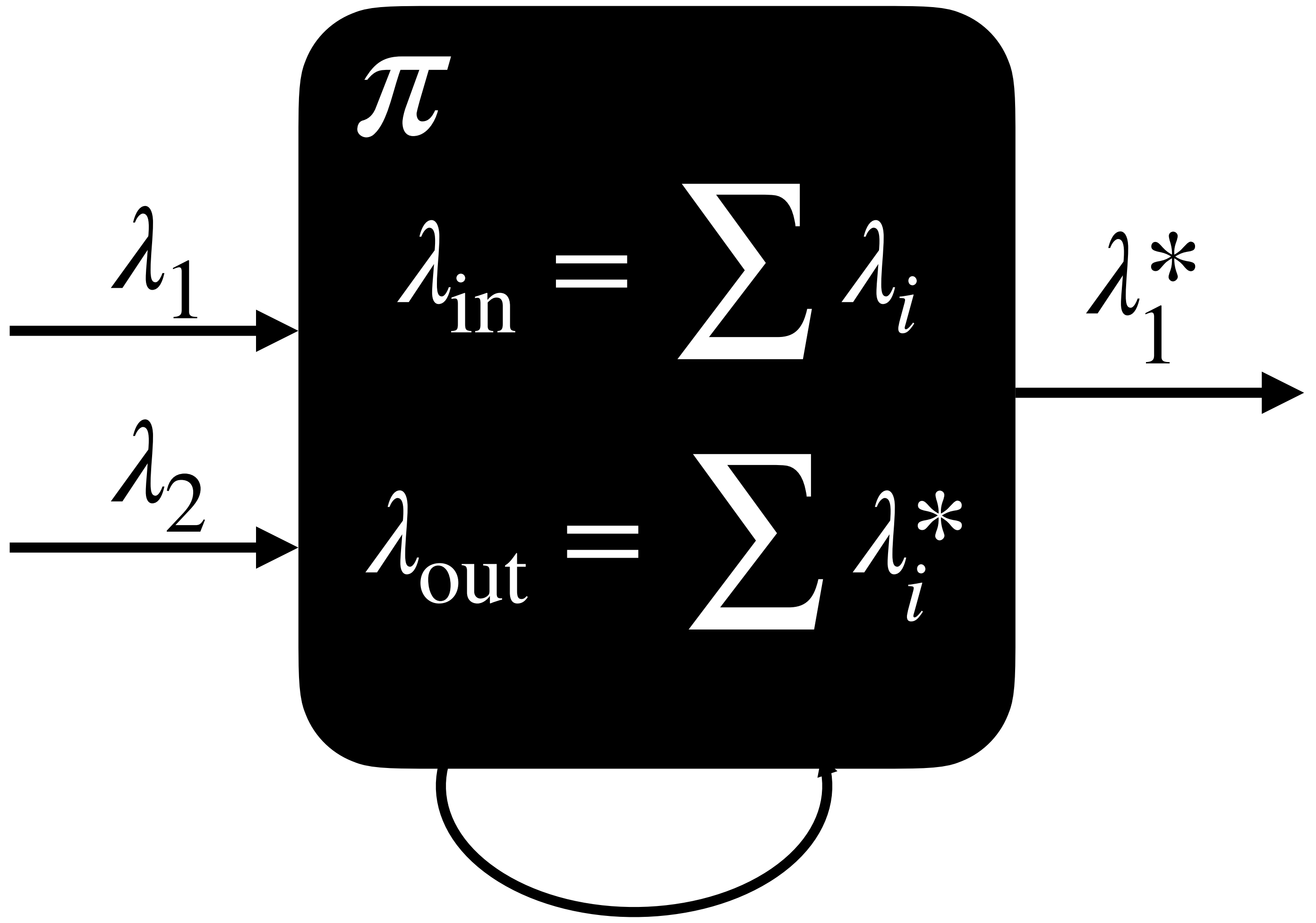
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Budgets

t_{q} query	ℓ_{p} proving
t_{p} programming	ℓ_{v} verification

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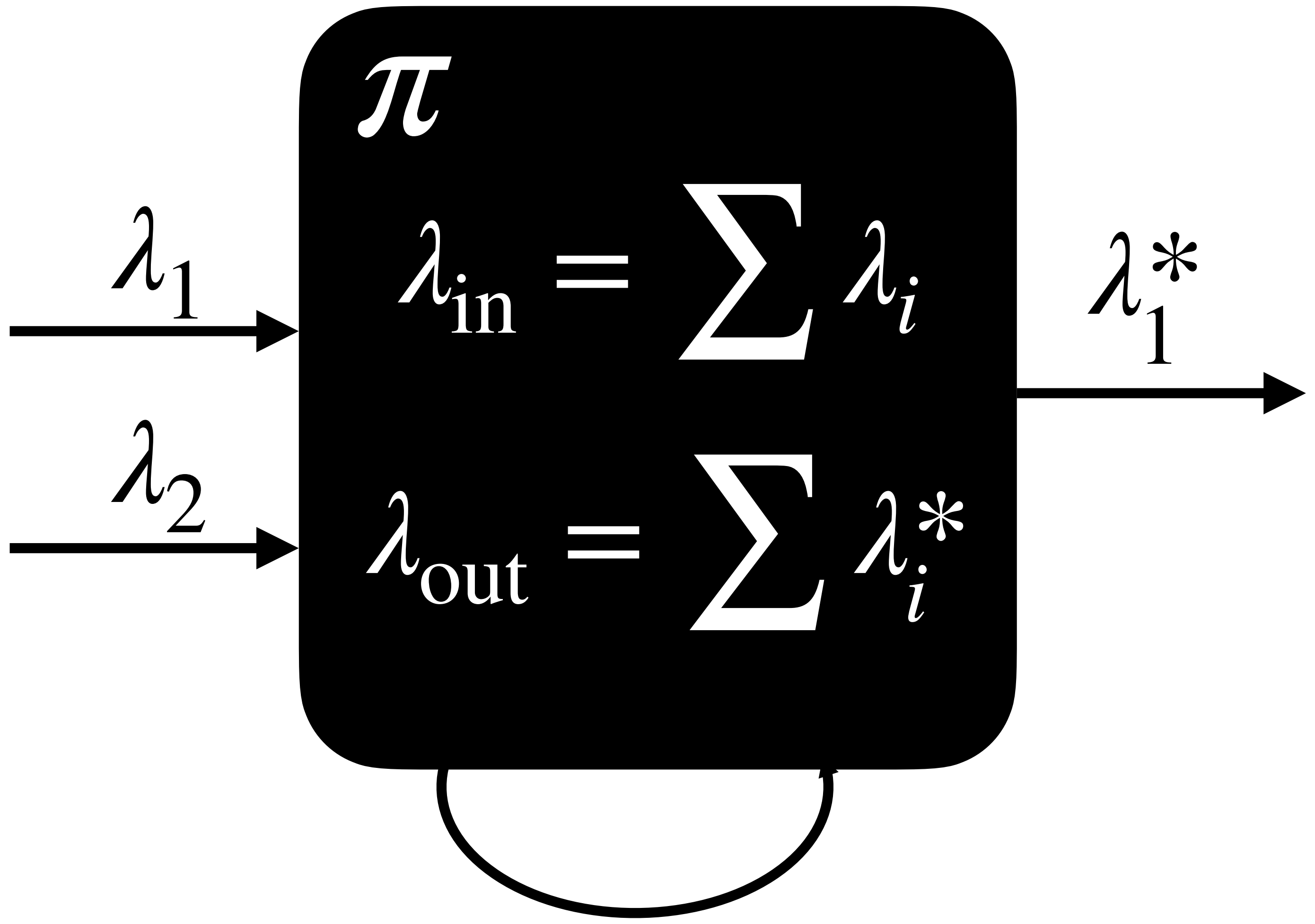

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Budgets

t_{q} query	ℓ_{p} proving
t_{p} programming	ℓ_{v} verification

Budget can then be spent on:

UC with Budgets

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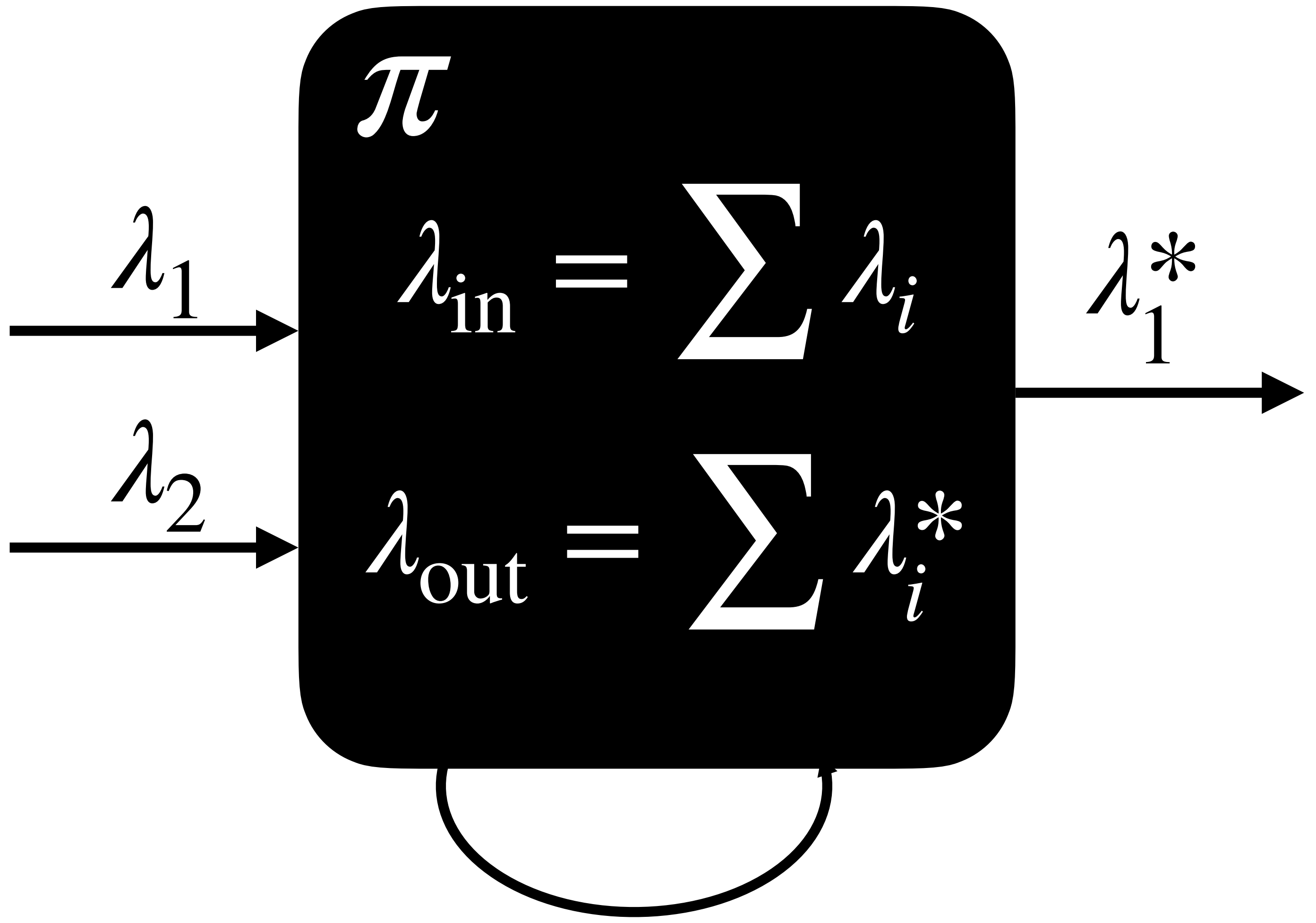
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Budgets

t_{q} query	ℓ_{p} proving
t_{p} programming	ℓ_{v} verification

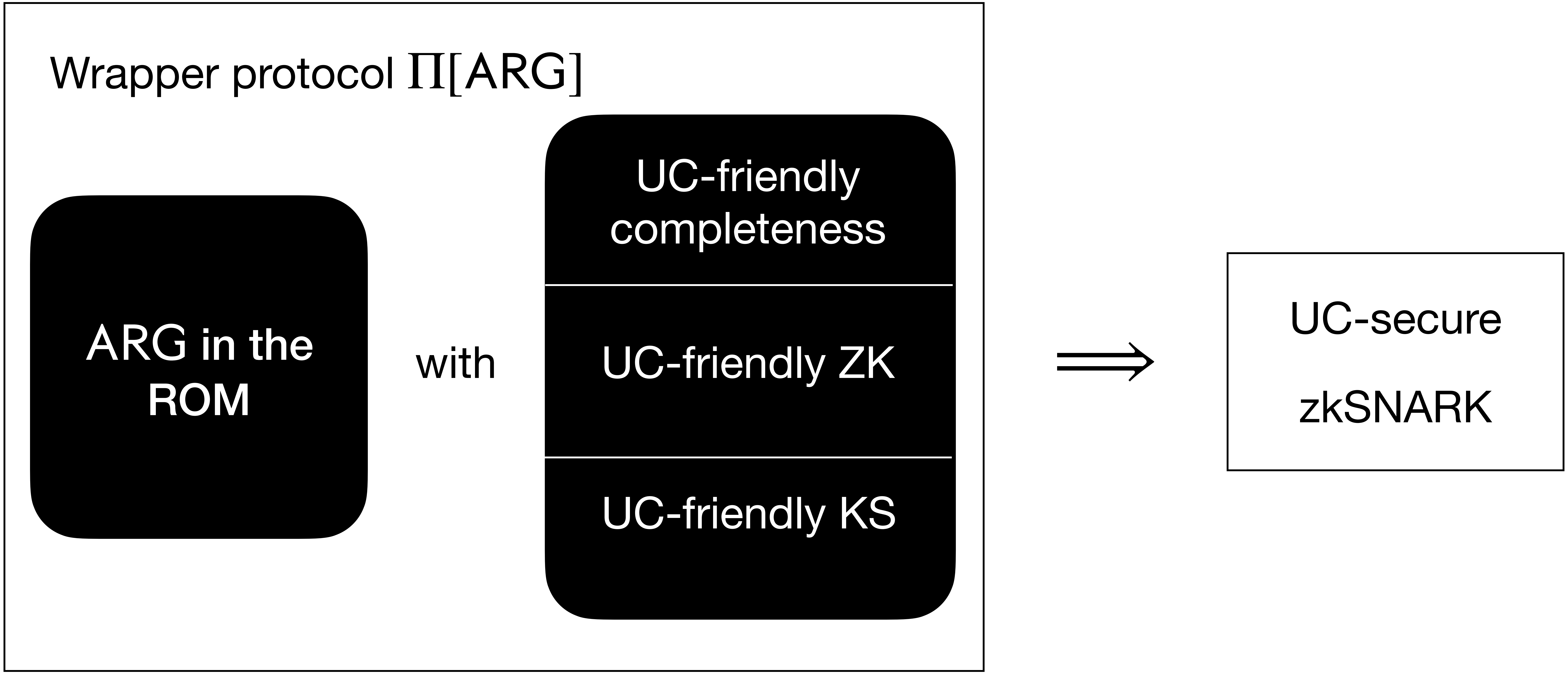
Budget can then be spent on:

GRO

Prove

Verify

Our main lemma



Wrapper protocol $\Pi[\mathrm{ARG}]$

ARG in the ROM

with

UC-friendly completeness

UC-friendly ZK

UC-friendly KS

⟹

UC-secure

zkSNARK

UC-friendly $\Longrightarrow$ UC-secure

UC-friendly $\Longrightarrow$ UC-secure

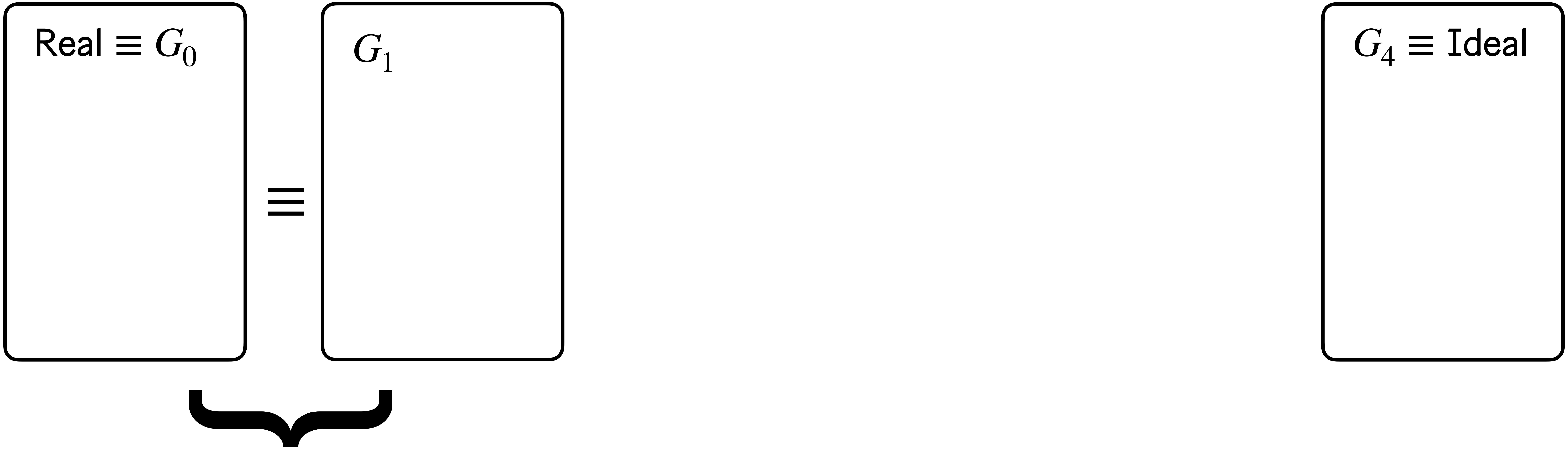
Real $\equiv G_0$

UC-friendly $\implies$ UC-secure

Real $\equiv G_0$

$G_4 \equiv$ Ideal

UC-friendly $\Longrightarrow$ UC-secure



$\mathsf{Real} \equiv G_0$

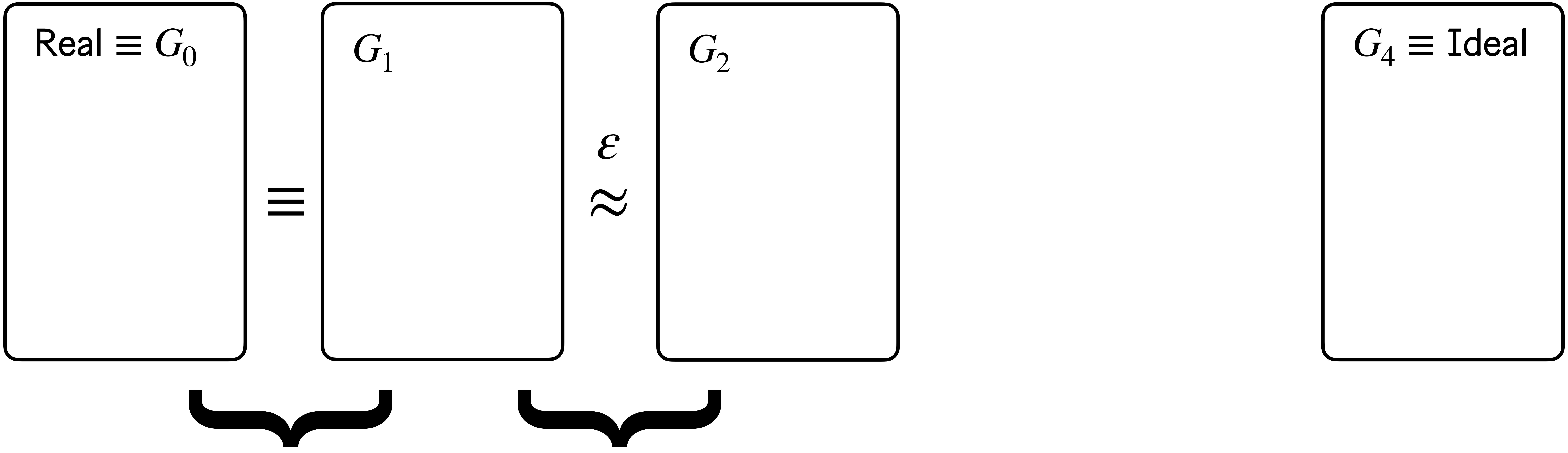
$\equiv$

G_1

$G_4 \equiv \mathtt{Ideal}$

Simulator can program undetectably

UC-friendly $\implies$ UC-secure



$\mathsf{Real} \equiv G_0$

$\equiv$

G_1

$\overset{\varepsilon}{\approx}$

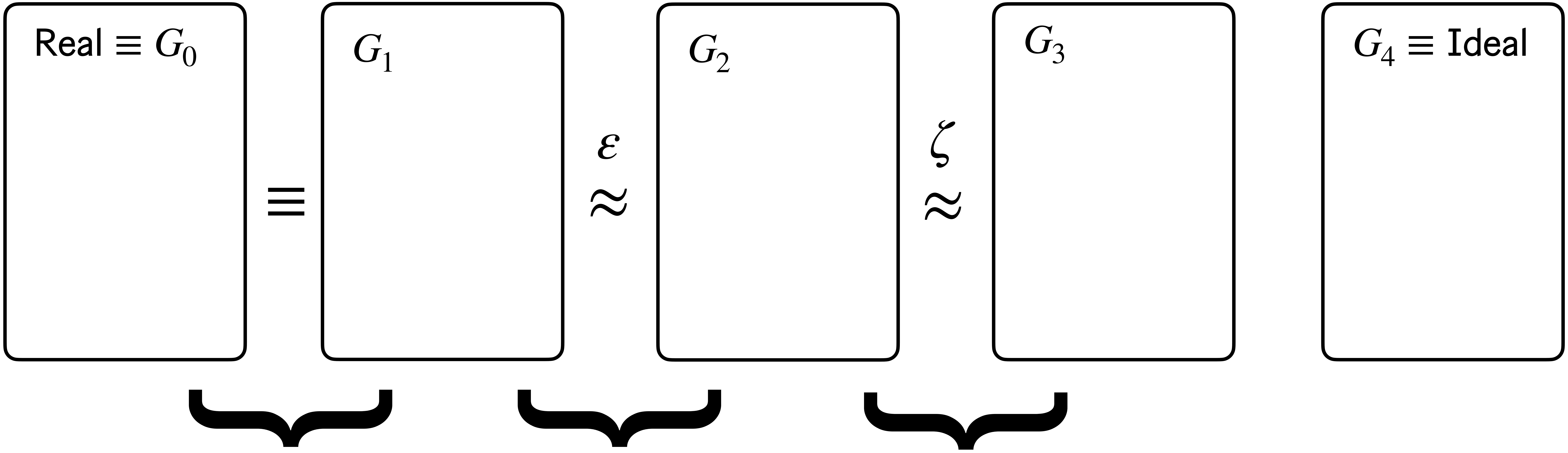
G_2

$G_4 \equiv \mathsf{Ideal}$

Simulator can program undetectably

UC-friendly completeness

UC-friendly $\Longrightarrow$ UC-secure



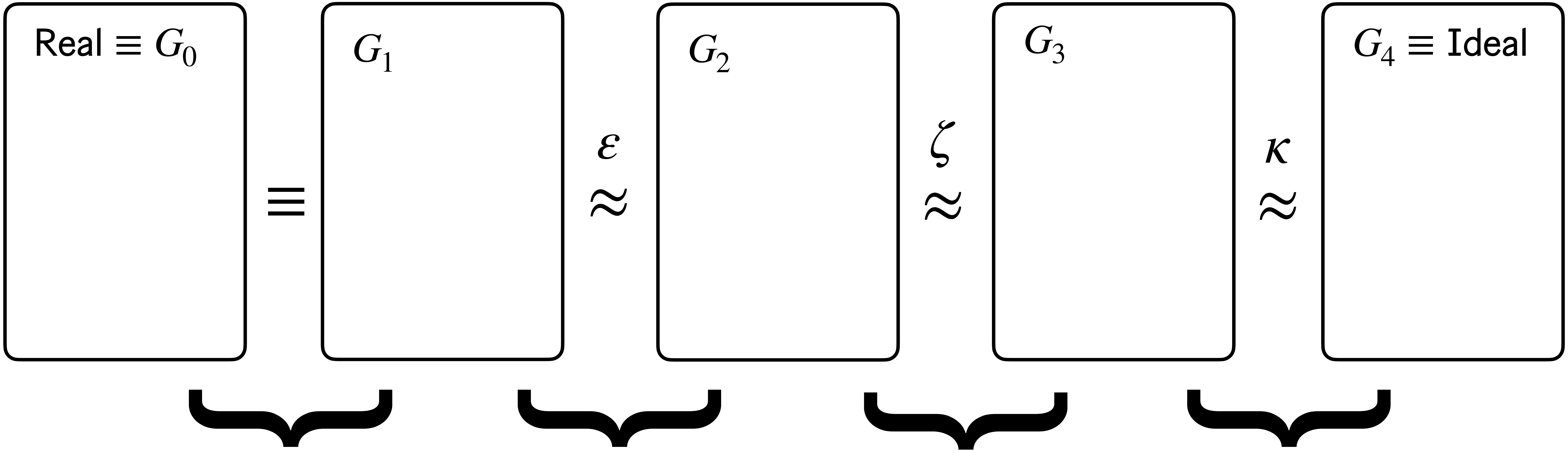
$\text{Real} \equiv G_0$ $\equiv$ G_1 $\overset{\varepsilon}{\approx}$ G_2 $\overset{\zeta}{\approx}$ G_3 $\quad$ $G_4 \equiv \texttt{Ideal}$

Simulator can program undetectably

UC-friendly completeness

UC-friendly ZK

UC-friendly $\implies$ UC-secure



$\text{Real} \equiv G_0$ $\equiv$ G_1 $\overset{\varepsilon}{\approx}$ G_2 $\overset{\zeta}{\approx}$ G_3 $\overset{\kappa}{\approx}$ $G_4 \equiv \text{Ideal}$

Simulator can program undetectably

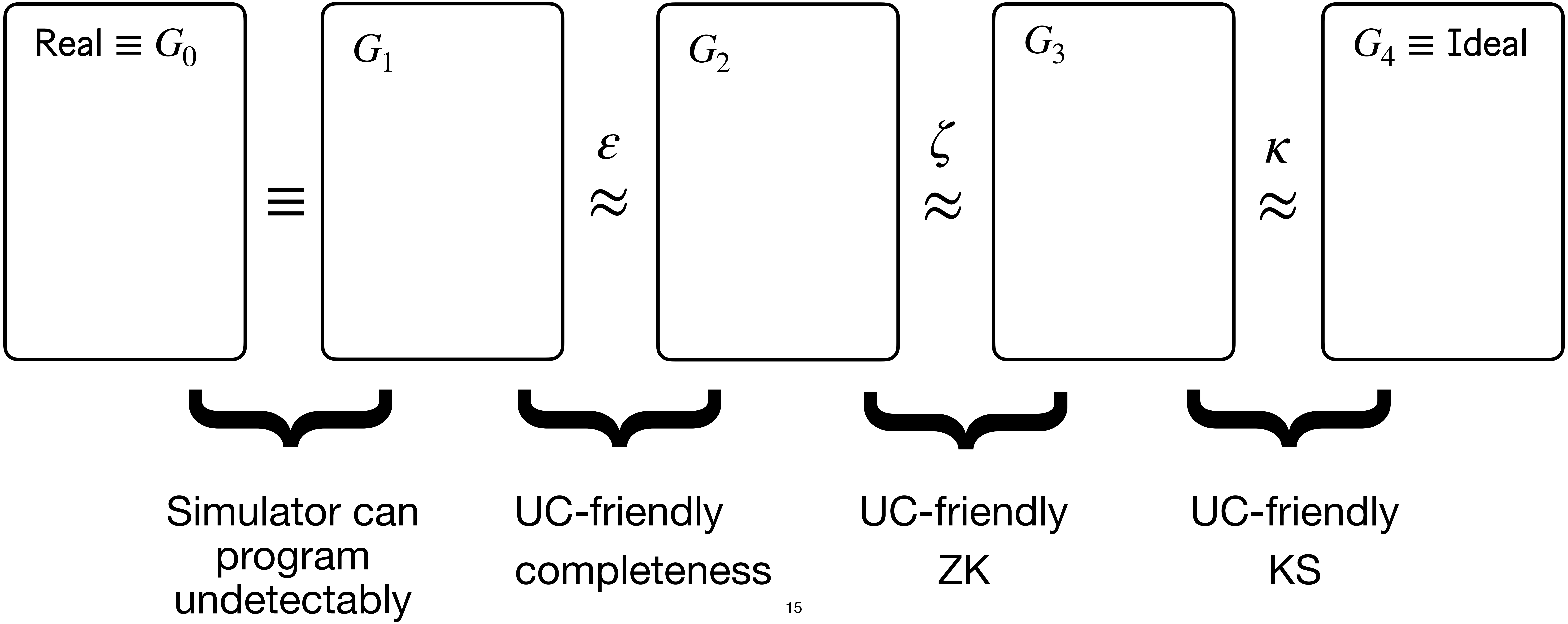
UC-friendly completeness

UC-friendly ZK

UC-friendly KS

UC-friendly $\Longrightarrow$ UC-secure

UC-friendly properties exactly defined for these game hops



Real $\equiv G_0$ $\equiv$ G_1 $\overset{\varepsilon}{\approx}$ G_2 $\overset{\zeta}{\approx}$ G_3 $\overset{\kappa}{\approx}$ $G_4 \equiv$ Ideal

Simulator can program undetectably

UC-friendly completeness

UC-friendly ZK

UC-friendly KS

UC-friendly completeness

Adversary should not be able to make honestly generated proofs fail to verify.

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$\boxed{\forall \mathscr{A}}$

UC-friendly completeness

Adversary should not be able to make honestly generated proofs fail to verify.

$\boxed{\forall \mathscr{A}}$

$$\Pr\left[\qquad \middle| \qquad \right]$$

UC-friendly completeness

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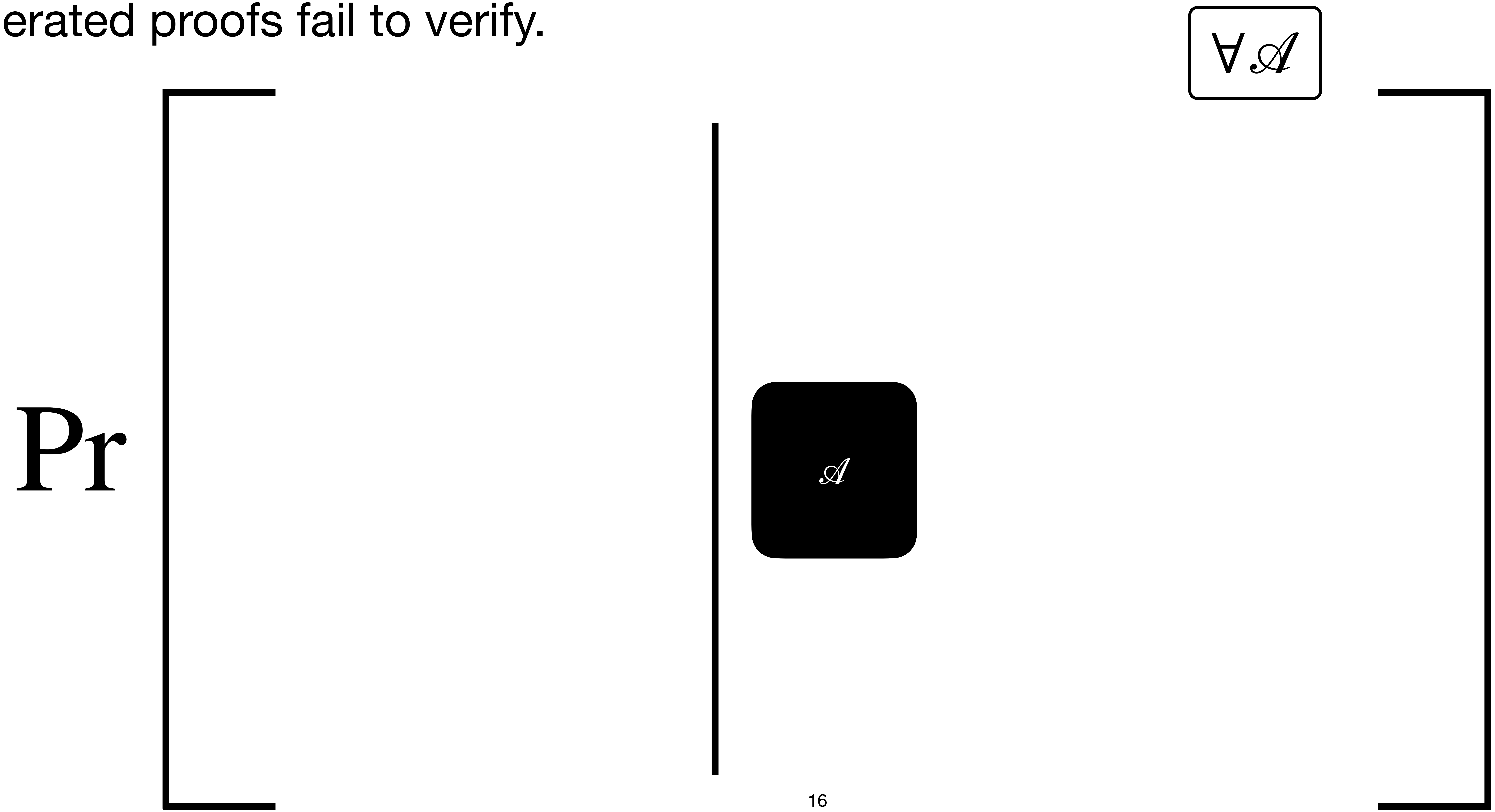

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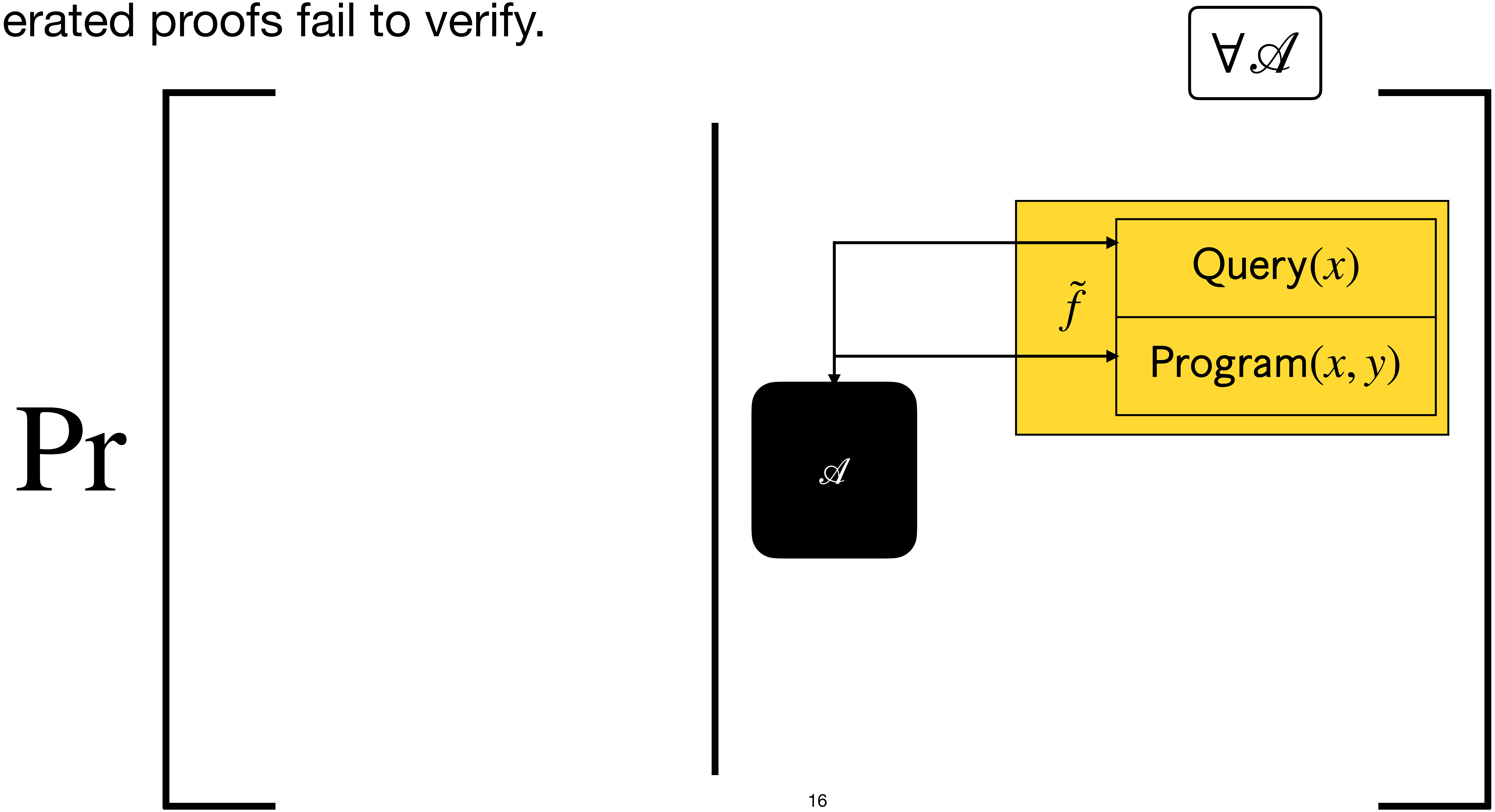

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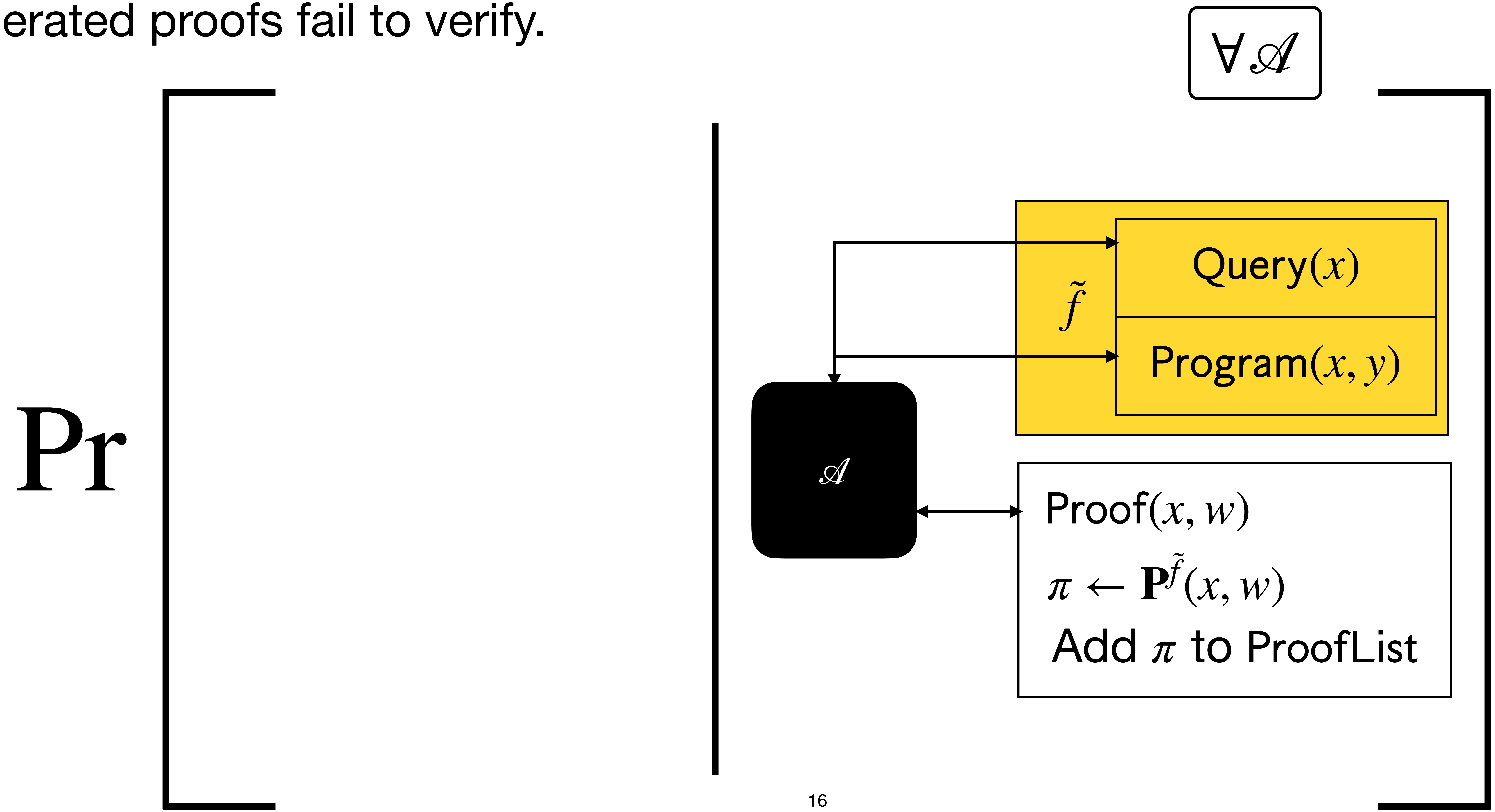

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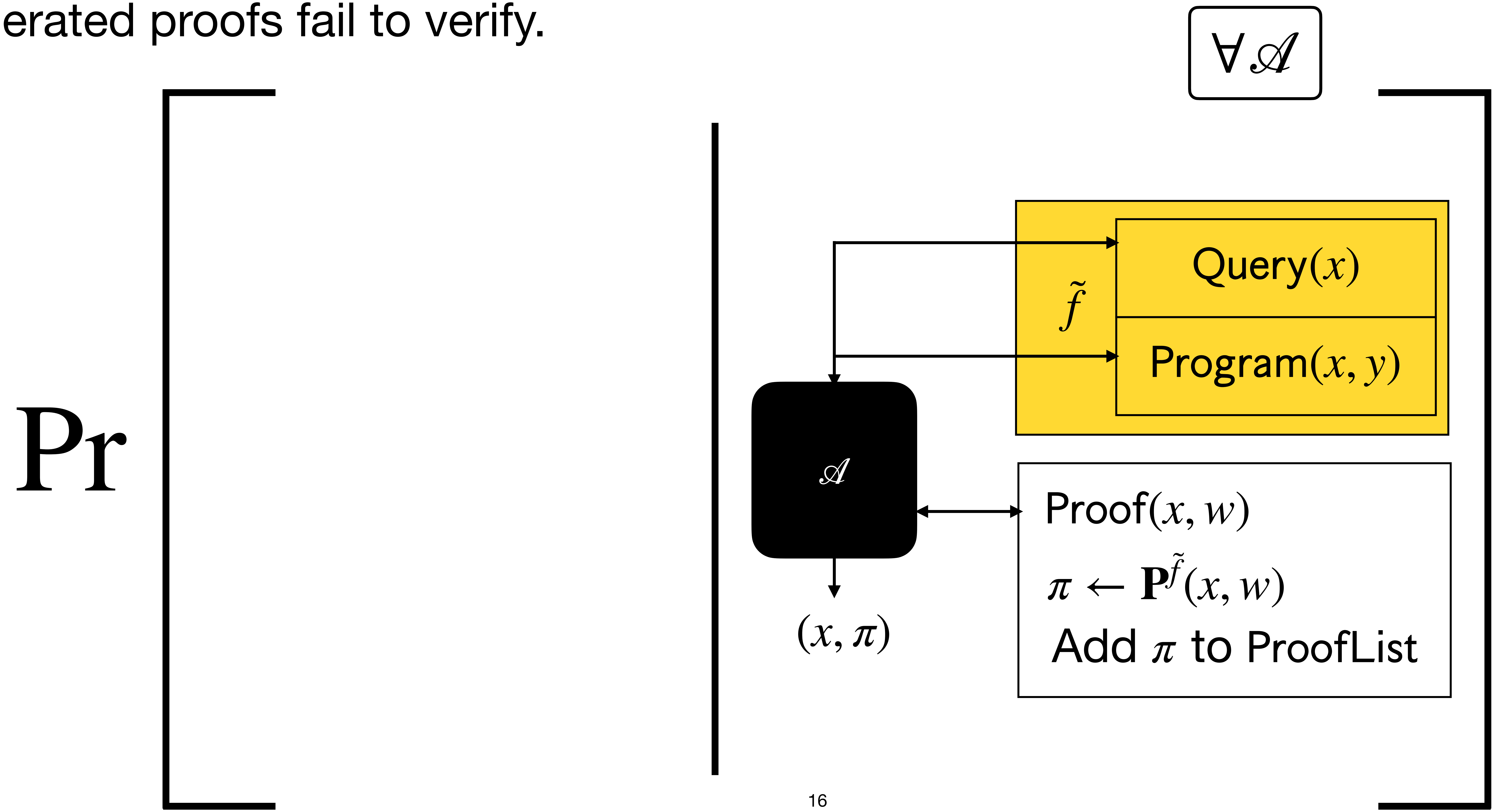


$\forall \mathscr{A}$

Pr

$\tilde{f}$

Query(x)

Program(x, y)

$\mathscr{A}$

(x, π)

Proof(x, w)

$\pi \leftarrow \mathbf{P}^{\tilde{f}}(x, w)$

Add π to ProofList

UC-friendly completeness

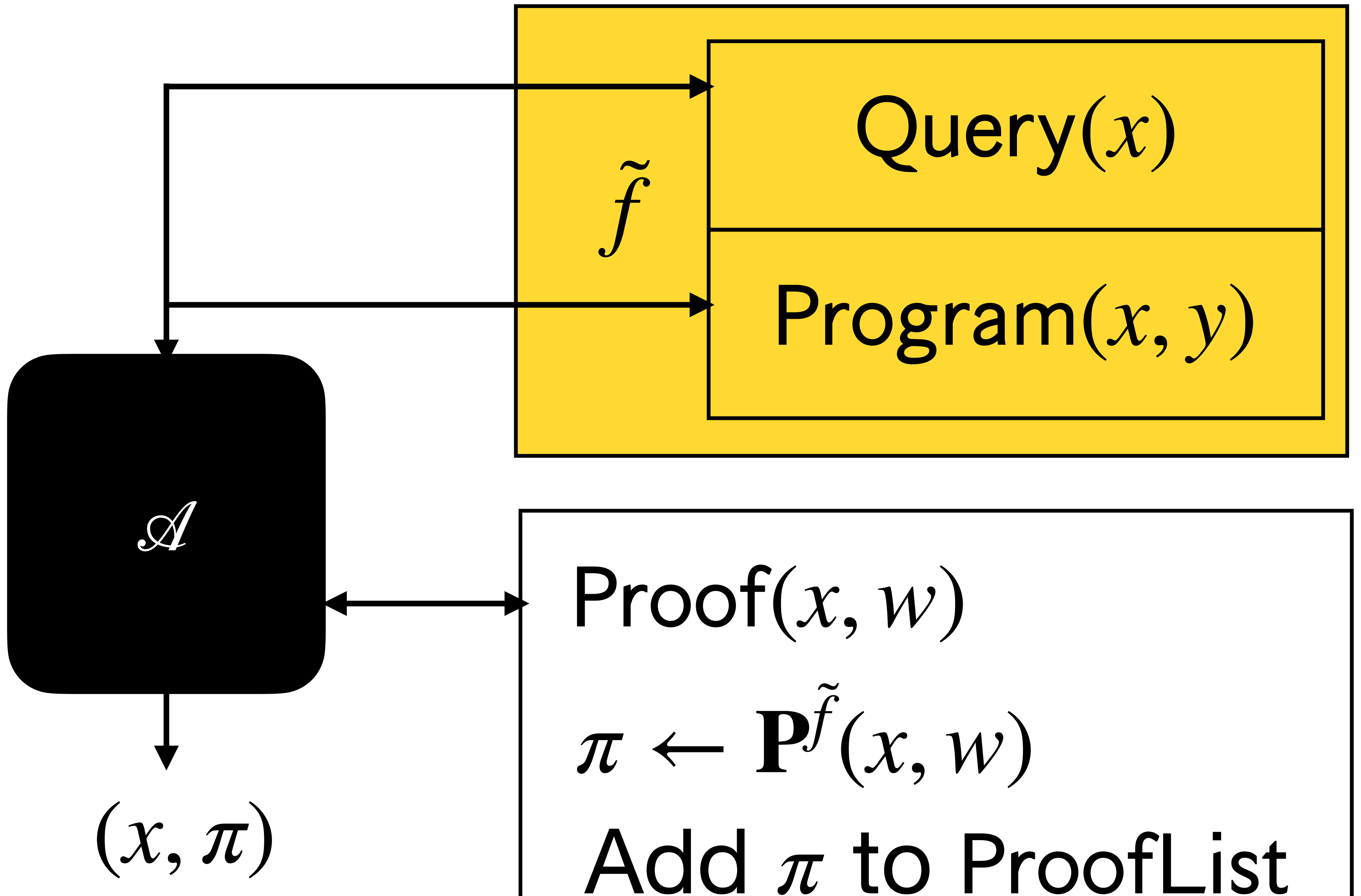
Adversary should not be able to make honestly generated proofs fail to verify.

$\forall \mathscr{A}$

$\Pr$ [$(x, \pi) \in \mathsf{ProofList}$

and

|



Proof(x, w)

$\pi \leftarrow \mathbf{P}^{\tilde{f}}(x, w)$

Add π to ProofList

]

UC-friendly completeness

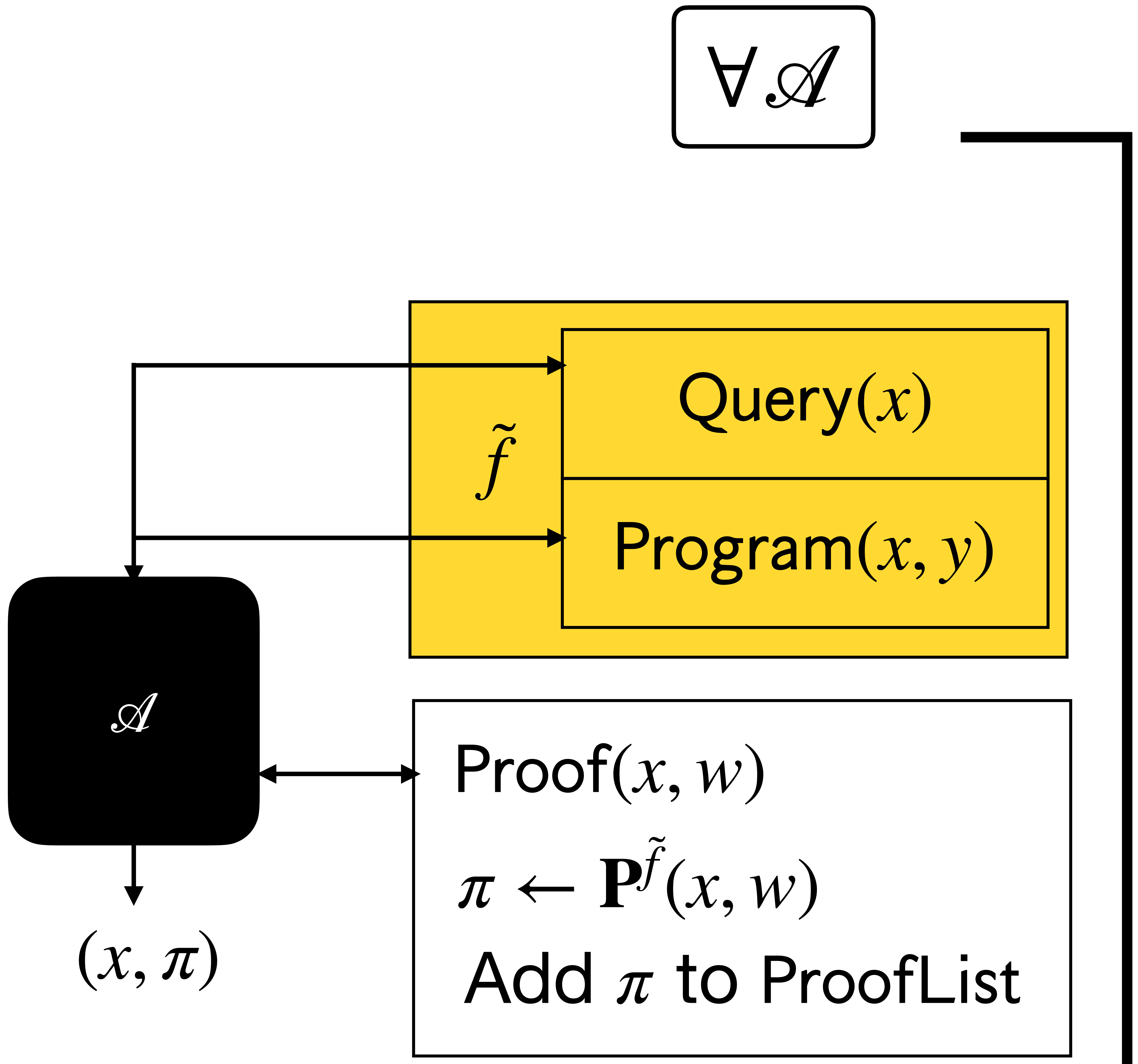
Adversary should not be able to make honestly generated proofs fail to verify.

$\Pr$

$(x, \pi) \in \text{ProofList}$

and

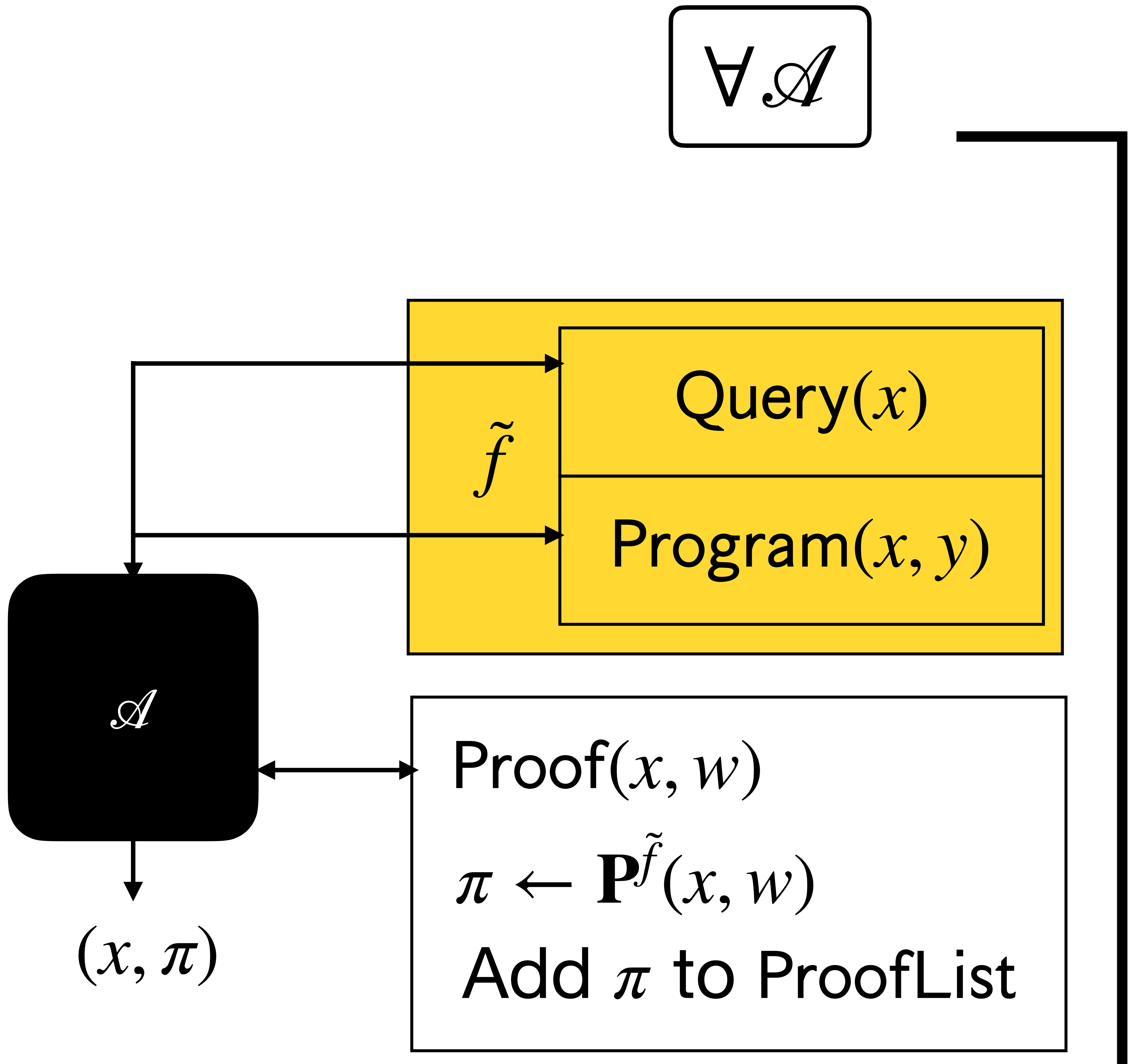
$\mathbf{V}^{\tilde{f}}(x, \pi) \neq 1$



UC-friendly completeness

Adversary should not be able to make honestly generated proofs fail to verify.

$$\Pr\left[\begin{array}{c} (x, \pi) \in \text{ProofList} \\ \text{and} \\ \left(\begin{array}{c} \boxed{\mathbf{V}^{\tilde{f}}(x, \pi) \neq 1} \\ \text{or} \\ \mathbf{V} \text{ queries} \\ \text{programmed points} \end{array} \right) \end{array} \;\middle|\; \right]$$



$\forall \mathscr{A}$

$\tilde{f}$

Query(x)

Program(x, y)

$\mathscr{A}$

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Proof(x, w)

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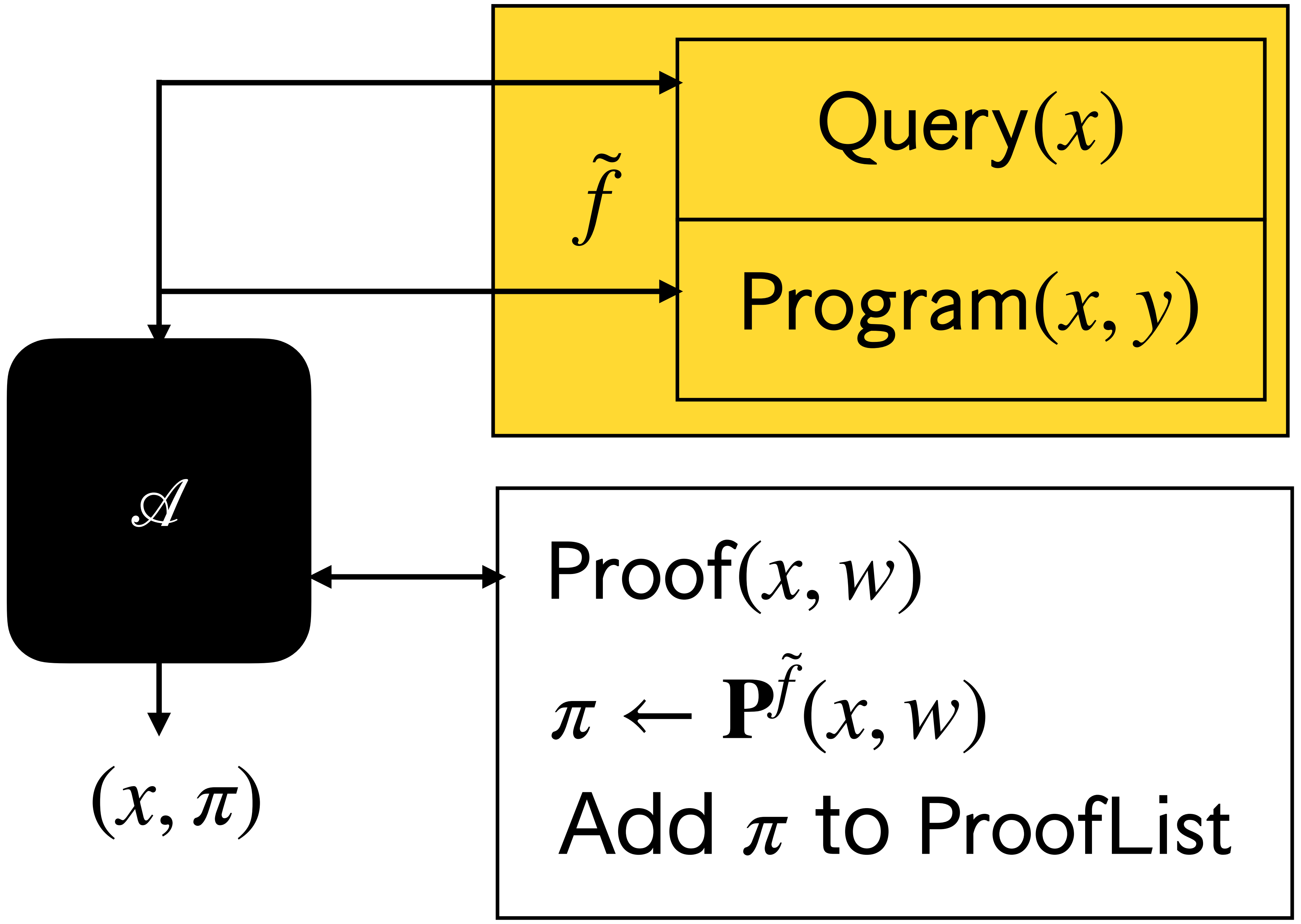
$\forall \mathscr{A}$

$$\Pr\left[\begin{array}{c}(x,\pi)\in\text{ProofList}\\ \text{and}\\ \left(\begin{array}{c}\boxed{\mathbf{V}^{\tilde{f}}(x,\pi)\neq 1}\\ \text{or}\\ \mathbf{V}\text{ queries}\\ \text{programmed points}\end{array}\right)\end{array}\ \middle|\ \quad\right] \le \varepsilon$$

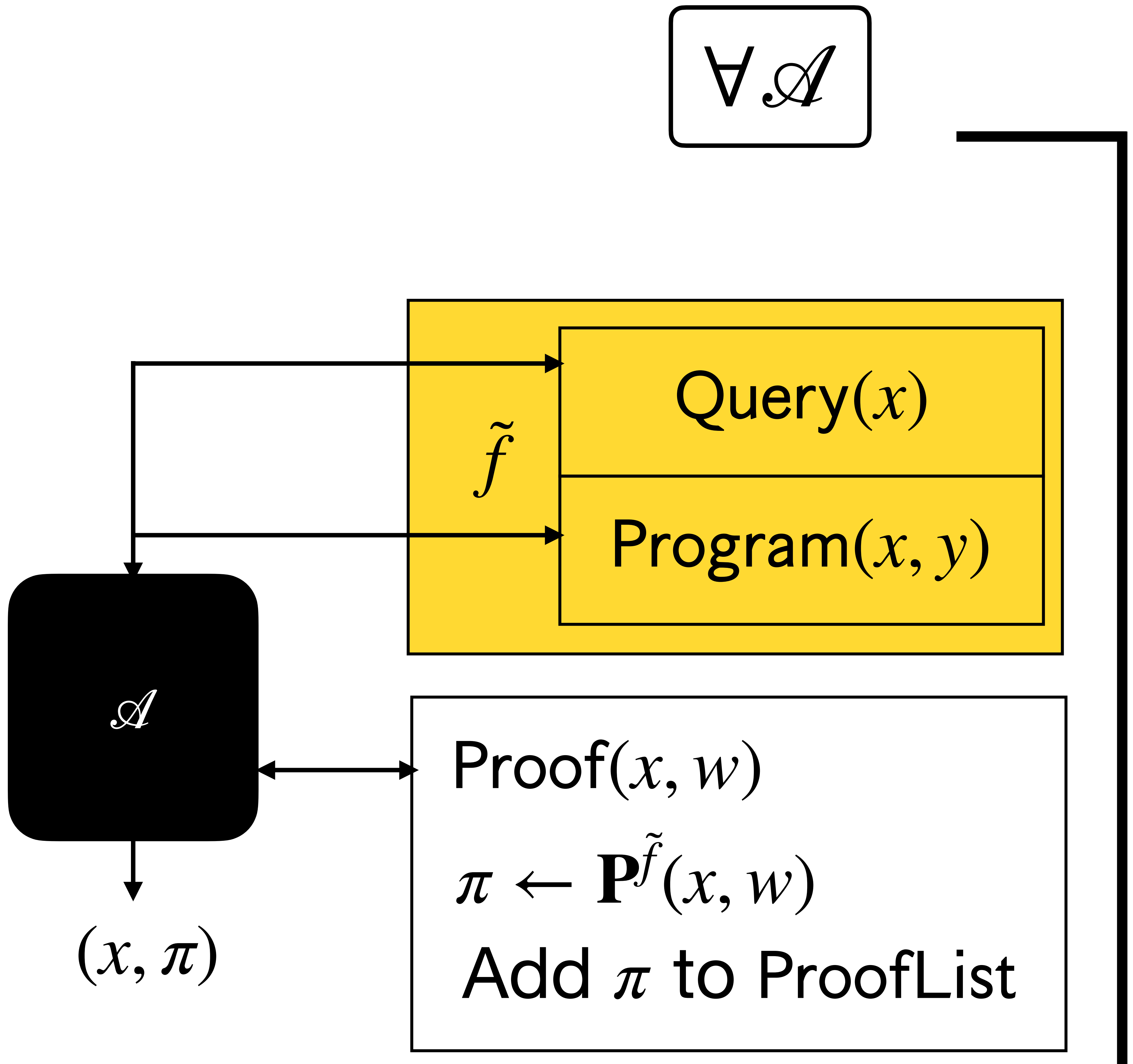


UC-friendly completeness

Micali has UC-friendly completeness because queries to GROM are **unpredictable!**

Adversary should not be able to make honestly generated proofs fail to verify.

$$\Pr\left[\left(\begin{array}{c} (x, \pi) \in \text{ProofList} \\ \text{and} \\ \boxed{\mathbf{V}^{\tilde{f}}(x, \pi) \neq 1} \\ \text{or} \\ \mathbf{V} \text{ queries} \\ \text{programmed points} \end{array} \right) \middle| \quad \right] \leq \varepsilon$$



$\forall \mathscr{A}$

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Query(x)

Program(x, y)

$\mathscr{A}$

(x, π)

Proof(x, w)

$\pi \leftarrow \mathbf{P}^{\tilde{f}}(x, w)$

Add π to ProofList

UC-friendly ZK

Adversary should not be able to distinguish real and simulated proofs, even with access to a programming oracle.

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$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

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$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

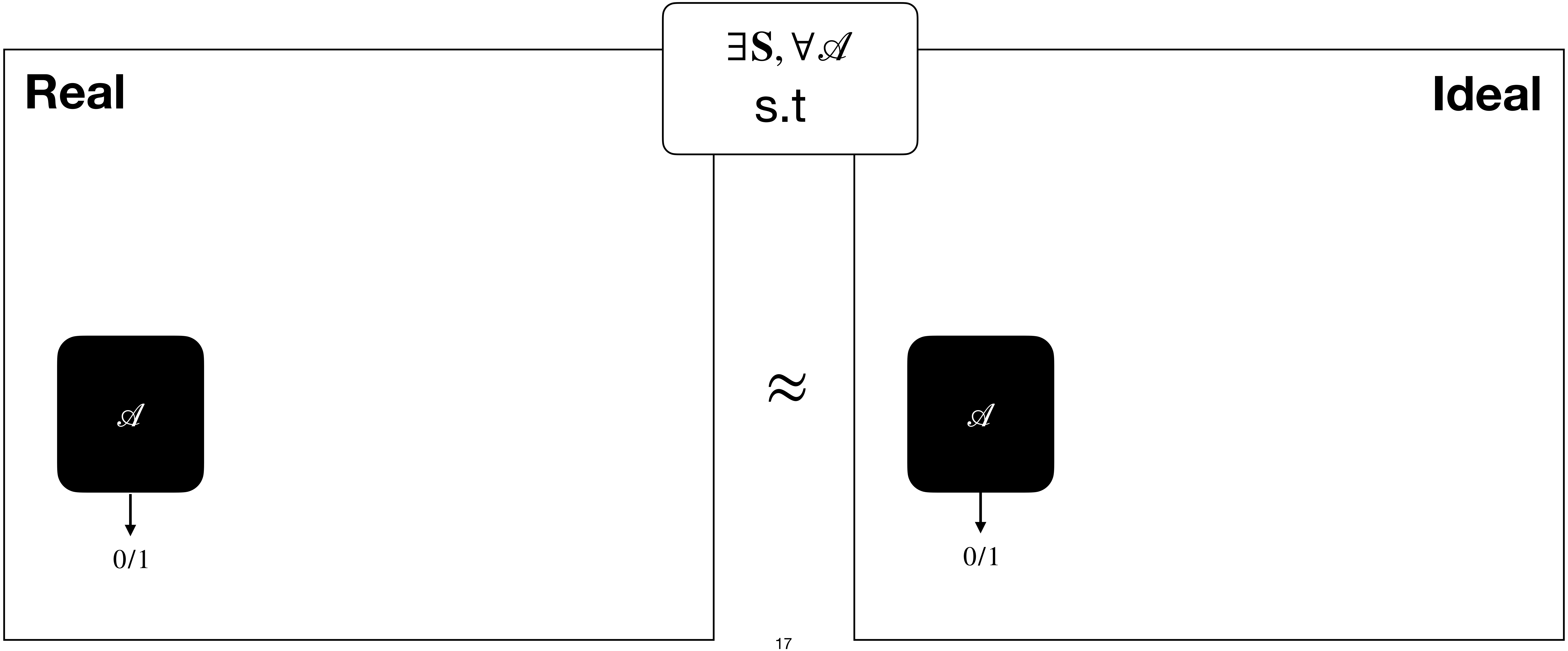
Real

Ideal

$\approx$

UC-friendly ZK

Adversary should not be able to distinguish real and simulated proofs, even with access to a programming oracle.



$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

Real

Ideal

$\approx$

$\mathscr{A}$

0/1

$\mathscr{A}$

0/1

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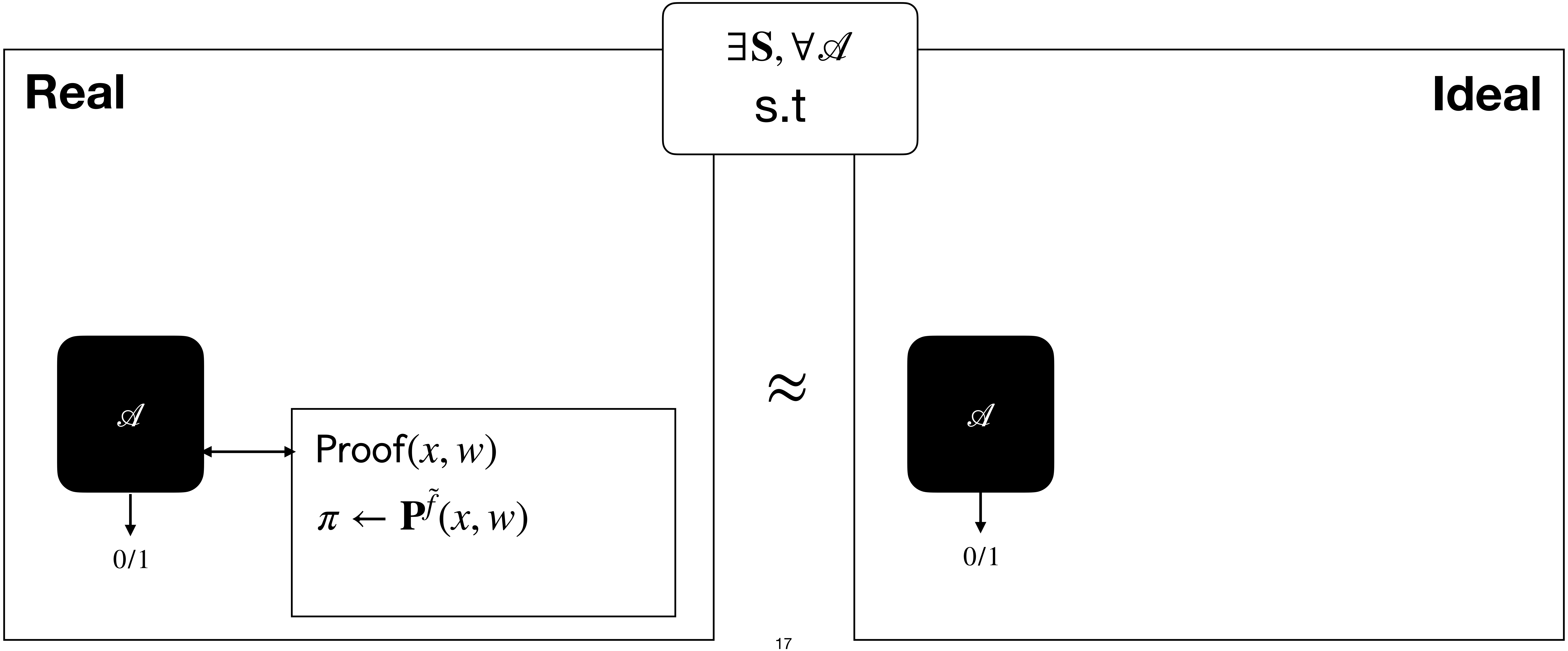

$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

Real

$\mathscr{A}$

0/1

Proof(x, w)

$\pi \leftarrow \mathbf{P}^{\tilde{f}}(x, w)$

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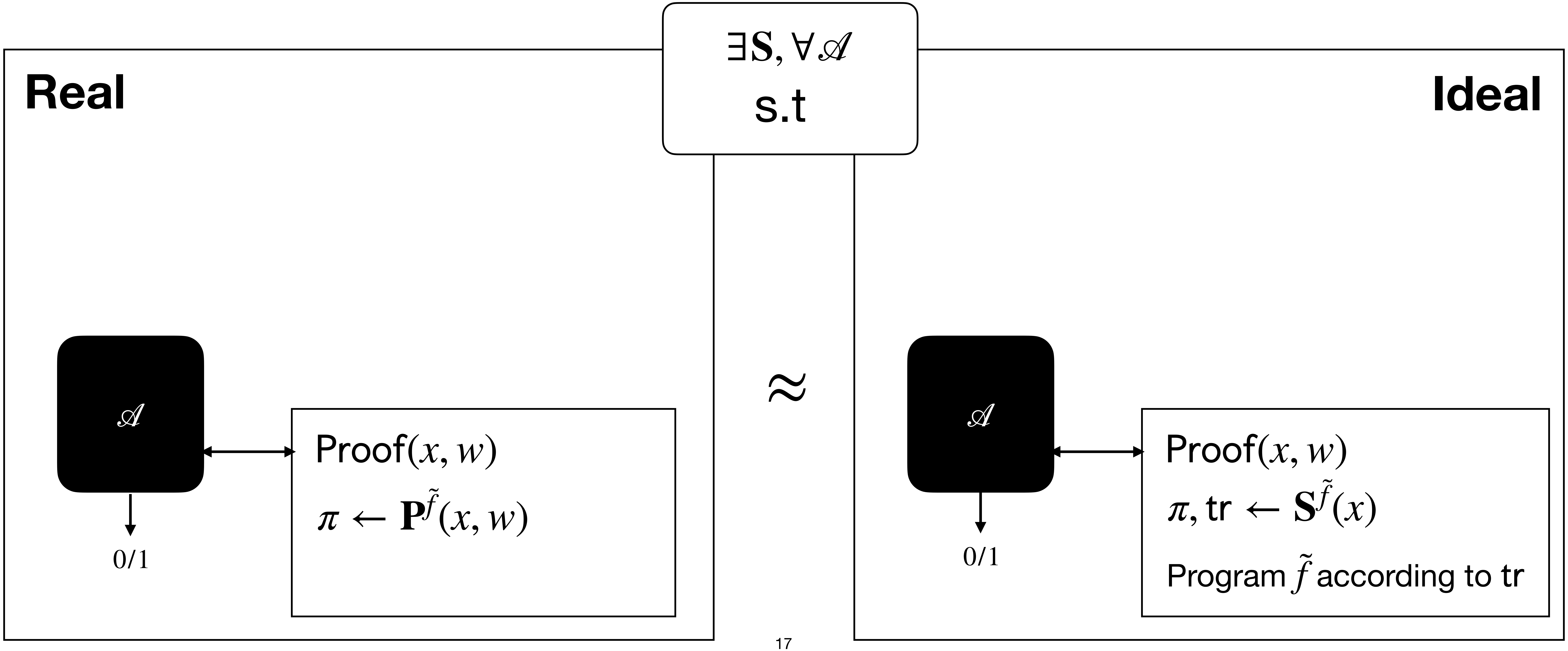


$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

Real

$\mathscr{A}$

$0/1$

Proof(x, w)

$\pi \leftarrow \mathbf{P}^{\tilde{f}}(x, w)$

$\approx$

Ideal

$\mathscr{A}$

$0/1$

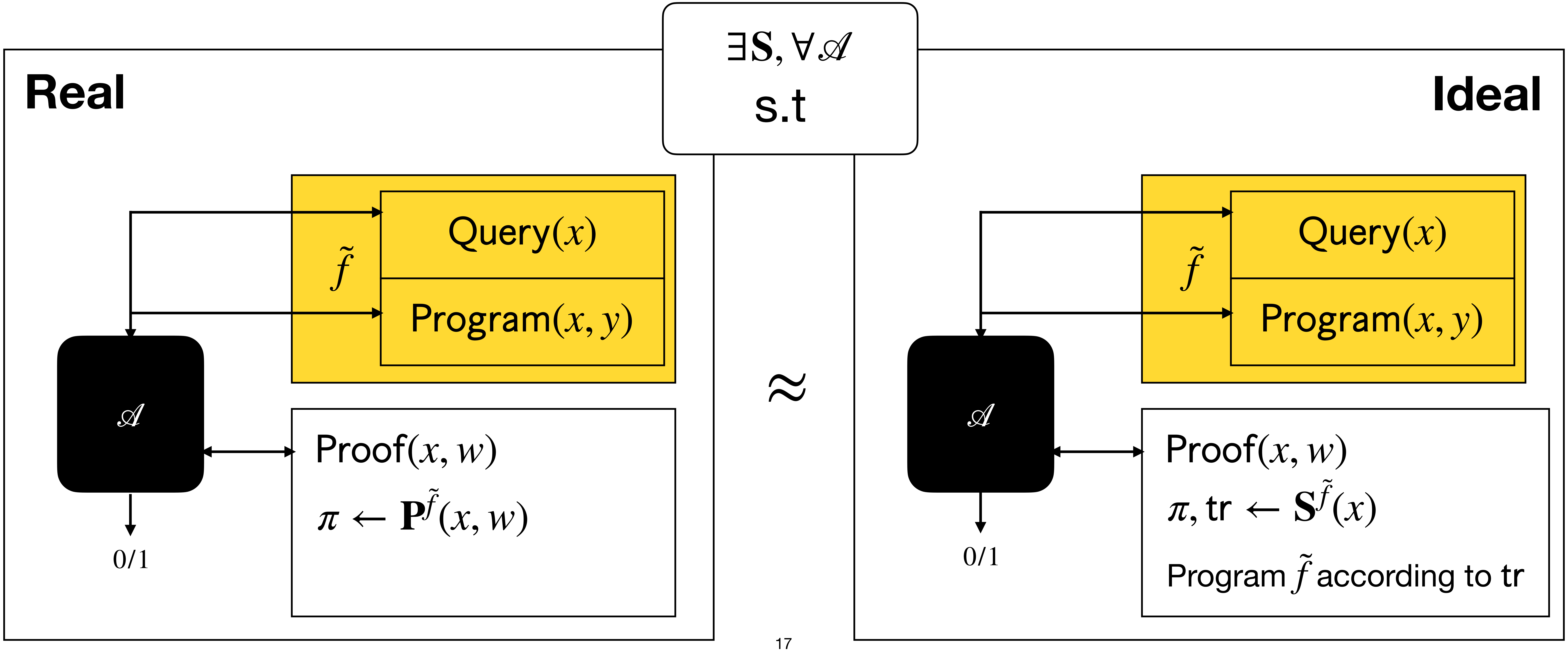
Proof(x, w)

$\pi,$ tr $\leftarrow \mathbf{S}^{\tilde{f}}(x)$

Program $\tilde{f}$ according to tr

UC-friendly ZK

Adversary should not be able to distinguish real and simulated proofs, even with access to a programming oracle.



$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

Real

$\tilde{f}$

Query(x)

Program(x, y)

$\mathscr{A}$

$0/1$

Proof(x, w)

$\pi \leftarrow \mathbf{P}^{\tilde{f}}(x, w)$

$\approx$

Ideal

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Program(x, y)

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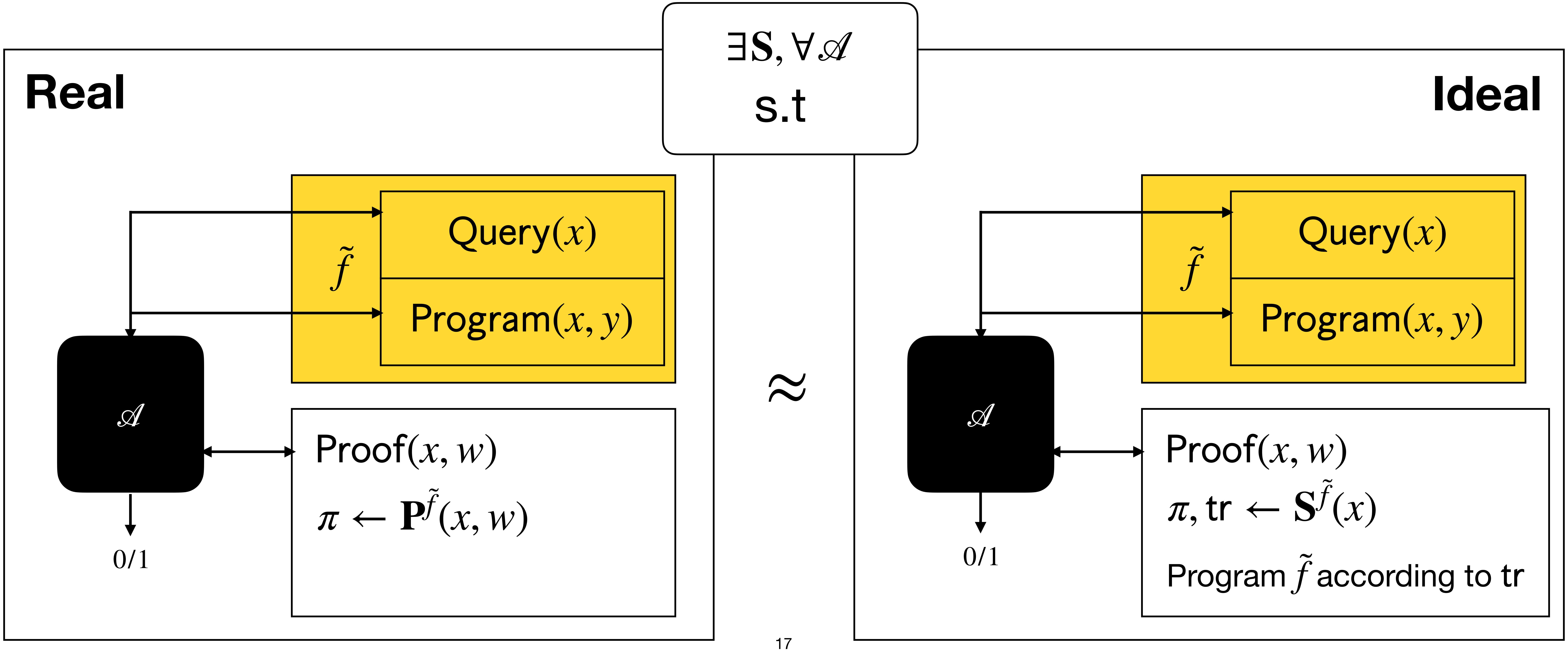
Program $\tilde{f}$ according to tr

UC-friendly ZK

Adversary should not be able to distinguish real and si even with access to a programming oracle.

Micali has UC-friendly zero knowledge, more involved but follows closely zero-knowledge of Micali in the ROM



$\exists \mathbf{S}, \forall \mathscr{A}$

s.t

Real

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Query(x)

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$\mathscr{A}$

$0/1$

Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x)$

Program $\tilde{f}$ according to tr

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs
that the extractor cannot extract a witness from

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Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$\boxed{\exists \mathscr{E} \, \forall \mathscr{A}}$

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$$\boxed{\exists \mathscr{E}\ \forall \mathscr{A}}$$

$$\Pr\left[\quad \middle| \quad\right]$$

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$$\Pr\left[\qquad \middle| \qquad \boxed{\mathscr{A}} \qquad \right]$$

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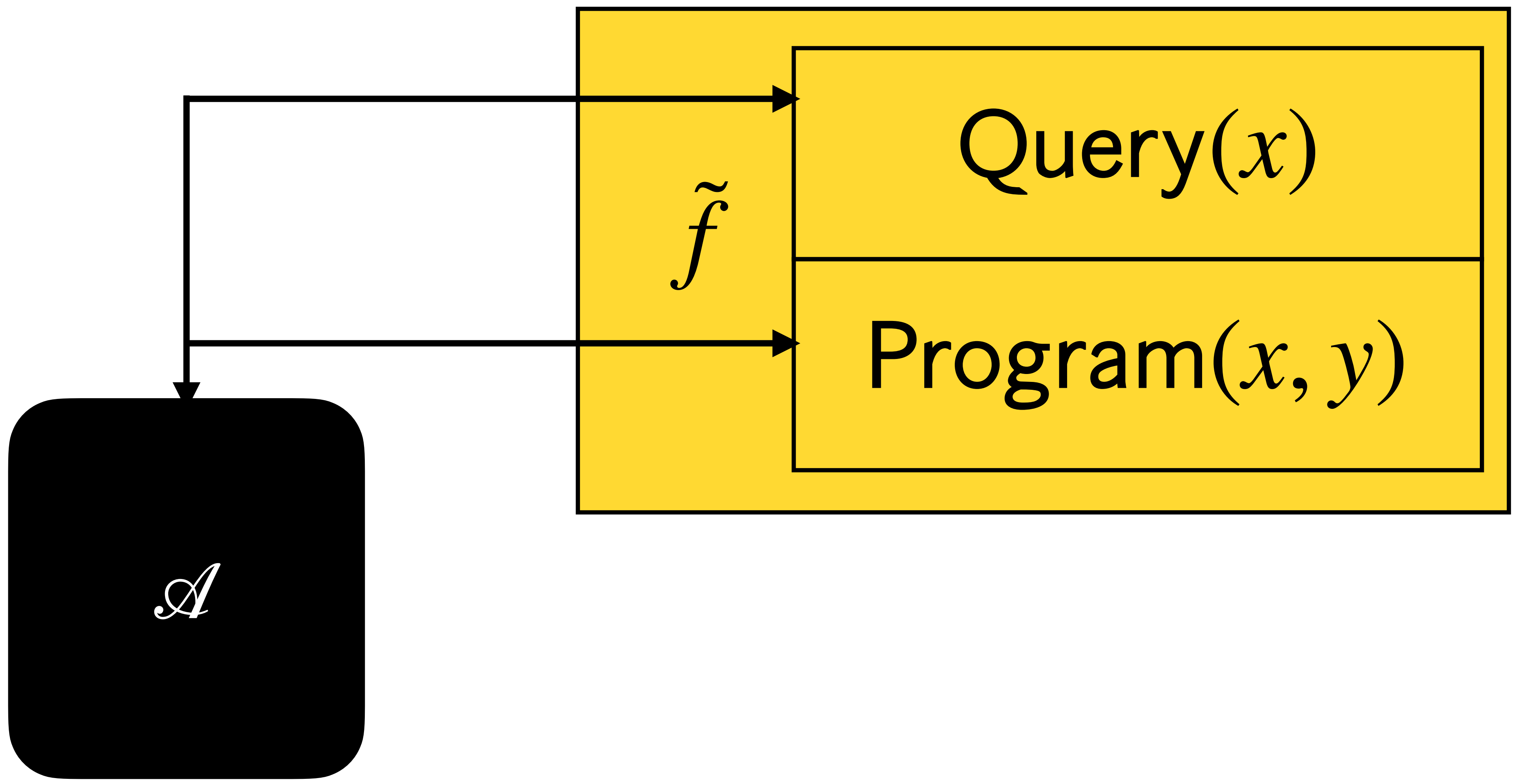

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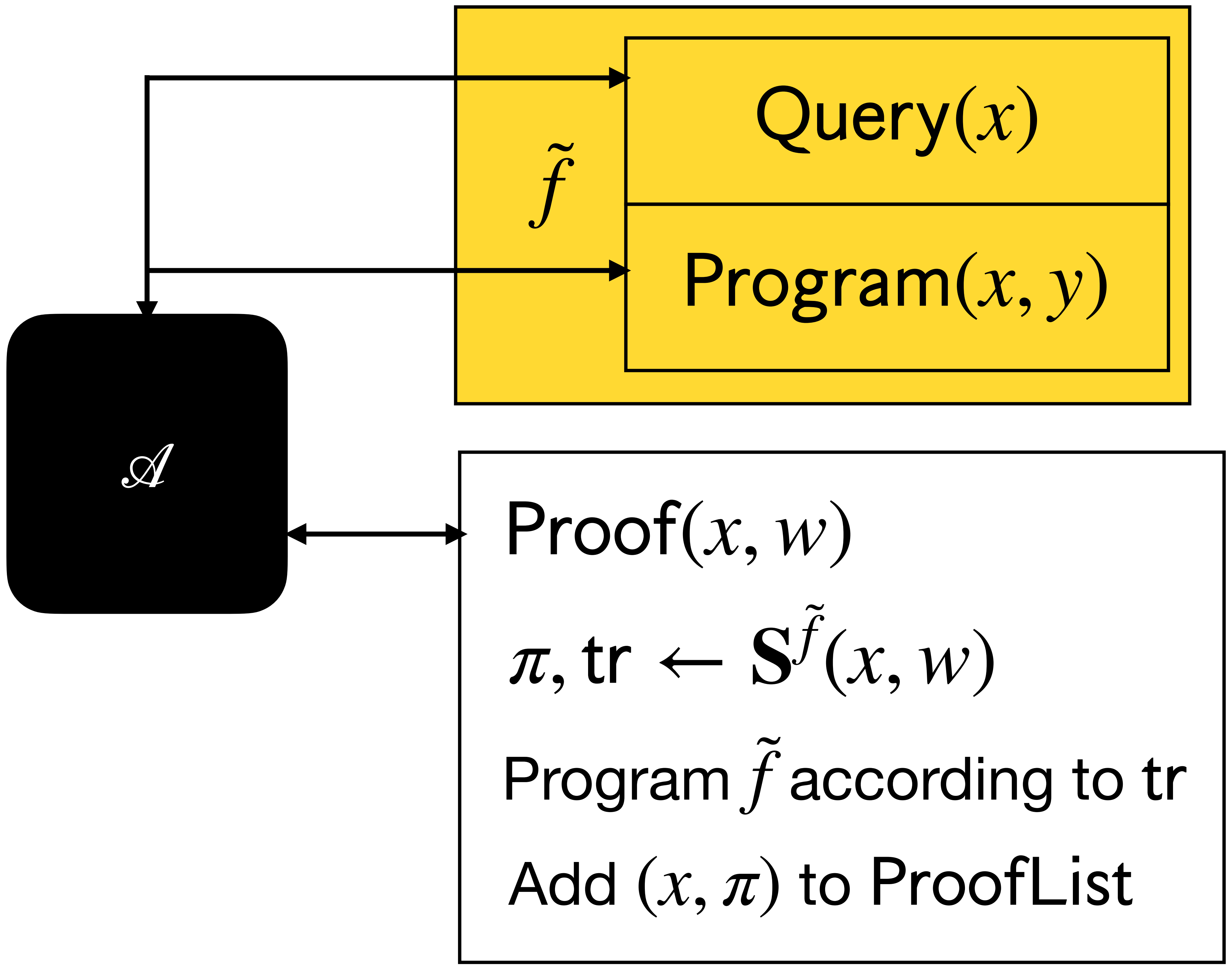
$\Pr\Big[$



$\tilde{f}$

Query(x)

Program(x, y)

$\mathscr{A}$

Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

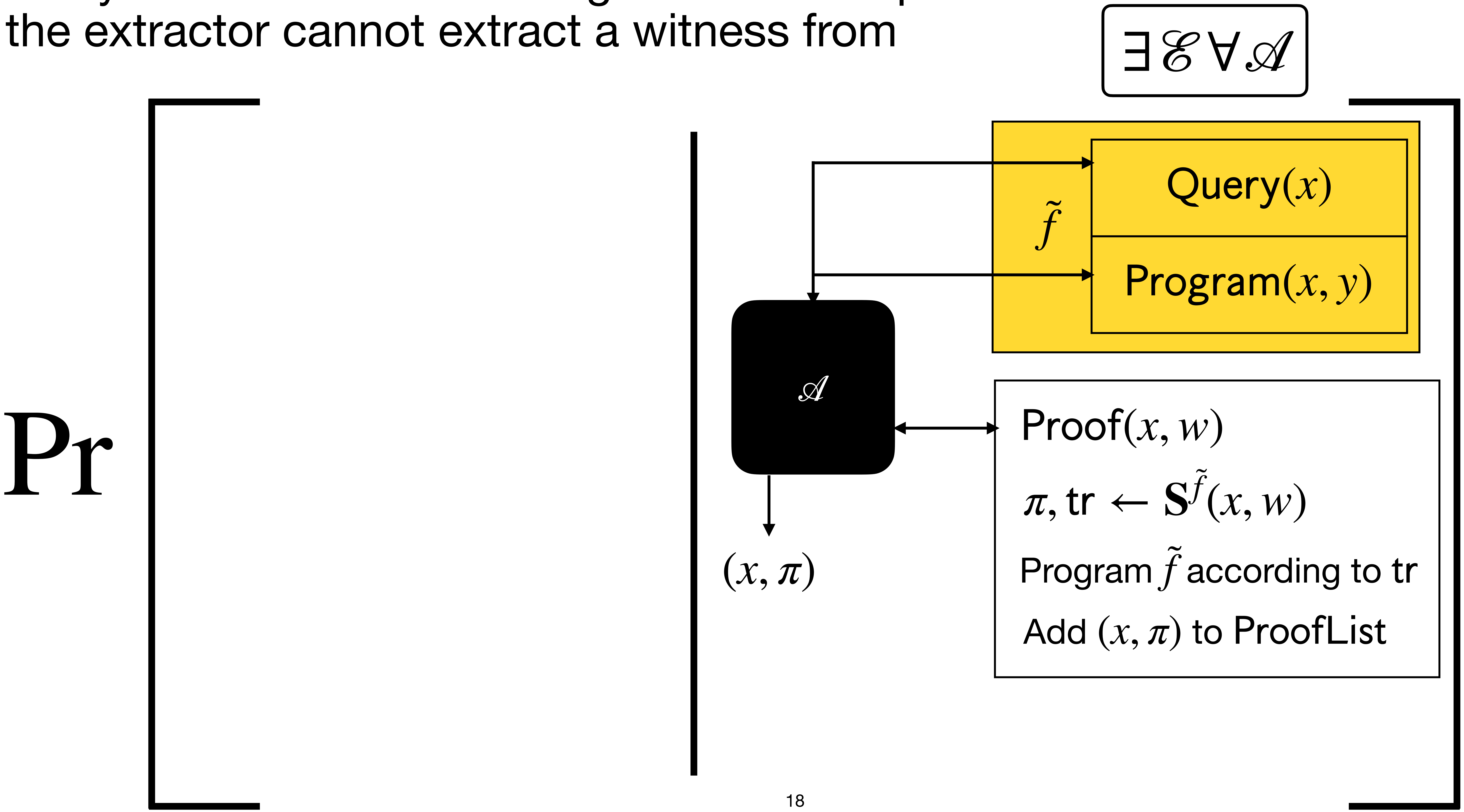
Program $\tilde{f}$ according to tr

Add (x, π) to ProofList

$\Big]$

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from



$\exists \mathscr{E} \forall \mathscr{A}$

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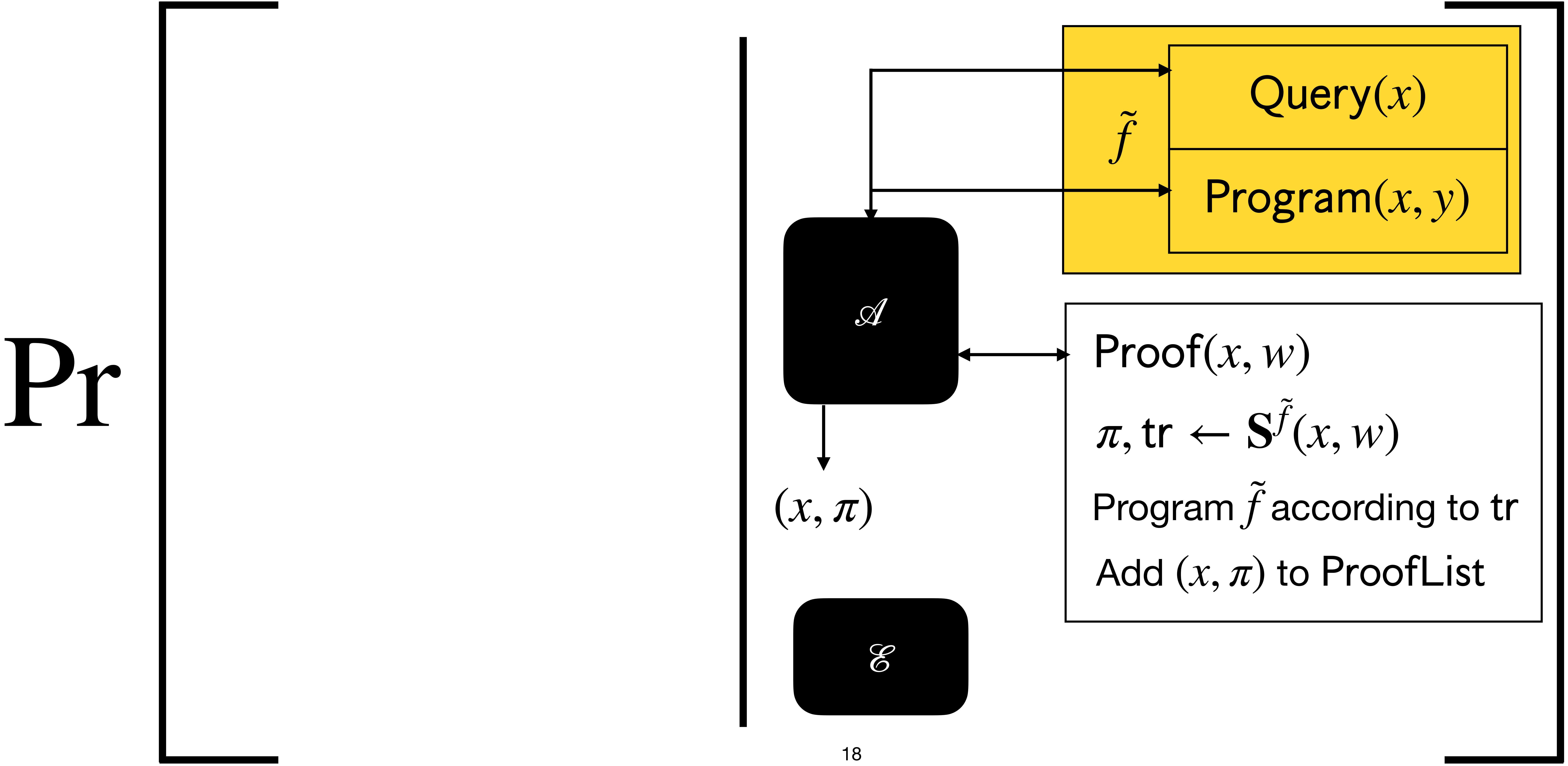

Proof(x, w)

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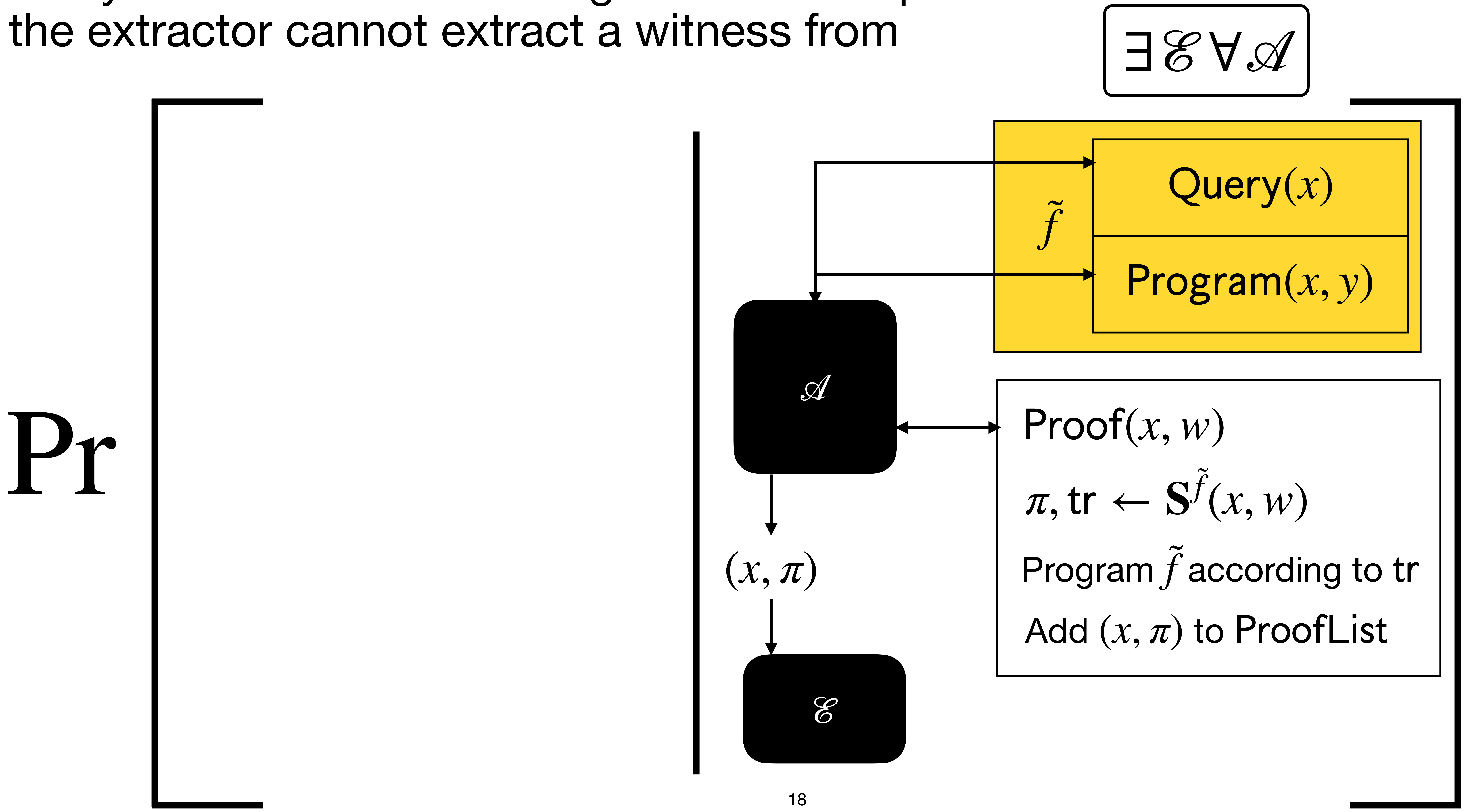

$\exists \mathscr{E} \forall \mathscr{A}$

$\Pr$

$\tilde{f}$

Query(x)

Program(x, y)

$\mathscr{A}$

(x, π)

$\mathscr{E}$

Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

Program $\tilde{f}$ according to tr

Add (x, π) to ProofList

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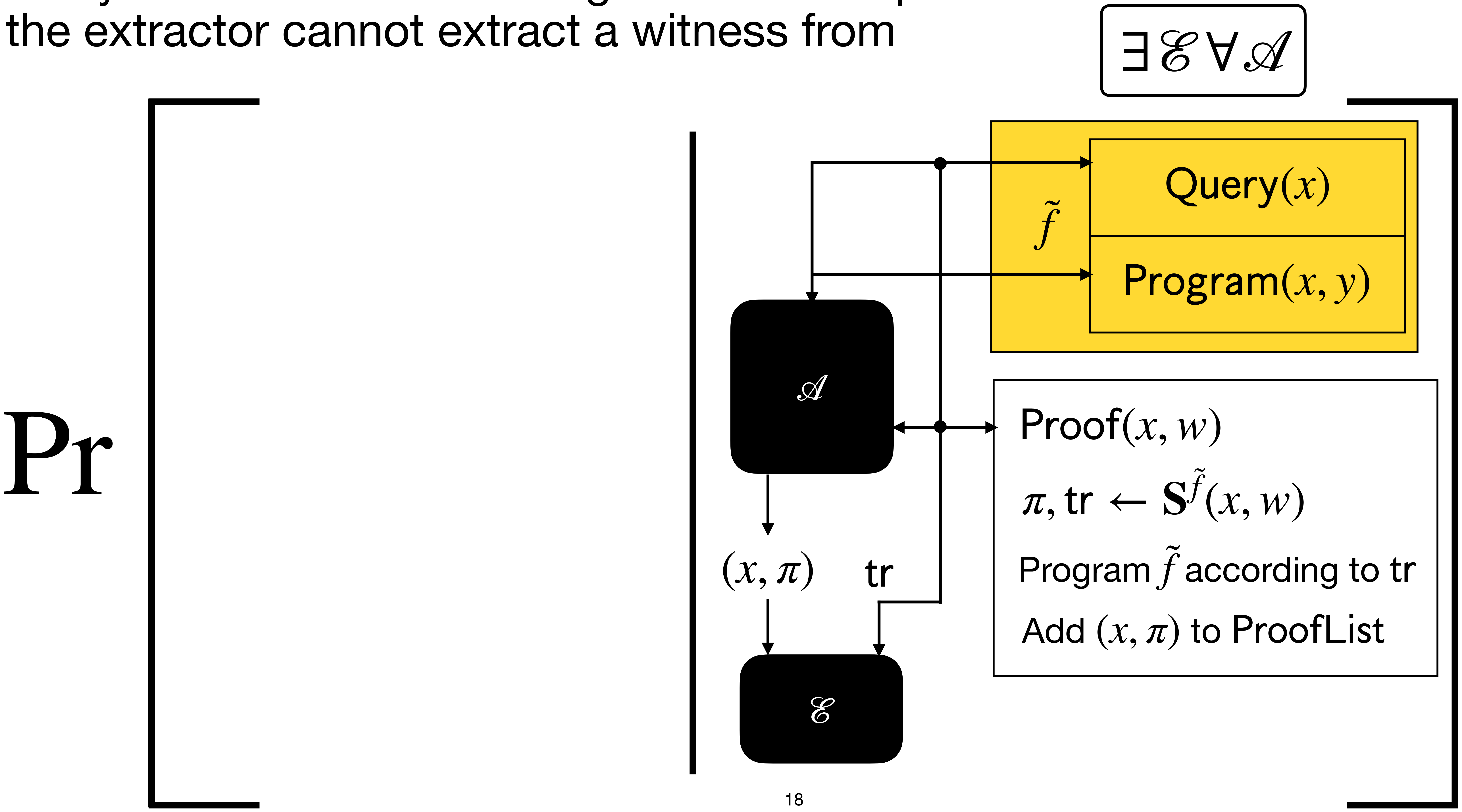

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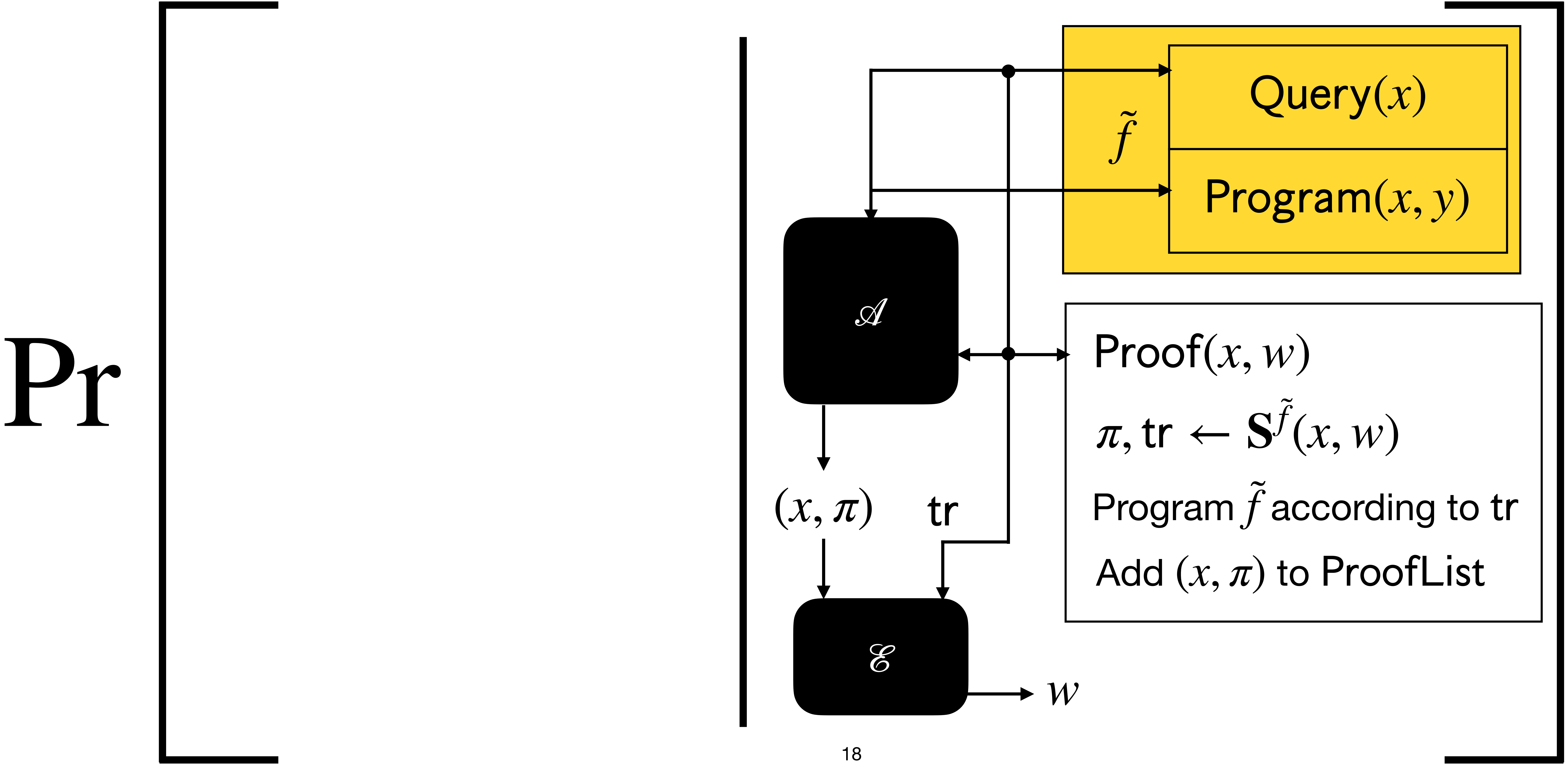


Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

Program $\tilde{f}$ according to tr

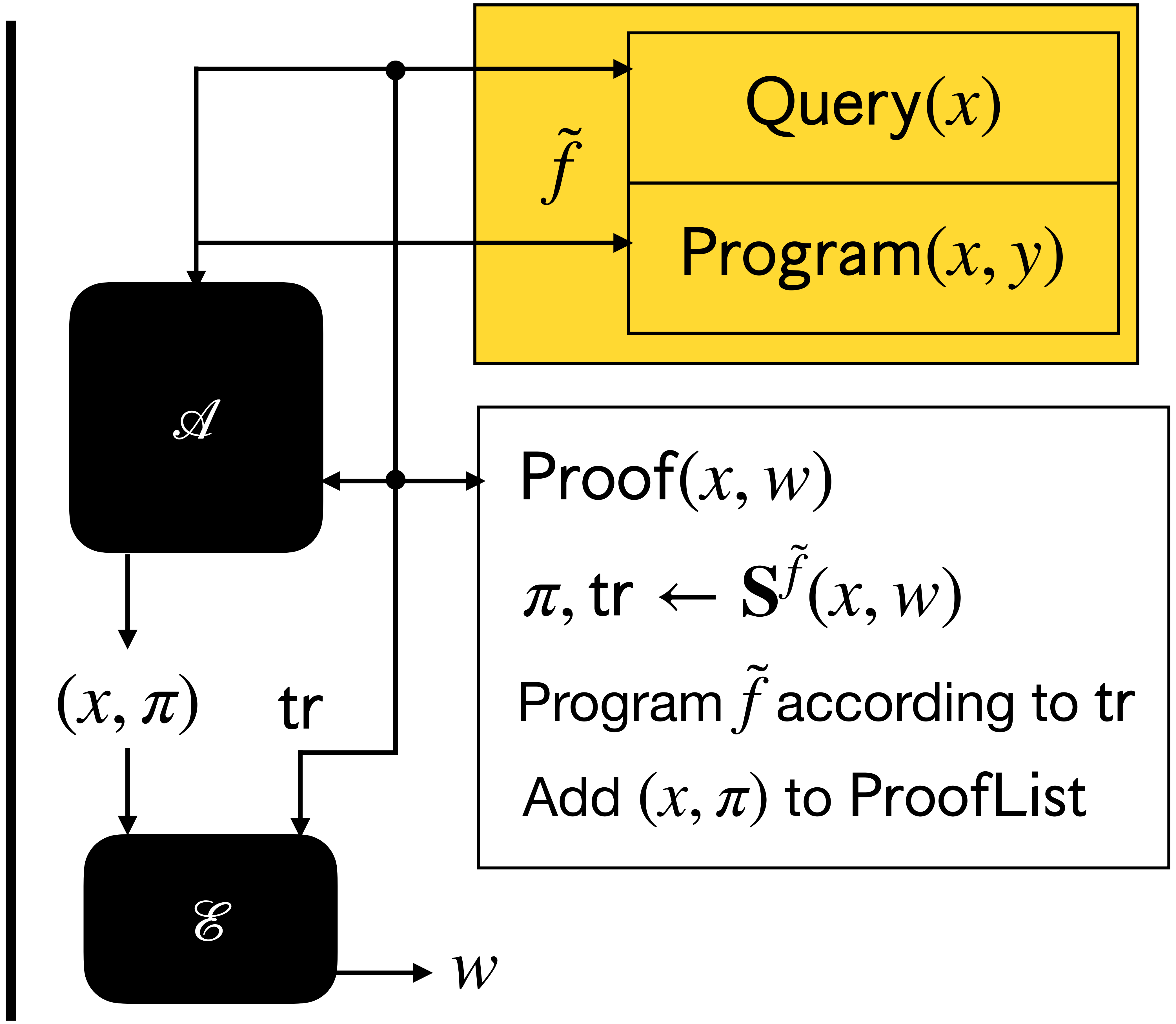
Add (x, π) to ProofList

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$\exists \mathscr{E} \forall \mathscr{A}$

$$\Pr\left[\ \mathbf{V}^{\tilde{f}}(x, \pi) = 1 \ \middle|\ \right]$$



Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

Program $\tilde{f}$ according to tr

Add (x, π) to ProofList

UC-friendly knowledge soundness

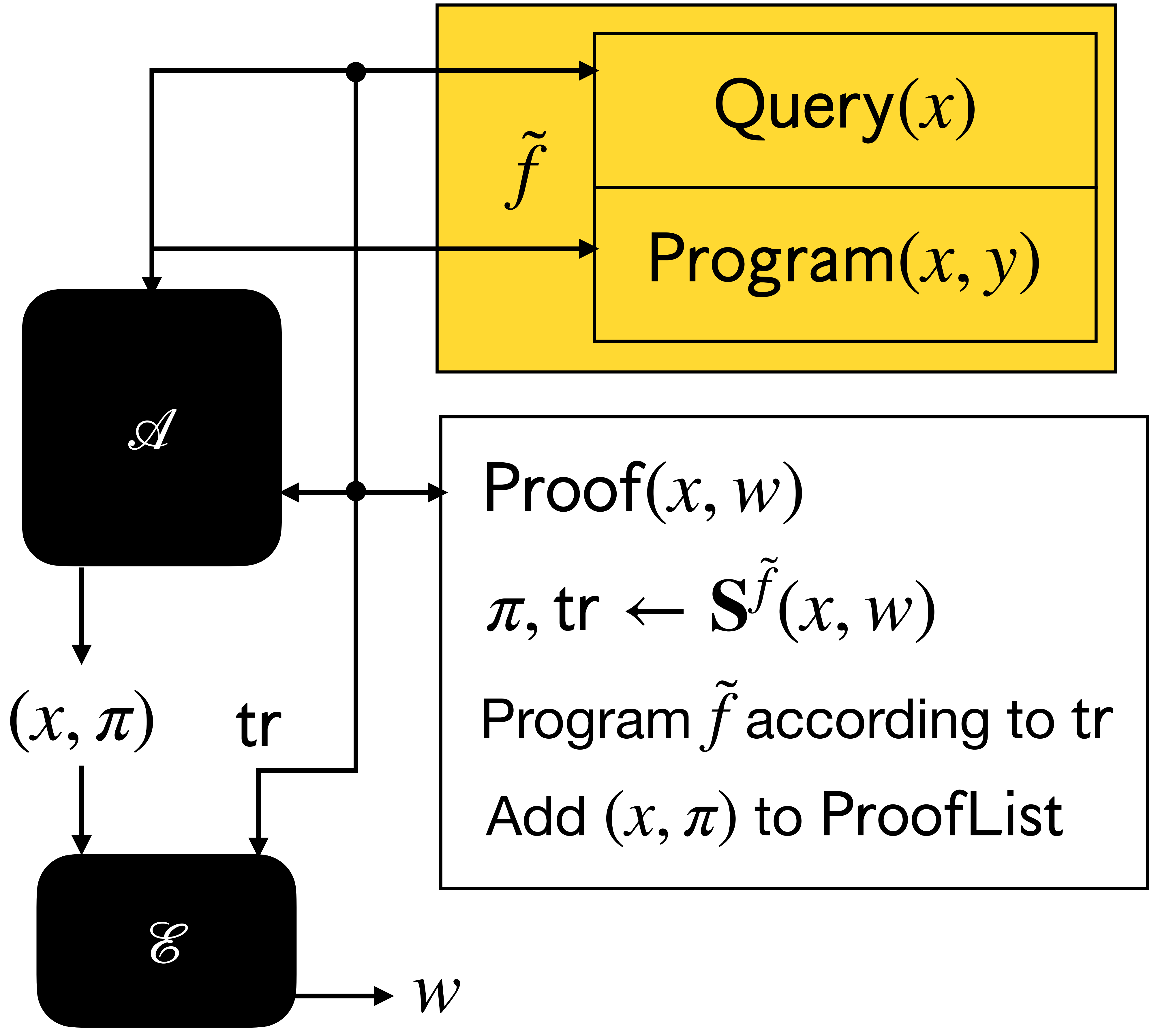
Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$\exists \mathscr{E} \forall \mathscr{A}$

$\Pr$

$\mathbf{V}^{\tilde{f}}(x, \pi) = 1$

V does not query programmed points



Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

Program $\tilde{f}$ according to tr

Add (x, π) to ProofList

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

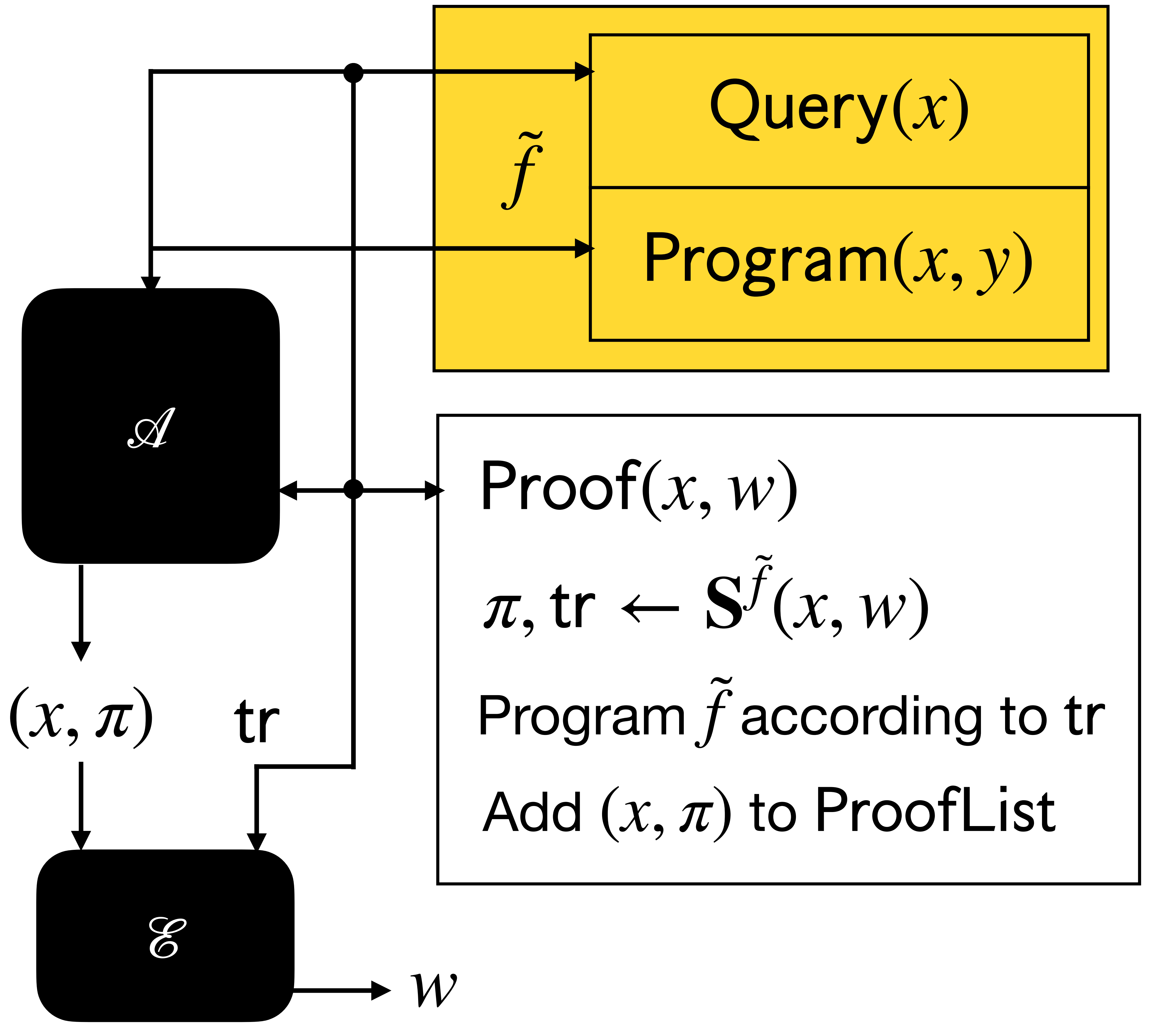
$\exists \mathscr{E} \forall \mathscr{A}$

Pr

$\mathbf{V}^{\tilde{f}}(x, \pi) = 1$

$\mathbf{V}$ does not query programmed points

$(x, \pi) \notin$ ProofList



Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

Program $\tilde{f}$ according to tr

Add (x, π) to ProofList

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$\exists \mathcal{E} \forall \mathcal{A}$

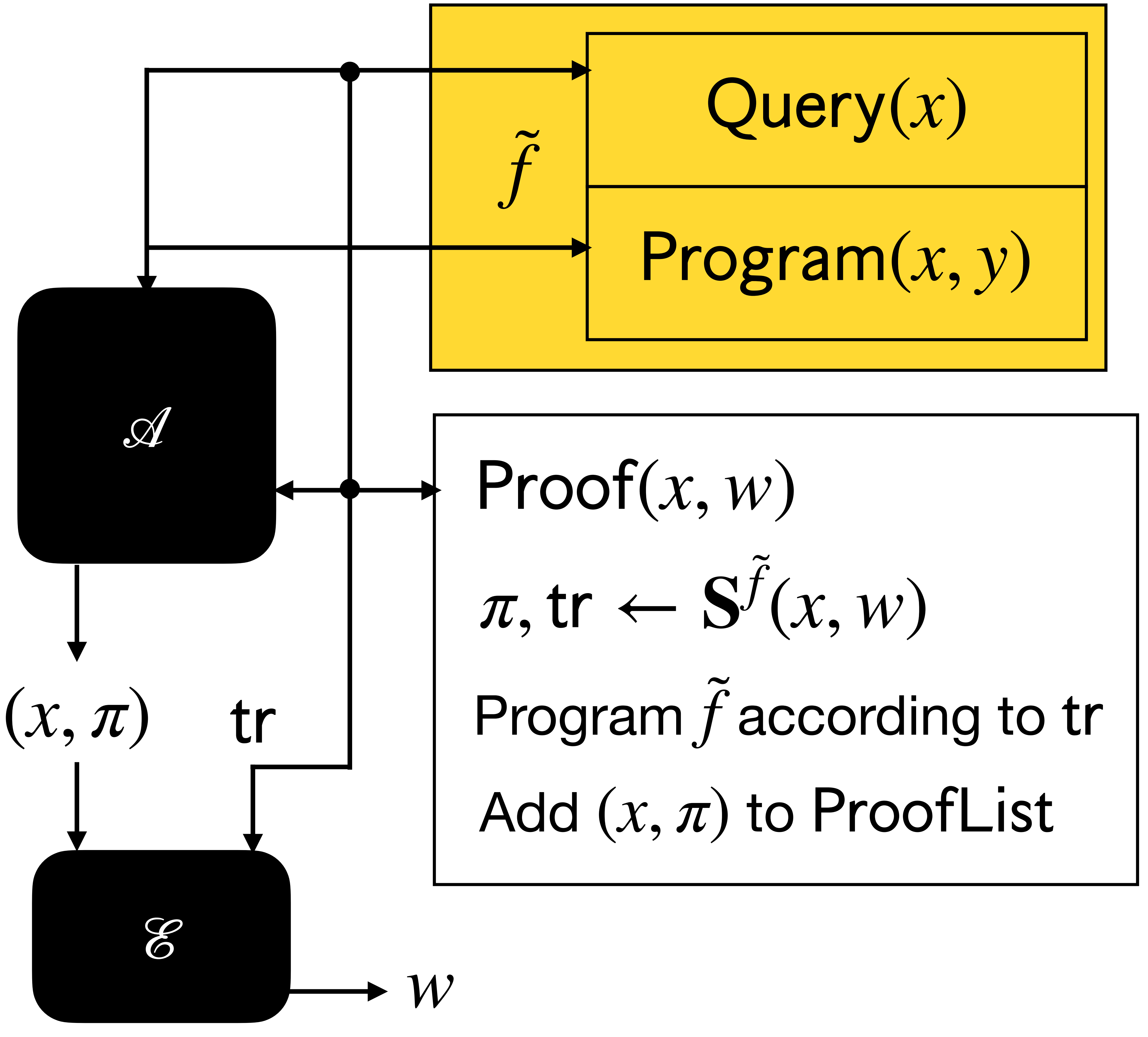
Pr

$\mathbf{V}^{\tilde{f}}(x, \pi) = 1$

V does not query programmed points

$(x, \pi) \notin$ ProofList

$(x, w) \notin R$



Proof(x, w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x, w)$

Program $\tilde{f}$ according to tr

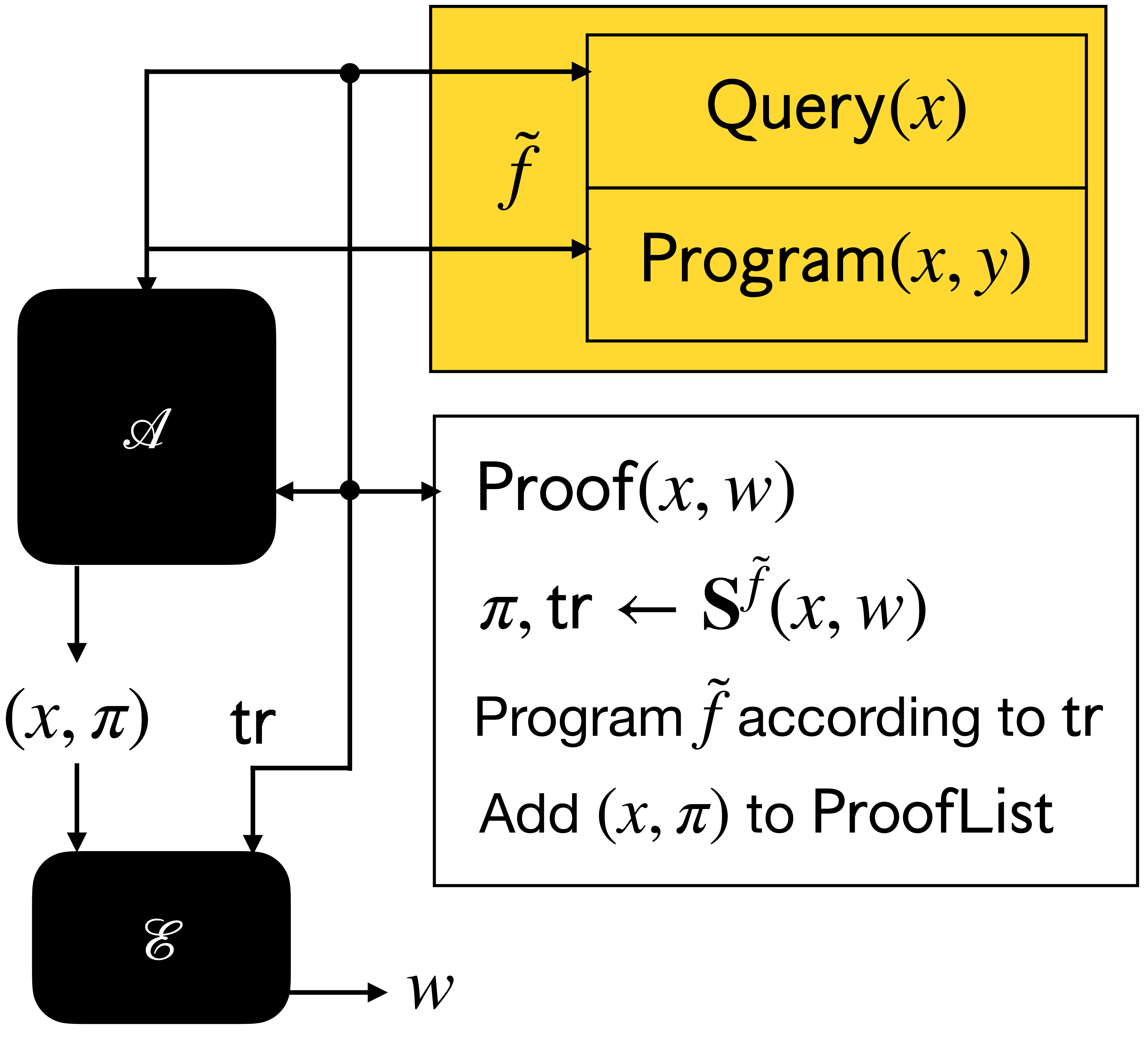
Add (x, π) to ProofList

UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$\boxed{\exists \mathscr{E} \forall \mathscr{A}}$

$$\Pr\left[\begin{array}{c|c} \boxed{\mathbf{V}^{\tilde{f}}(x,\pi)=1} & \\ \mathbf{V} \text{ does not query programmed points} & \\ (x,\pi) \notin \text{ProofList} & \\ (x,w) \notin R & \end{array}\right] \leq \kappa$$



Proof(x,w)

π, tr $\leftarrow \mathbf{S}^{\tilde{f}}(x,w)$

Program $\tilde{f}$ according to tr

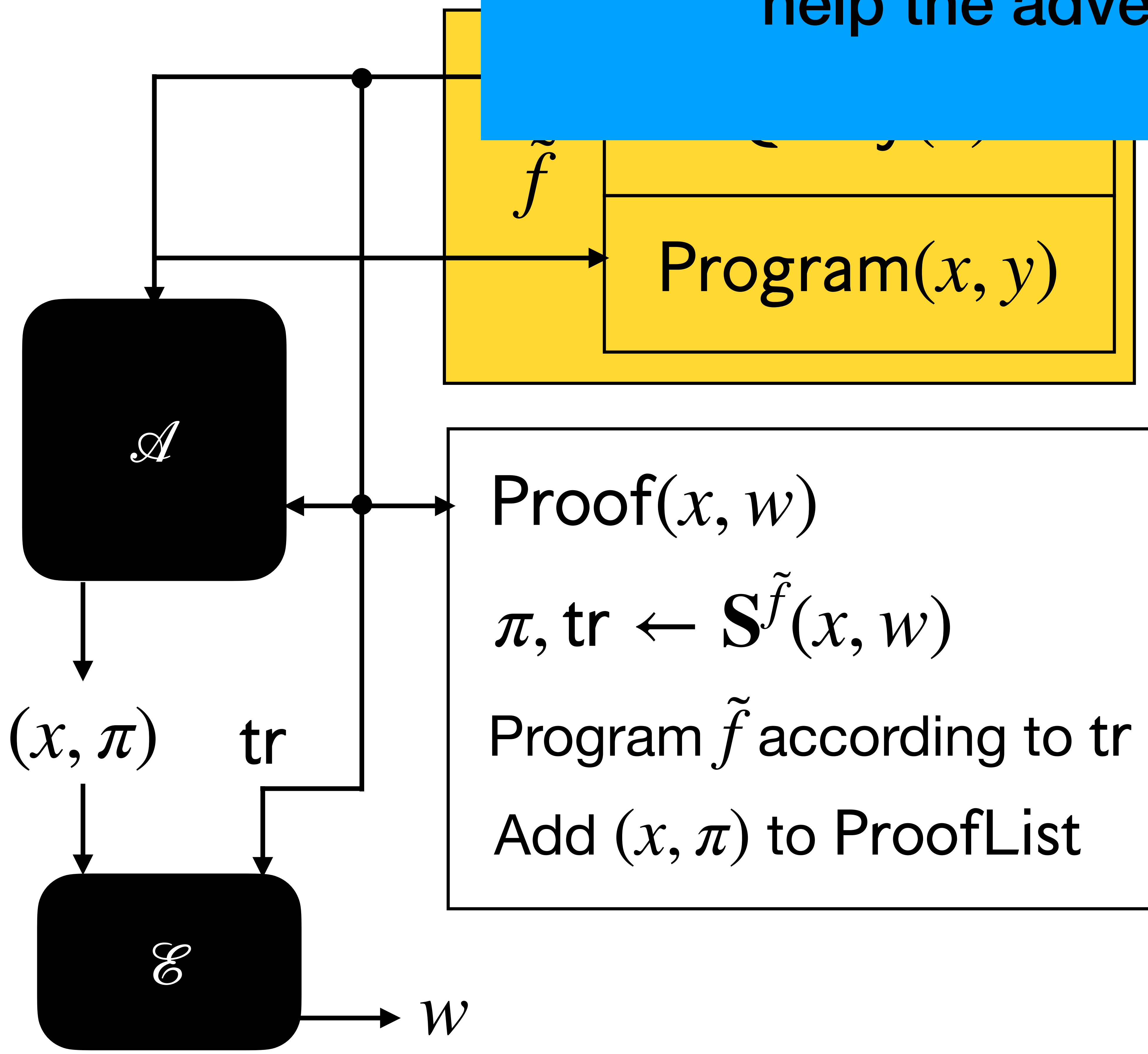
Add (x,π) to ProofList

UC-friendly knowledge sound

Similar to simulation-extractability: in Micali it holds because Merkle trees have strong extraction properties in the ROM, and programming does not help the adversary

Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

$$\Pr\left[\begin{array}{c} \mathbf{V}^{\tilde f}(x,\pi)=1 \\ \mathbf{V}\text{ does not query programmed points} \\ (x,\pi)\notin \text{ProofList} \\ (x,w)\notin R \end{array}\right|$$



Proof(x,w)

π, tr $\leftarrow \mathbf{S}^{\tilde f}(x,w)$

Program $\tilde f$ according to tr

Add (x,π) to ProofList

$$\Big] \le \kappa$$

Conclusion

Recap:

What we talked about

Recap:

What we talked about

- UC with budgets

Recap:

What we talked about

- UC with budgets
- UC-friendly security properties imply UC-security

Recap:

What we talked about

- UC with budgets
- UC-friendly security properties imply UC-security
    - UC-friendly completeness

Recap:

What we talked about

- UC with budgets
- UC-friendly security properties imply UC-security
    - UC-friendly completeness
    - UC-friendly zero knowledge

Recap:

What we talked about

- UC with budgets
- UC-friendly security properties imply UC-security
    - UC-friendly completeness
    - UC-friendly zero knowledge
    - UC-friendly knowledge soundness

There is more!

What we did not talk about

There is more!

What we did not talk about

- Concrete security bounds

There is more!

What we did not talk about

- Concrete security bounds
- UC-security of Micali & BCS (leads to UC-security of **deployed** zkSNARKs)

There is more!

What we did not talk about

- Concrete security bounds
- UC-security of Micali & BCS (leads to UC-security of **deployed** zkSNARKs)
- UC-friendly properties are **necessary**

There is more!

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- We can handle adaptive corruptions with **strong** UC-friendly properties
- Merkle trees have (strong) UC-friendly hiding
- Merkle trees have (strong) UC-friendly extraction
- **Open question:** extend the result to IOPs without straightline KS

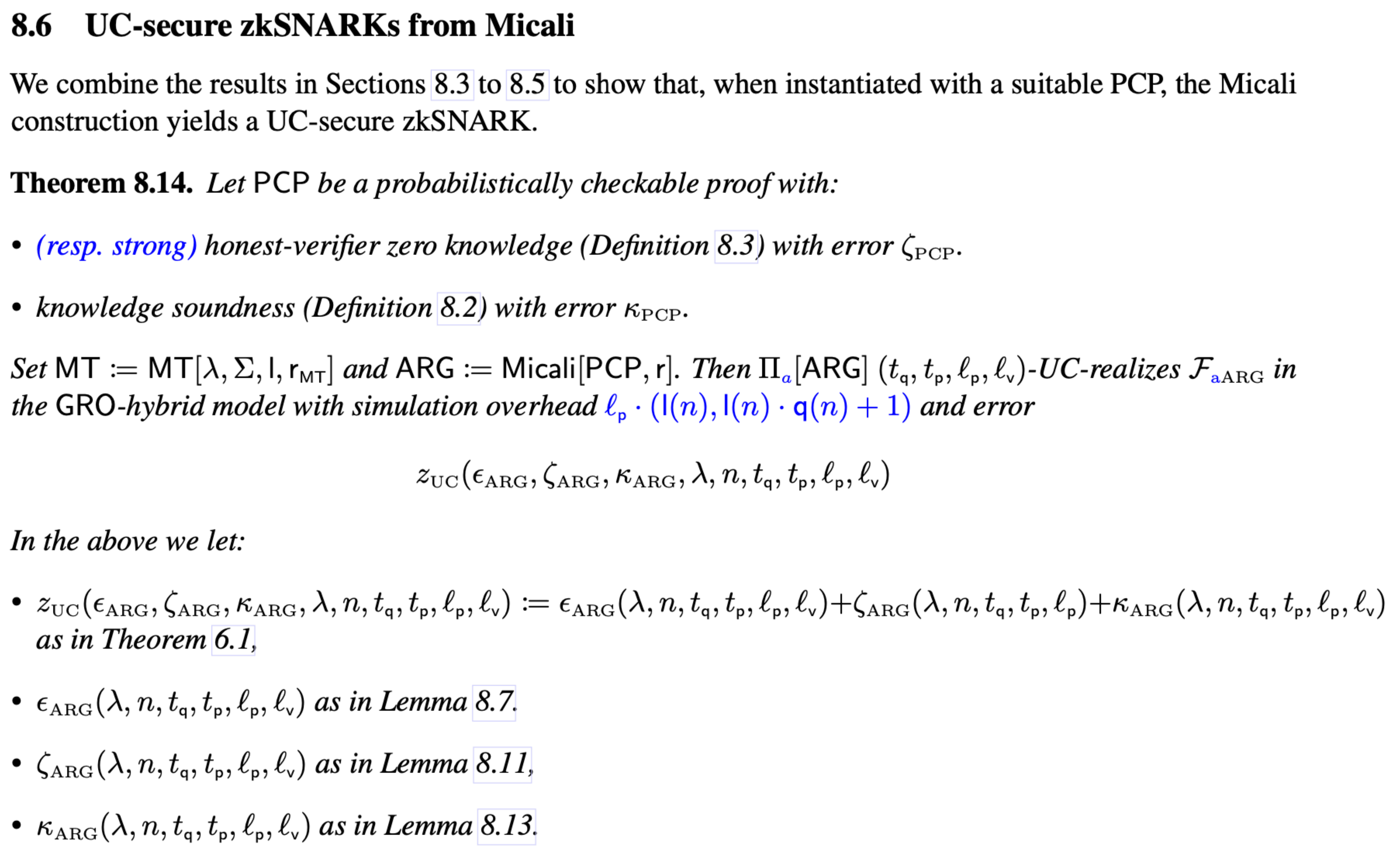
Conclusion

Micali

&

BCS

These zkSNARKs are UC-secure in the GROM



8.6 UC-secure zkSNARKs from Micali

We combine the results in Sections 8.3 to 8.5 to show that, when instantiated with a suitable PCP, the Micali construction yields a UC-secure zkSNARK.

Theorem 8.14. *Let* PCP *be a probabilistically checkable proof with:*

- *(resp. strong) honest-verifier zero knowledge (Definition 8.3) with error* ζ_{PCP}.
- *knowledge soundness (Definition 8.2) with error* κ_{PCP}.

Set $\mathsf{MT} := \mathsf{MT}[\lambda, \Sigma, \mathsf{l}, \mathsf{r}_{\mathsf{MT}}]$ *and* $\mathsf{ARG} := \mathsf{Micali}[\mathsf{PCP}, \mathsf{r}]$. *Then* $\Pi_{a}[\mathsf{ARG}]$ $(t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$*-UC-realizes* $\mathcal{F}_{\mathrm{aARG}}$ *in the* GRO*-hybrid model with simulation overhead* $\ell_{\mathsf{p}} \cdot (\mathsf{l}(n), \mathsf{l}(n) \cdot \mathsf{q}(n) + 1)$ *and error*

$$z_{\mathrm{UC}}(\epsilon_{\mathrm{ARG}}, \zeta_{\mathrm{ARG}}, \kappa_{\mathrm{ARG}}, \lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$$

In the above we let:

- $z_{\mathrm{UC}}(\epsilon_{\mathrm{ARG}}, \zeta_{\mathrm{ARG}}, \kappa_{\mathrm{ARG}}, \lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}}) := \epsilon_{\mathrm{ARG}}(\lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}}) + \zeta_{\mathrm{ARG}}(\lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}) + \kappa_{\mathrm{ARG}}(\lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$ *as in Theorem 6.1,*
- $\epsilon_{\mathrm{ARG}}(\lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$ *as in Lemma 8.7.*
- $\zeta_{\mathrm{ARG}}(\lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$ *as in Lemma 8.11,*
- $\kappa_{\mathrm{ARG}}(\lambda, n, t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$ *as in Lemma 8.13.*

Concrete security bounds!

Thank you!

Extra slides

Modelling shared functionalities [BCHTZ22]

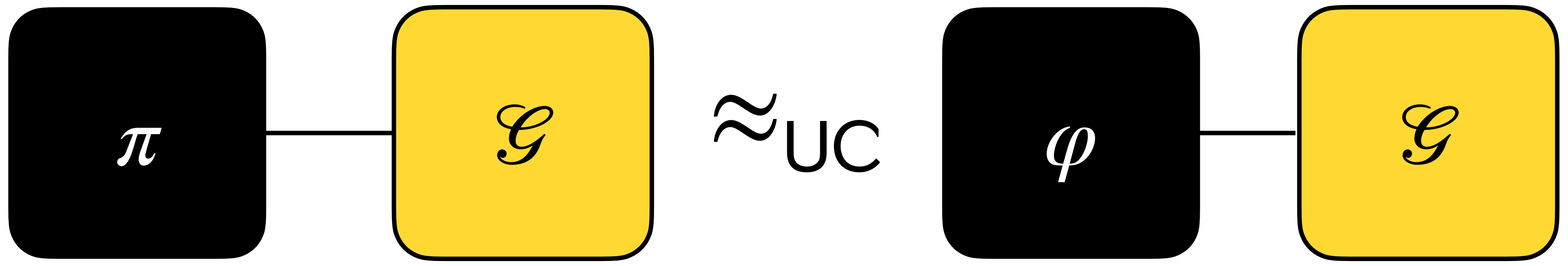
Modelling shared functionalities [BCHTZ22]

Plain UC security **not enough** for **shared** setups

Modelling shared functionalities [BCHTZ22]

Plain UC security **not enough** for **shared** setups

Plain UC:



Modelling shared functionalities

[BCHTZ22]

Plain UC security **not enough** for **shared** setups

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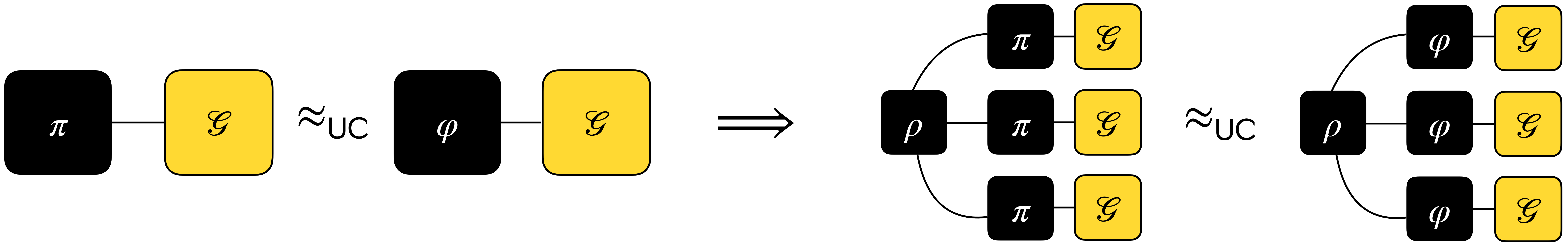

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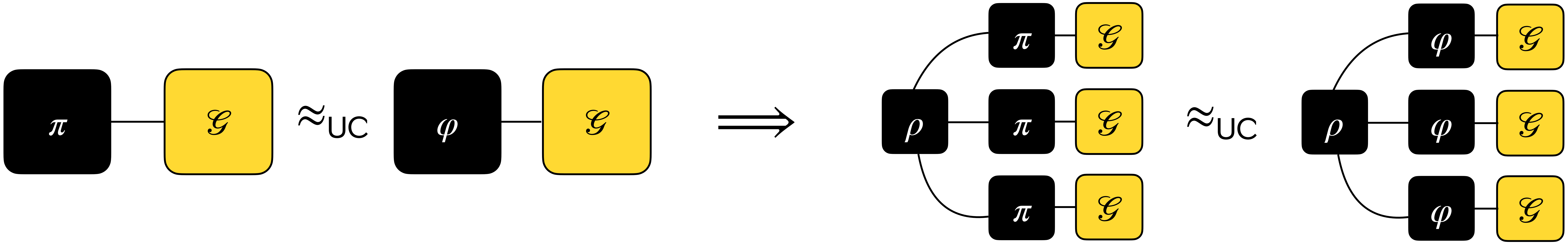

Solution: UC with Global Subroutines!

Modelling shared functionalities

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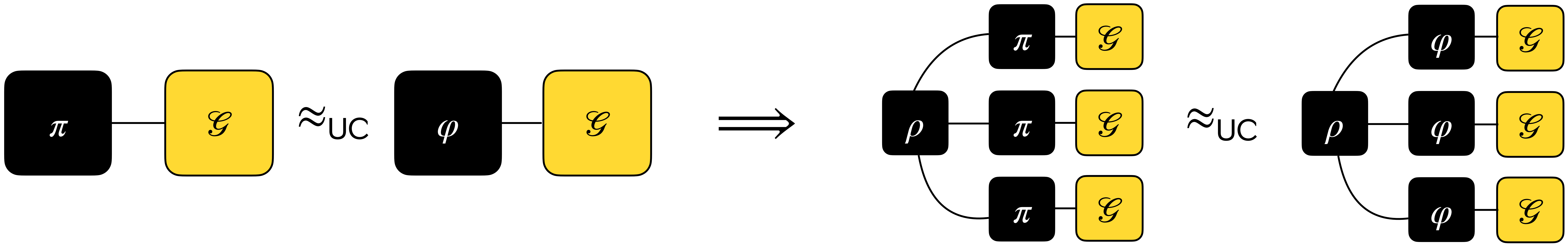

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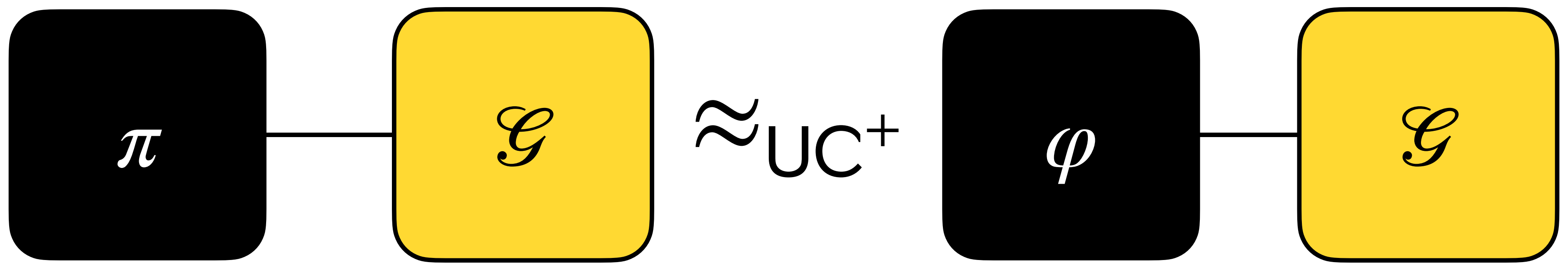

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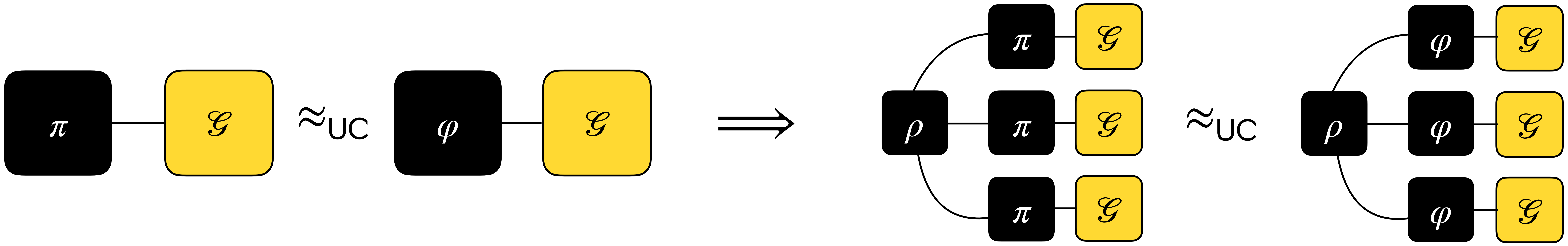

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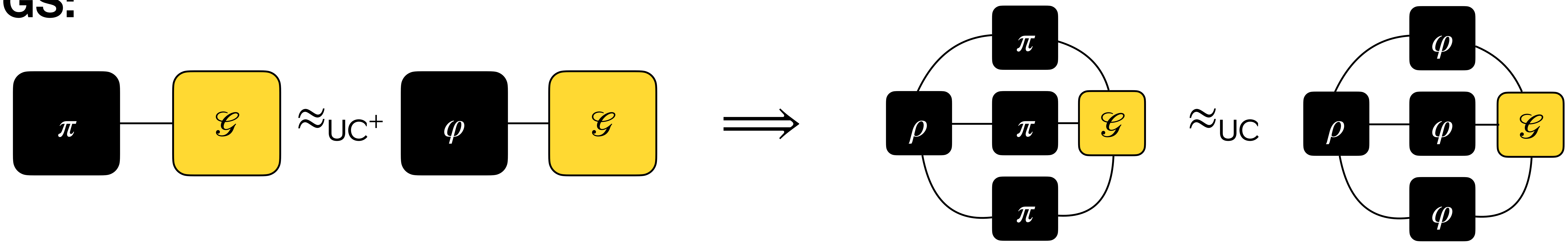

Micali has UC-friendly ZK

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Real $\equiv G_0$

Micali has UC-friendly ZK

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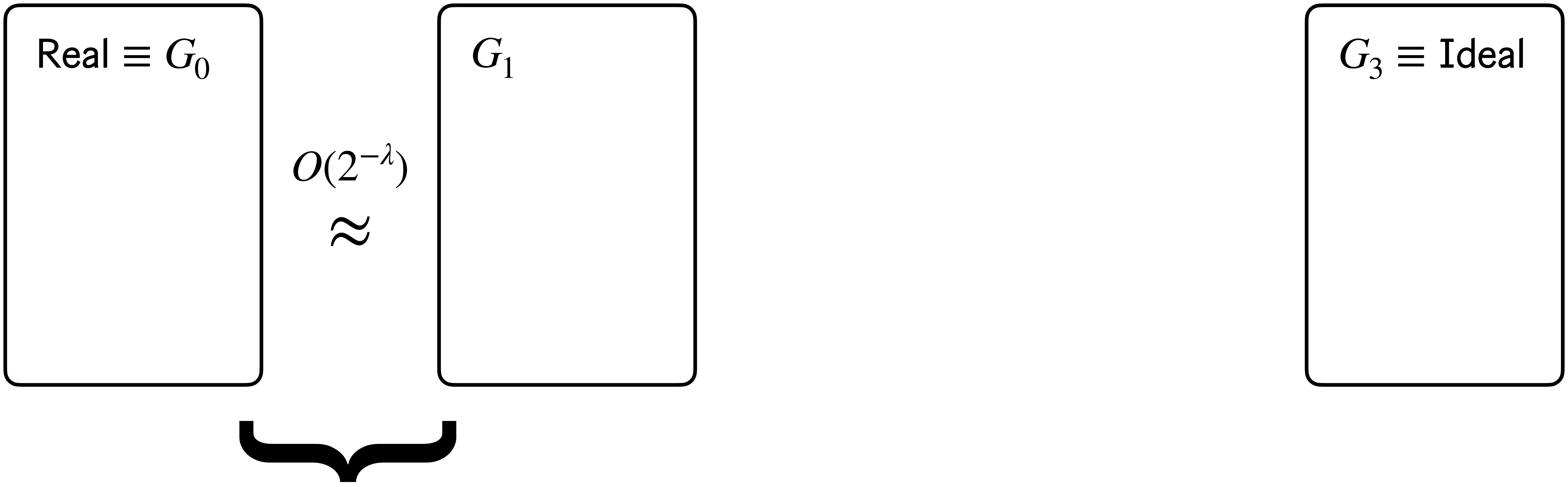
$G_3 \equiv$ Ideal

Micali has UC-friendly ZK



Real $\equiv G_0$

$O(2^{-\lambda})$

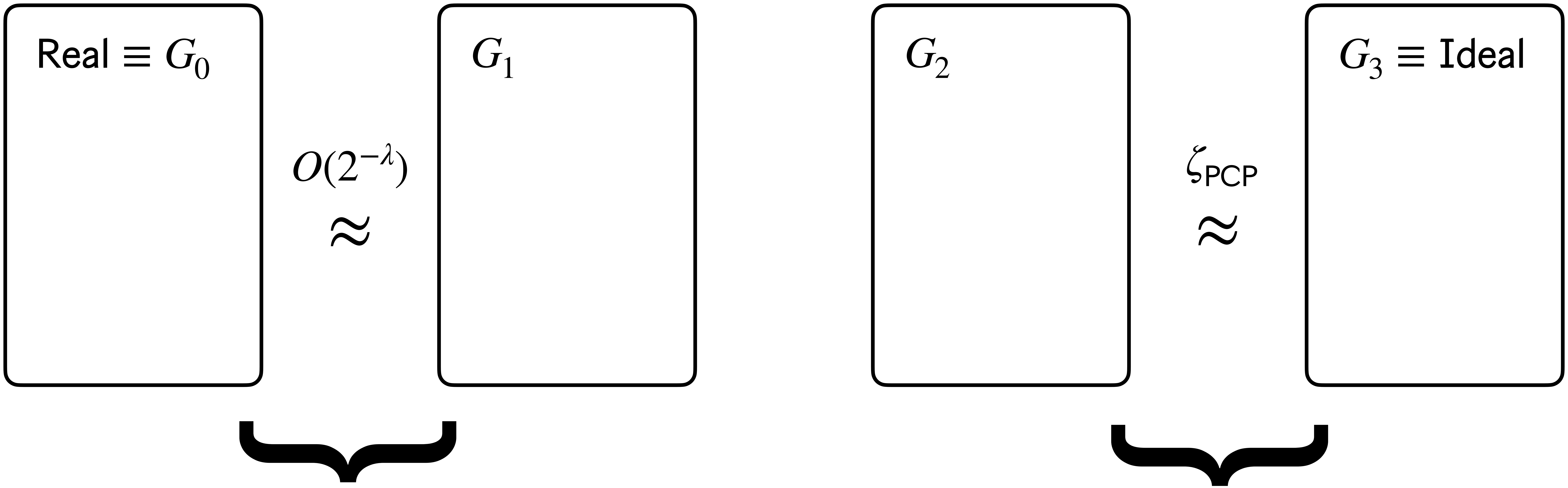
$\approx$

G_1

$G_3 \equiv$ Ideal

FS input hard
to predict

Micali has UC-friendly ZK



$\mathsf{Real} \equiv G_0$

G_1

G_2

$G_3 \equiv \mathsf{Ideal}$

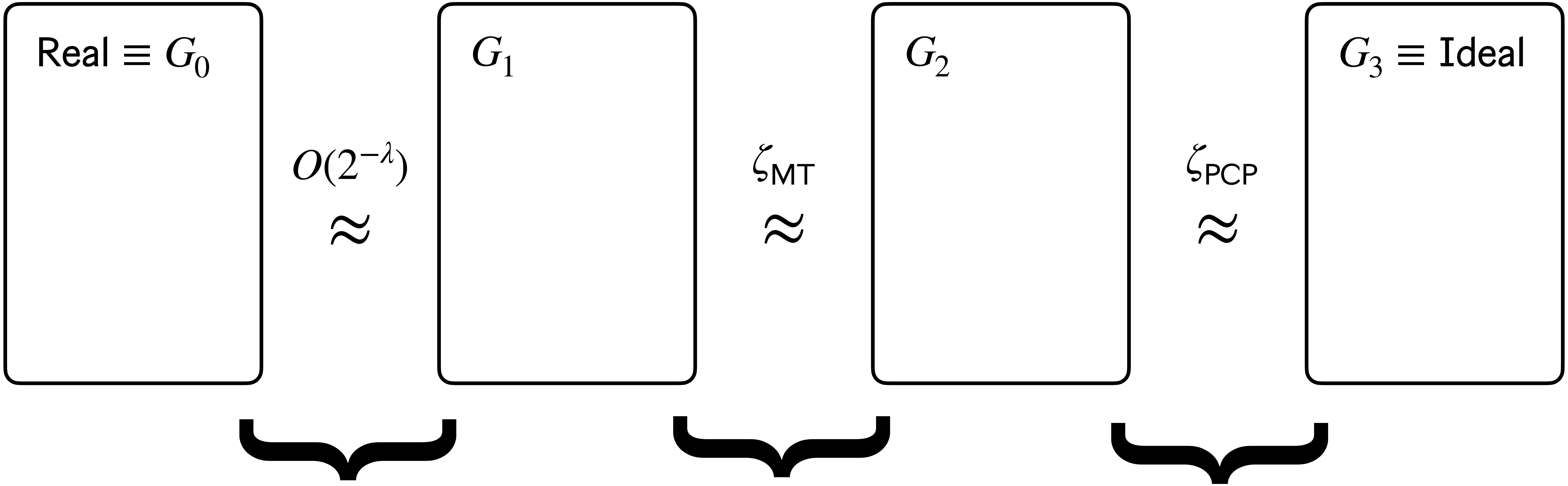
$\overset{O(2^{-\lambda})}{\approx}$

$\overset{\zeta_{\mathsf{PCP}}}{\approx}$

FS input hard
to predict

PCP honest-verifier
ZK

Micali has UC-friendly ZK



Real $\equiv G_0$

$O(2^{-\lambda})$ $\approx$

G_1

ζ_{MT} $\approx$

G_2

ζ_{PCP} $\approx$

$G_3 \equiv$ Ideal

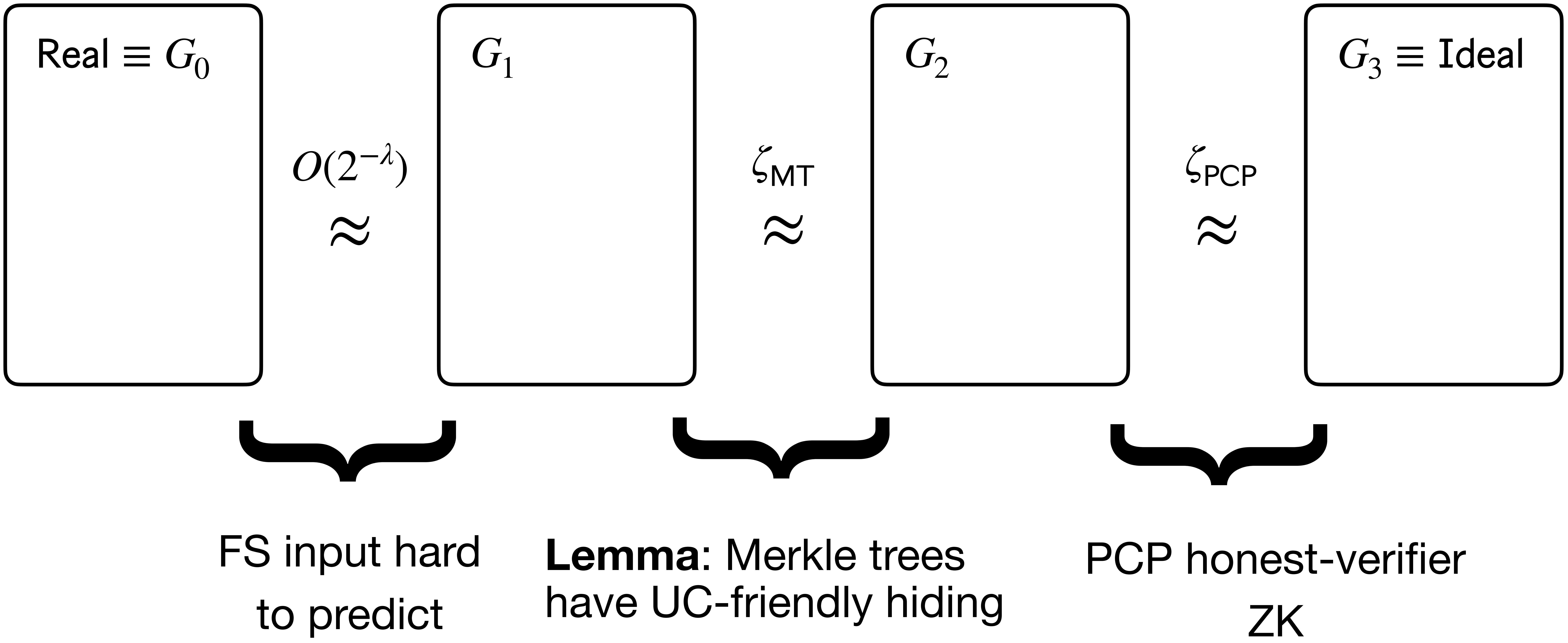
FS input hard to predict

Lemma: Merkle trees have UC-friendly hiding

PCP honest-verifier ZK

Micali has UC-friendly ZK

Follows similarly to standard Micali ZK + Merkle trees are UC-friendly.



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Lemma: Merkle trees have UC-friendly hiding

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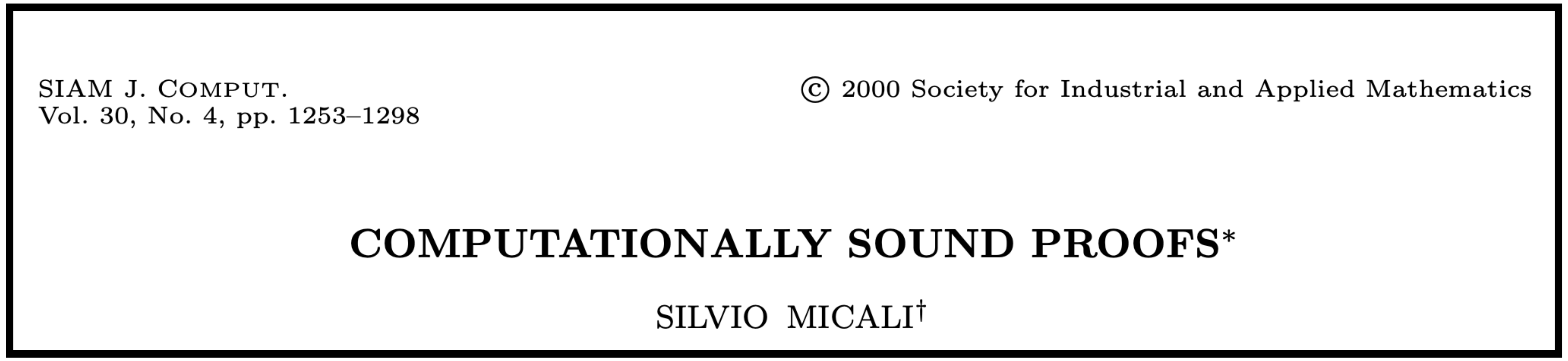
Micali’s construction I



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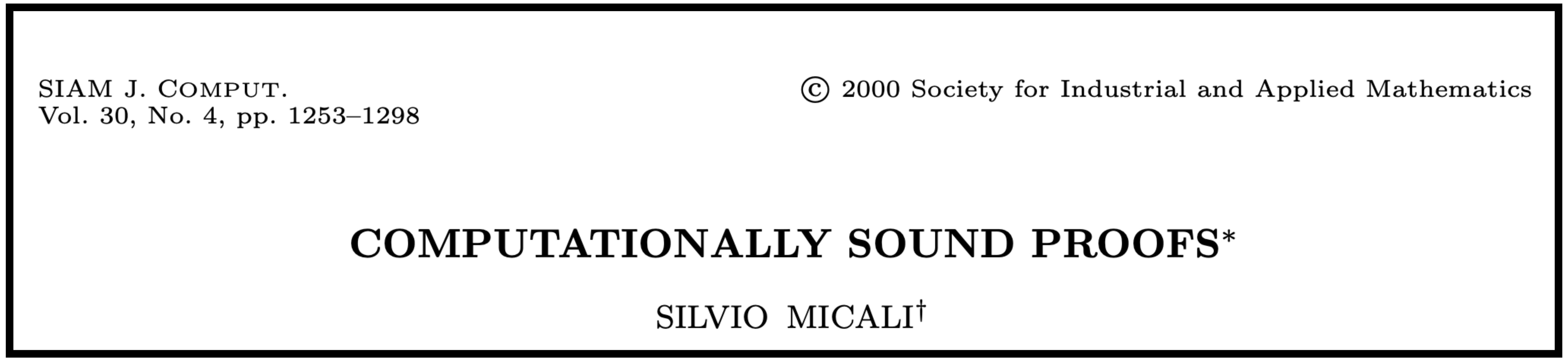
COMPUTATIONALLY SOUND PROOFS*

SILVIO MICALI†

Micali’s construction I



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Canonical construction of zkSNARK in the ROM

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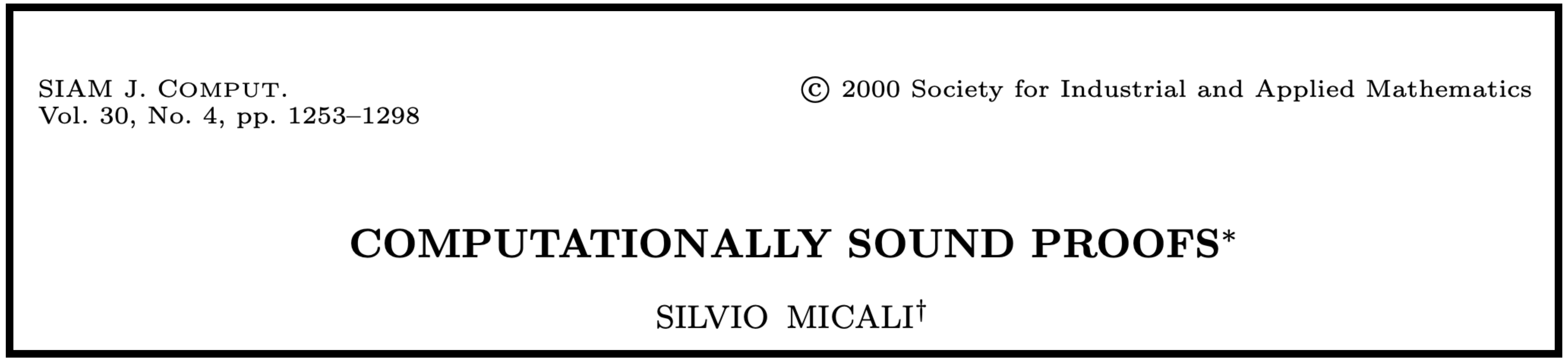

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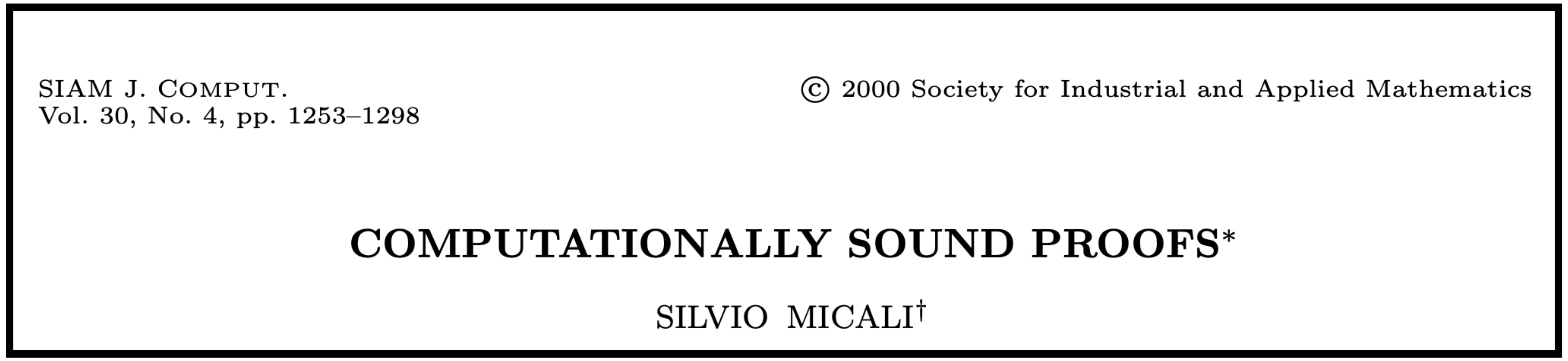

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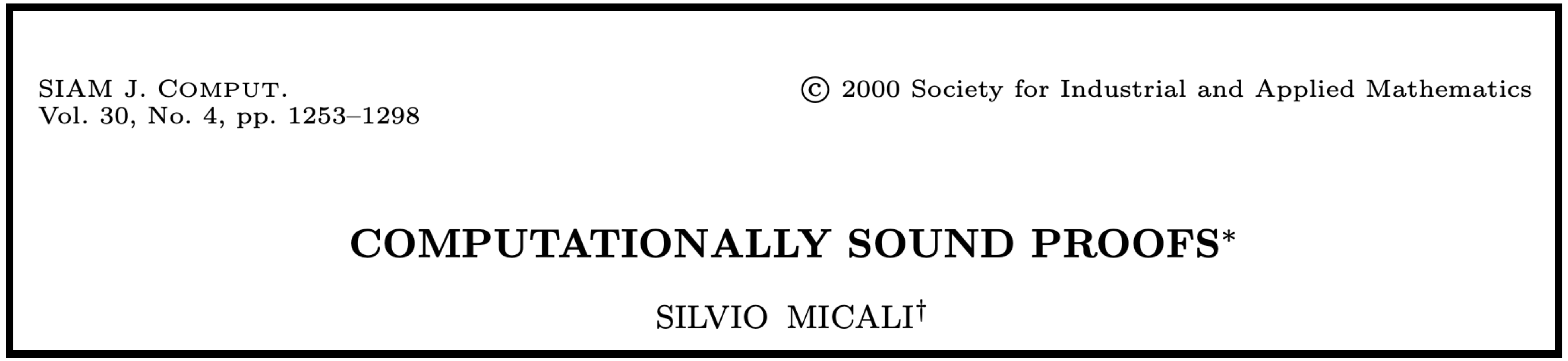

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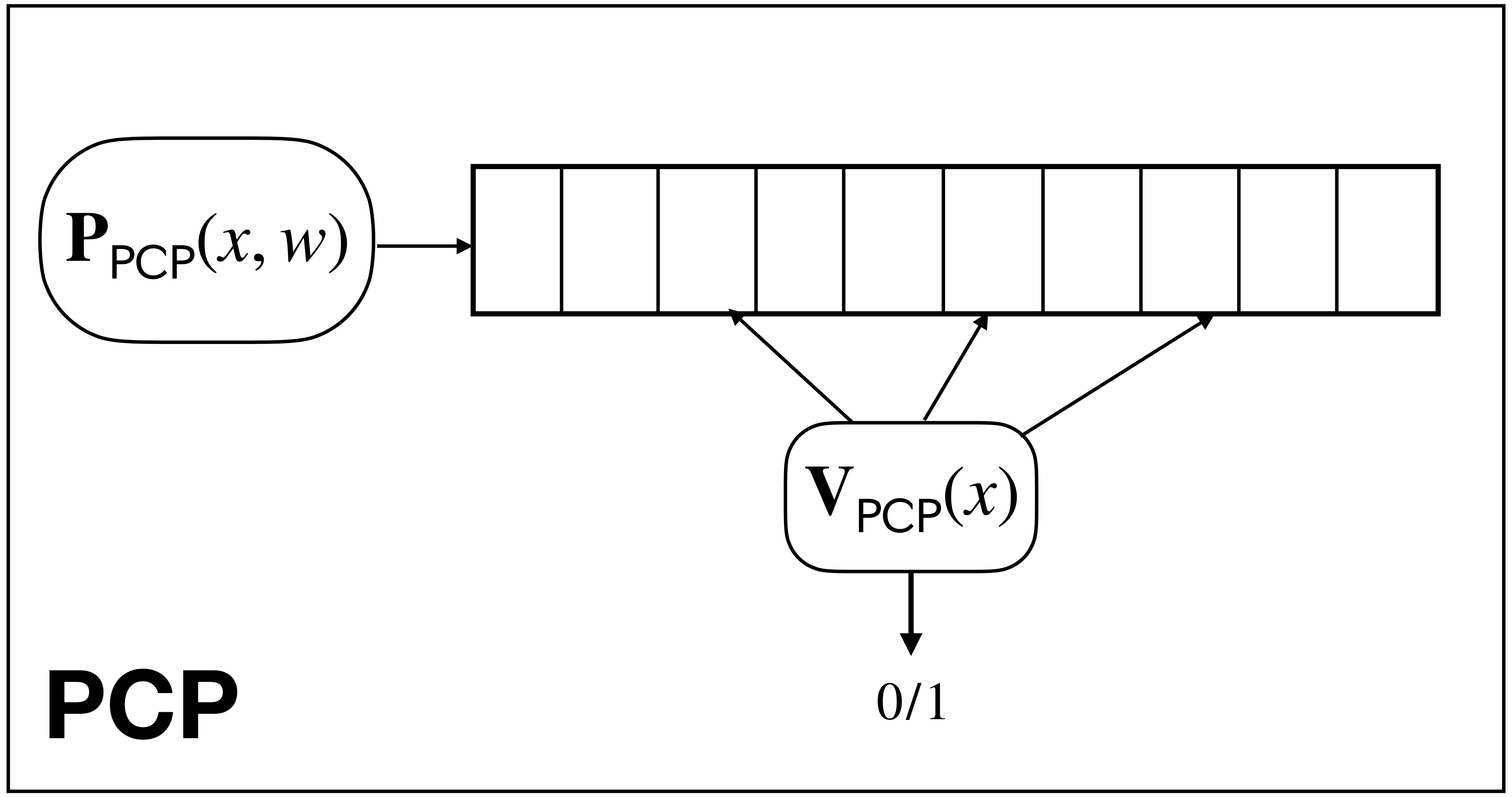
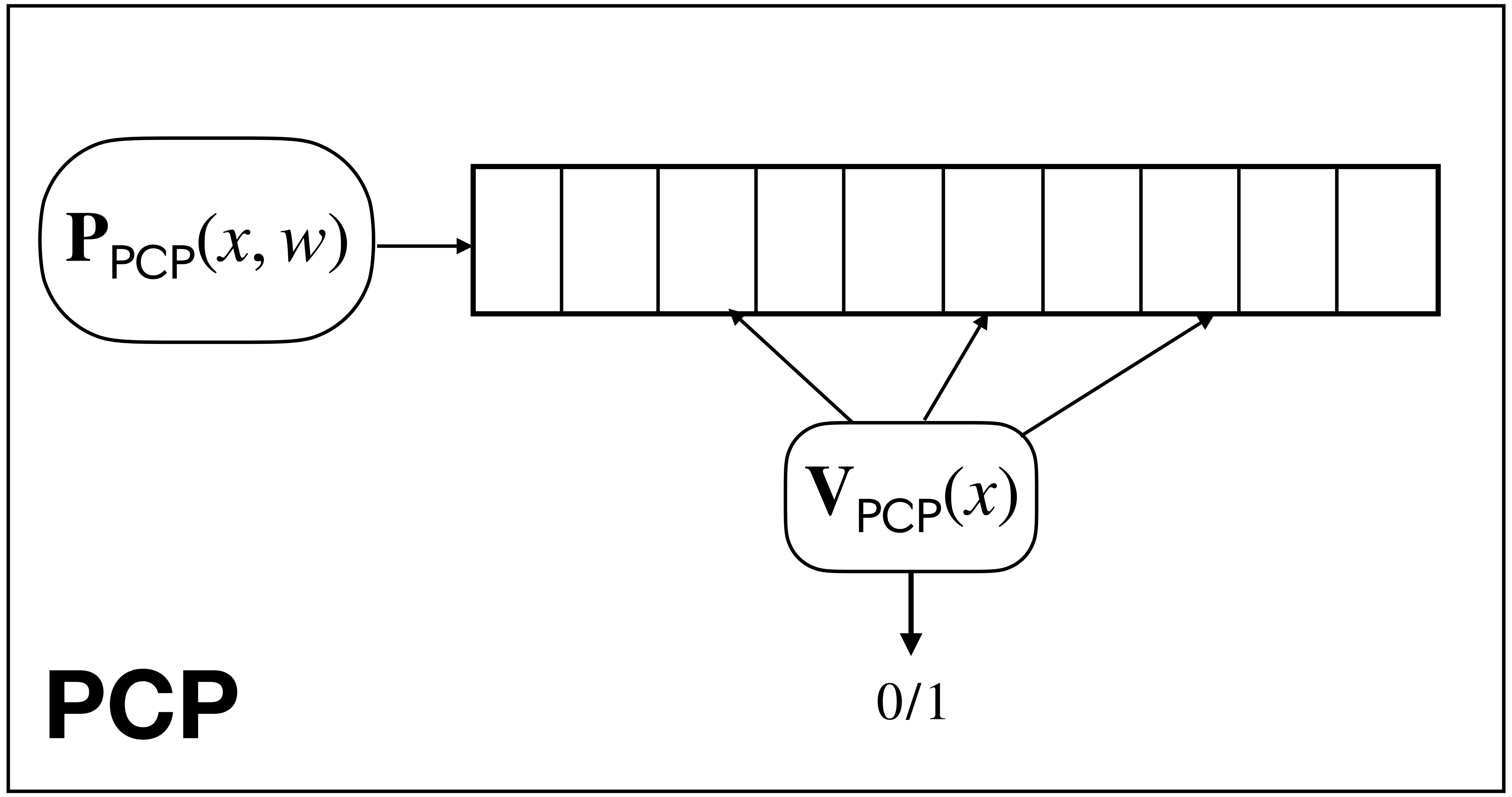
Stepping stone to BCS, which underlies **deployed** zkSNARKs

Micali’s construction II

Micali's construction II


$\mathbf{P}_{\mathsf{PCP}}(x, w)$
$\mathbf{V}_{\mathsf{PCP}}(x)$
0/1
PCP

Micali's construction II


$\mathbf{P}_{\mathsf{PCP}}(x, w)$
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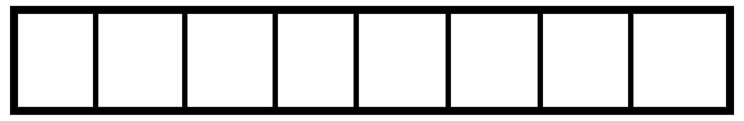
+



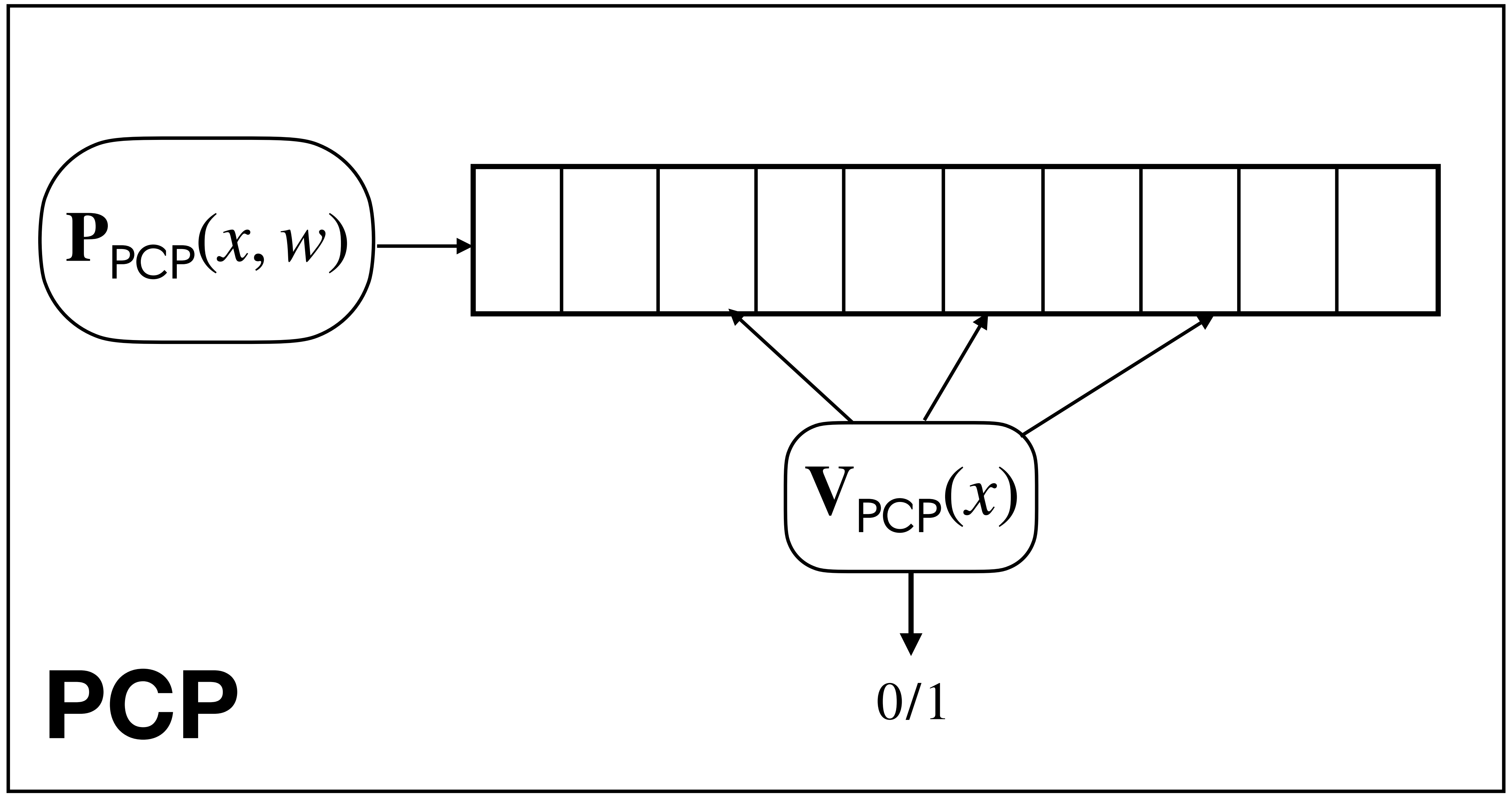
$\xrightarrow{\mathsf{Commit}^f} \mathsf{rt}, \mathsf{aux}$

$\mathsf{MTOpen}(\mathsf{rt}, I, \vec{a}, \mathsf{aux}) \to \pi$

$\mathsf{MTCheck}^f(\mathsf{rt}, I, \vec{a}, \pi) = 1 \iff$
$\tilde{\exists}\Pi : \mathsf{rt} = \mathsf{MTCommit}^f(\Pi) \wedge \Pi|_I = \vec{a}$

Merkle trees

Micali’s construction II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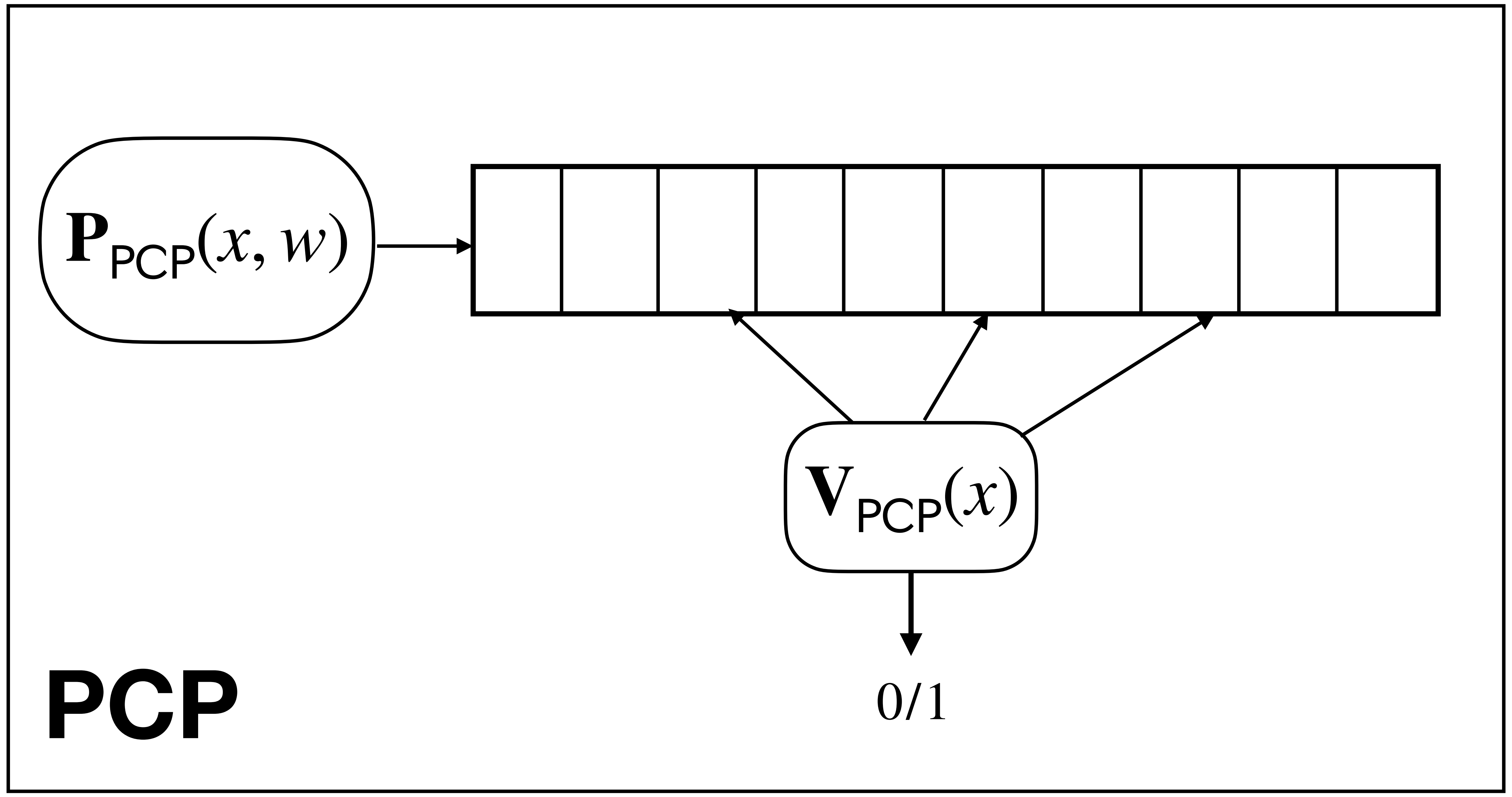
Merkle trees

+

Fiat Shamir

=

Micali's construction II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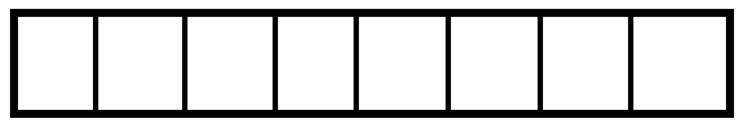
PCP

+



$\xrightarrow{\mathsf{Commit}^f}$ rt, aux

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zkSNARK in the ROM

Micali’s construction III

Commit to PCP string using MT,
then apply FS transform

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$\mathbf{P}(x, w)$

$\mathbf{V}(x)$

Micali’s construction III

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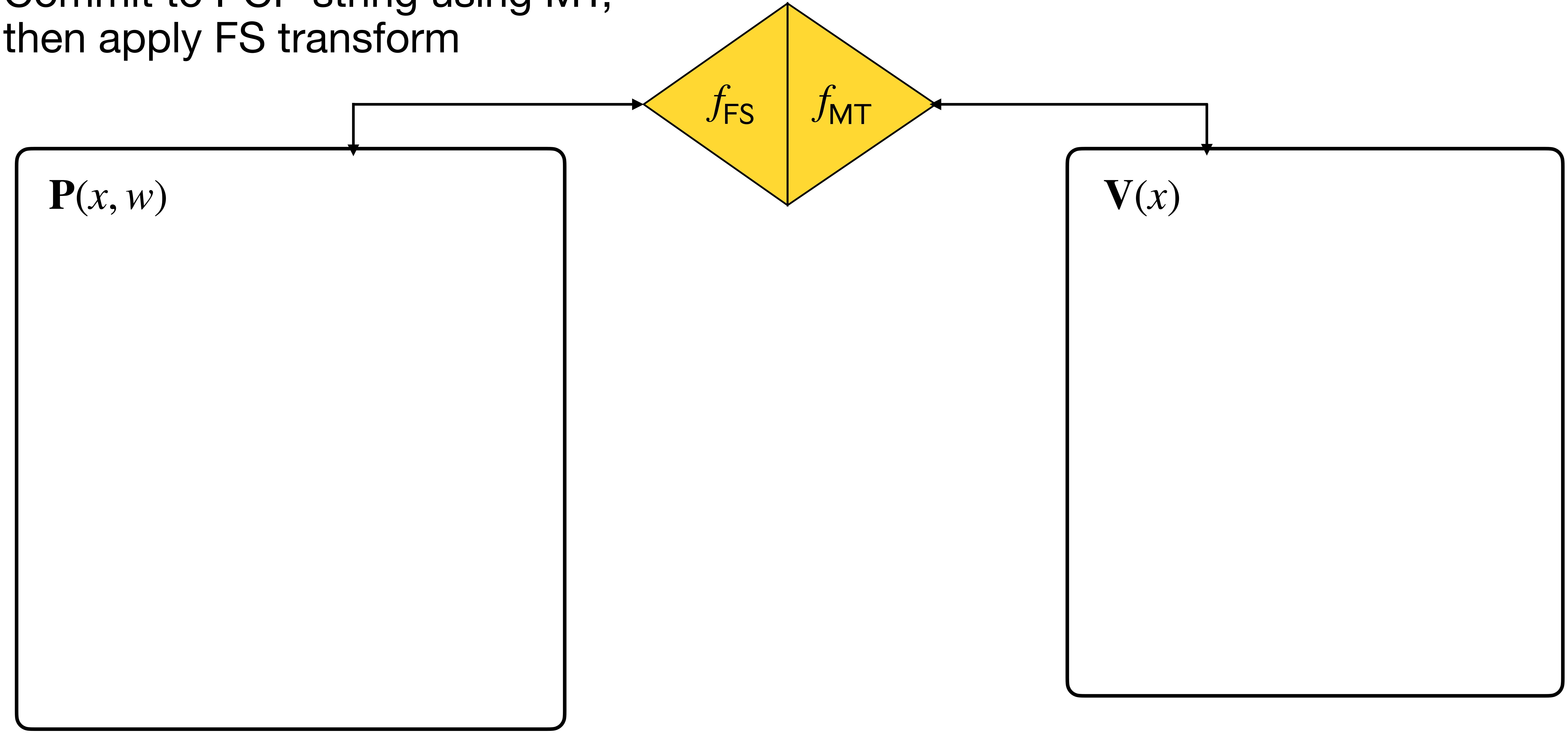

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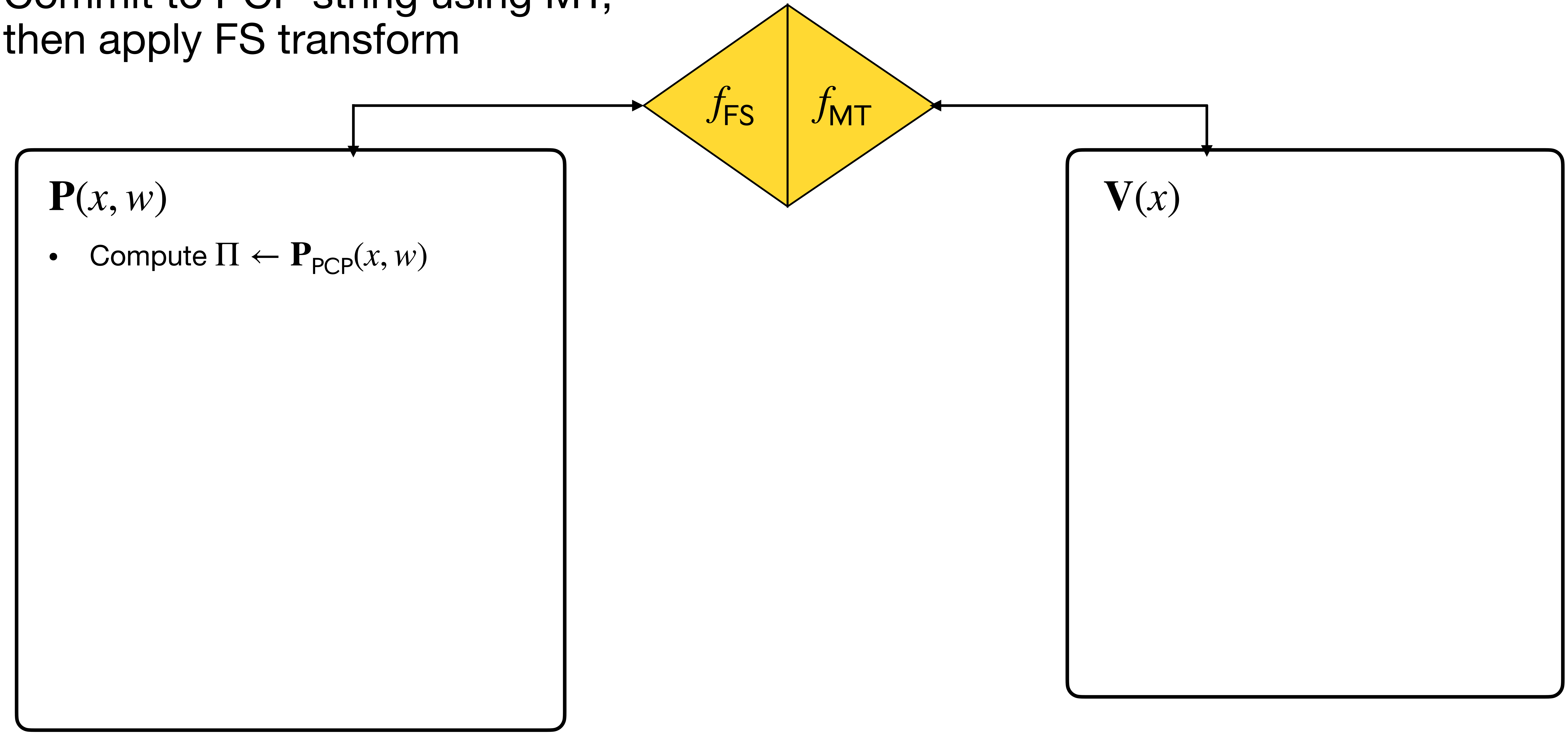

f_{FS} f_{MT}

$\mathbf{P}(x, w)$

- Compute $\Pi \leftarrow \mathbf{P}_{\text{PCP}}(x, w)$

$\mathbf{V}(x)$

Micali’s construction III

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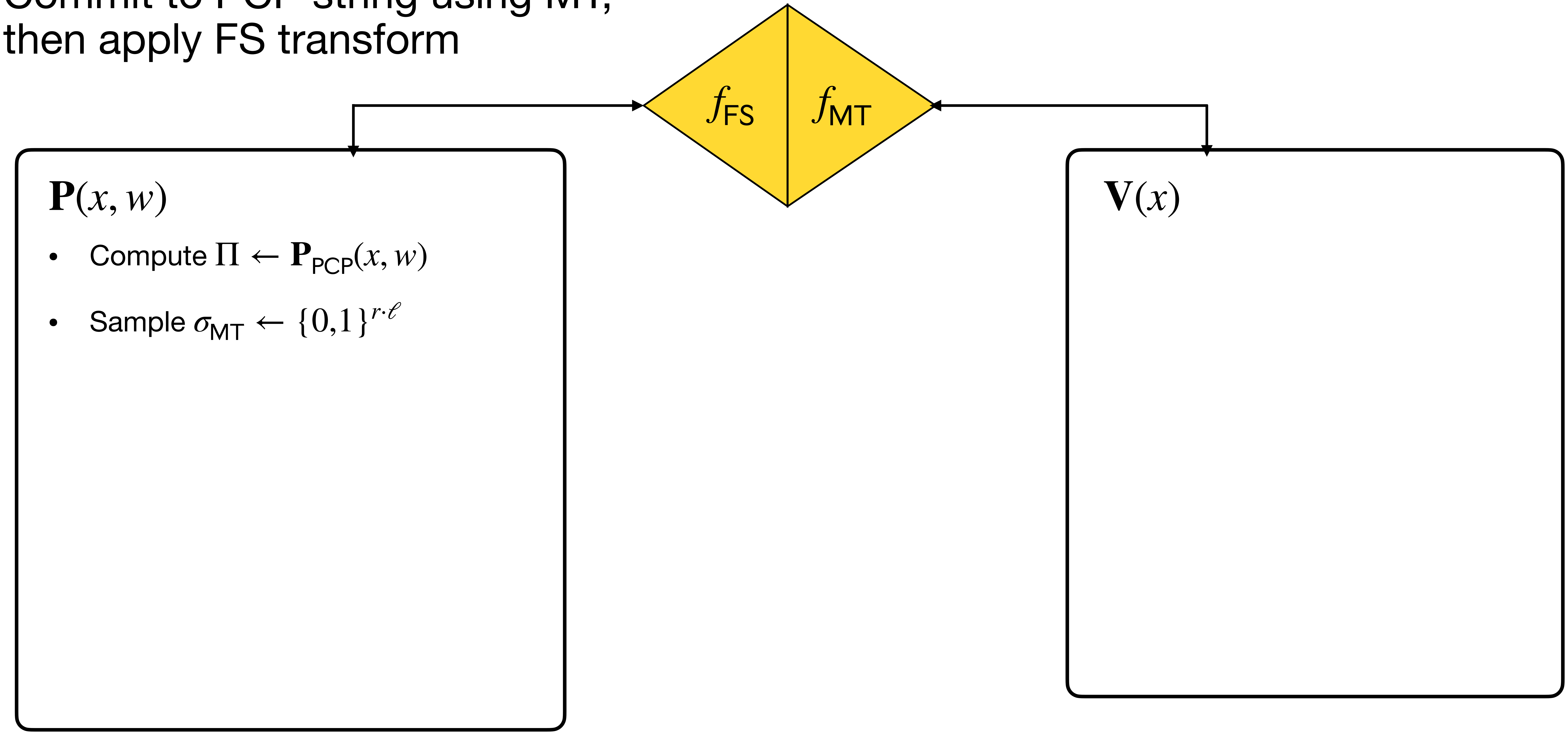

$\mathbf{P}(x, w)$

- Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$
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$\mathbf{V}(x)$

Micali’s construction III

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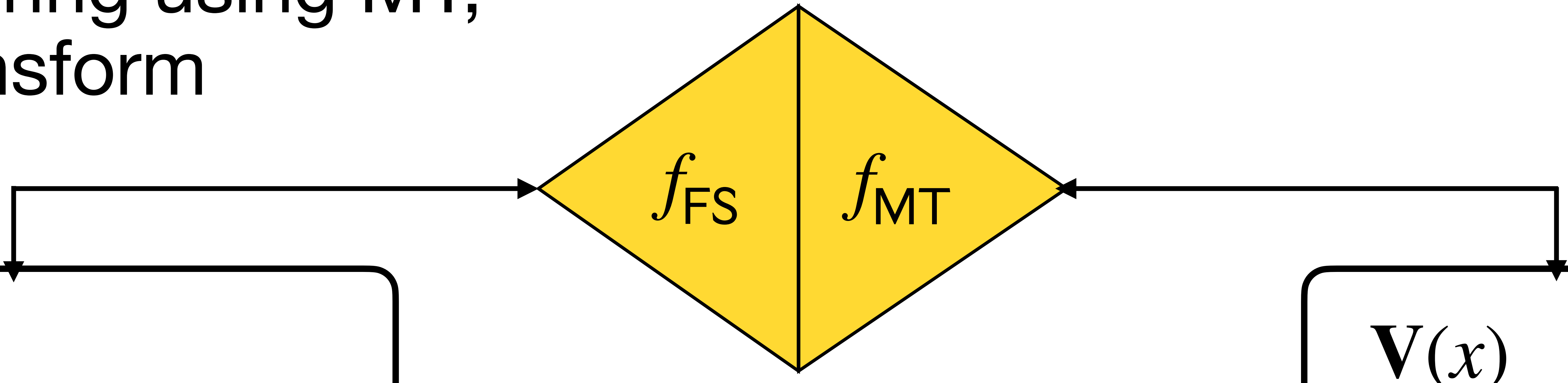

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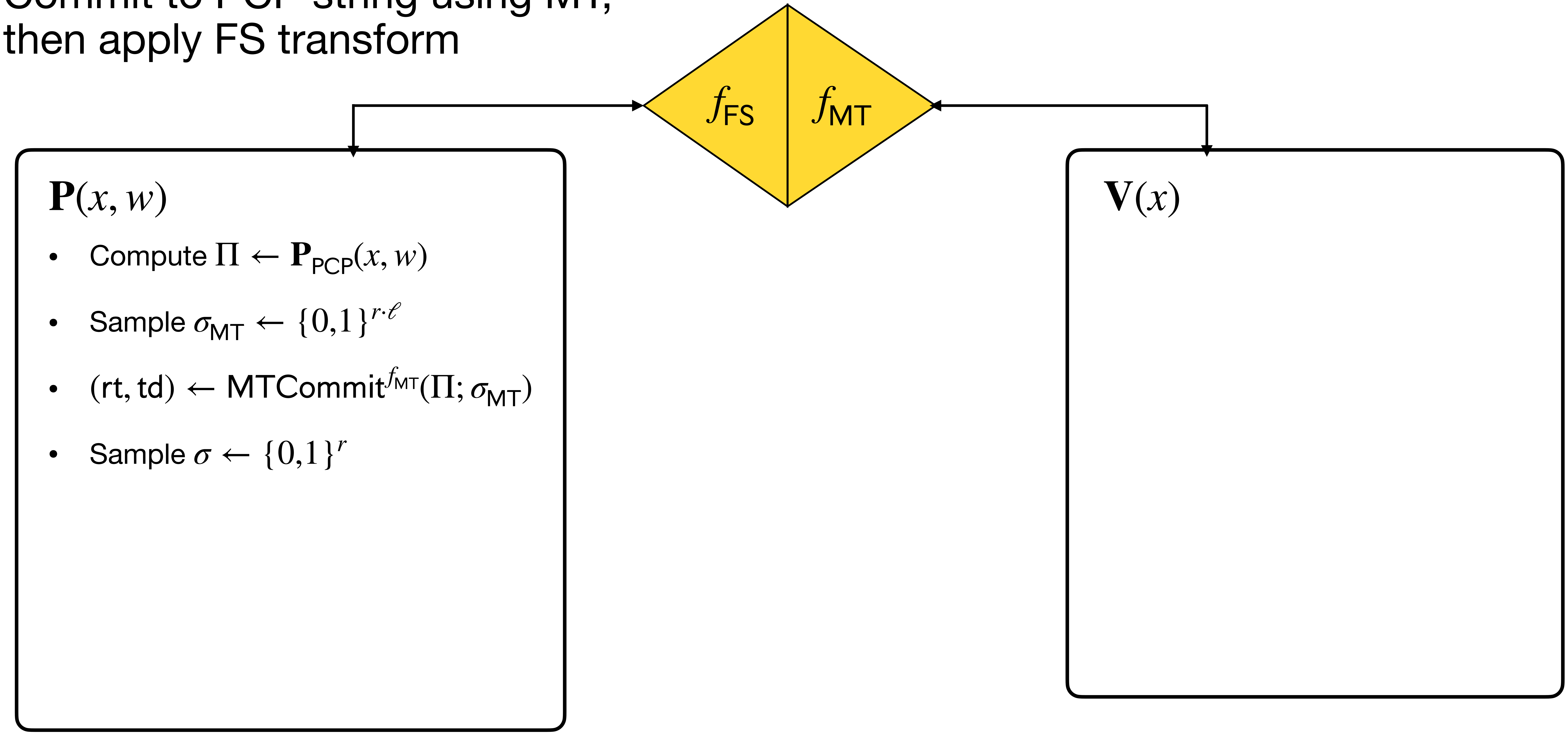
- Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$
- Sample $\sigma_{\mathsf{MT}} \leftarrow \{0,1\}^{r \cdot \ell}$
- $(\mathsf{rt}, \mathsf{td}) \leftarrow \mathsf{MTCommit}^{f_{\mathsf{MT}}}(\Pi; \sigma_{\mathsf{MT}})$

$\mathbf{V}(x)$

Micali’s construction III

Commit to PCP string using MT, then apply FS transform



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$\mathbf{V}(x)$

Micali’s construction III

Commit to PCP string using MT,
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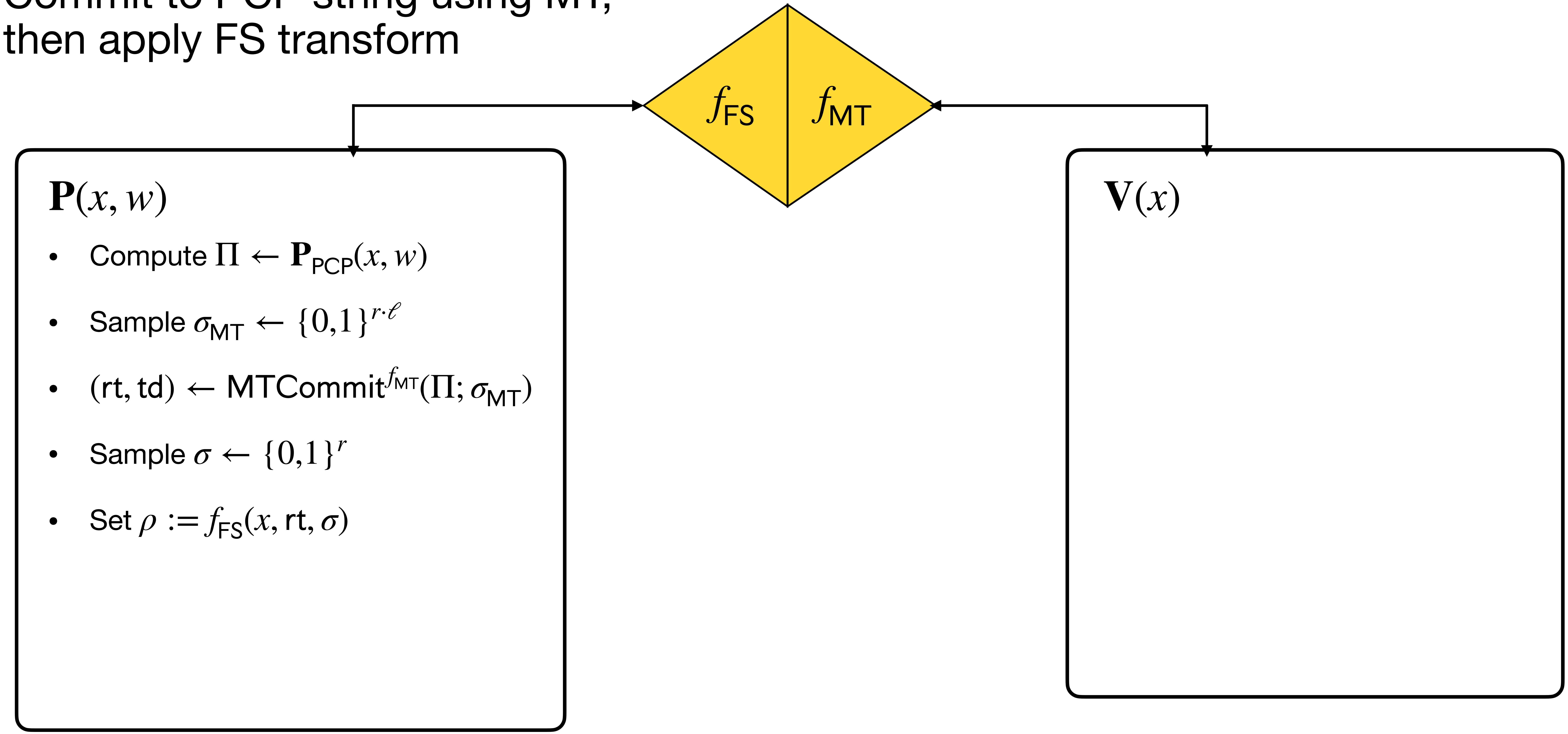


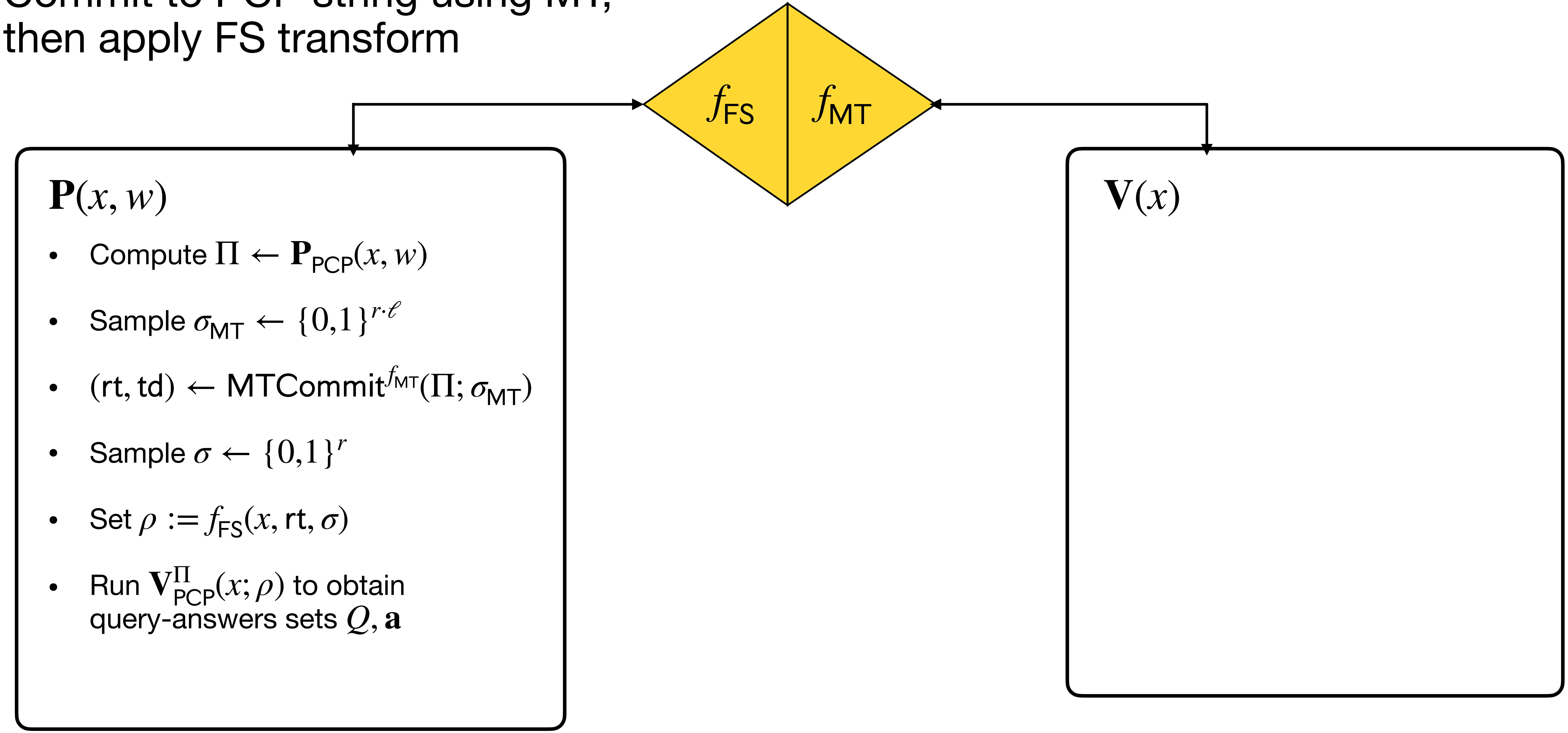
$\mathbf{P}(x, w)$

- Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$
- Sample $\sigma_{\mathsf{MT}} \leftarrow \{0,1\}^{r \cdot \ell}$
- $(\mathsf{rt}, \mathsf{td}) \leftarrow \mathsf{MTCommit}^{f_{\mathsf{MT}}}(\Pi; \sigma_{\mathsf{MT}})$
- Sample $\sigma \leftarrow \{0,1\}^{r}$
- Set $\rho := f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma)$

$\mathbf{V}(x)$

Micali's construction III

Commit to PCP string using MT,
then apply FS transform



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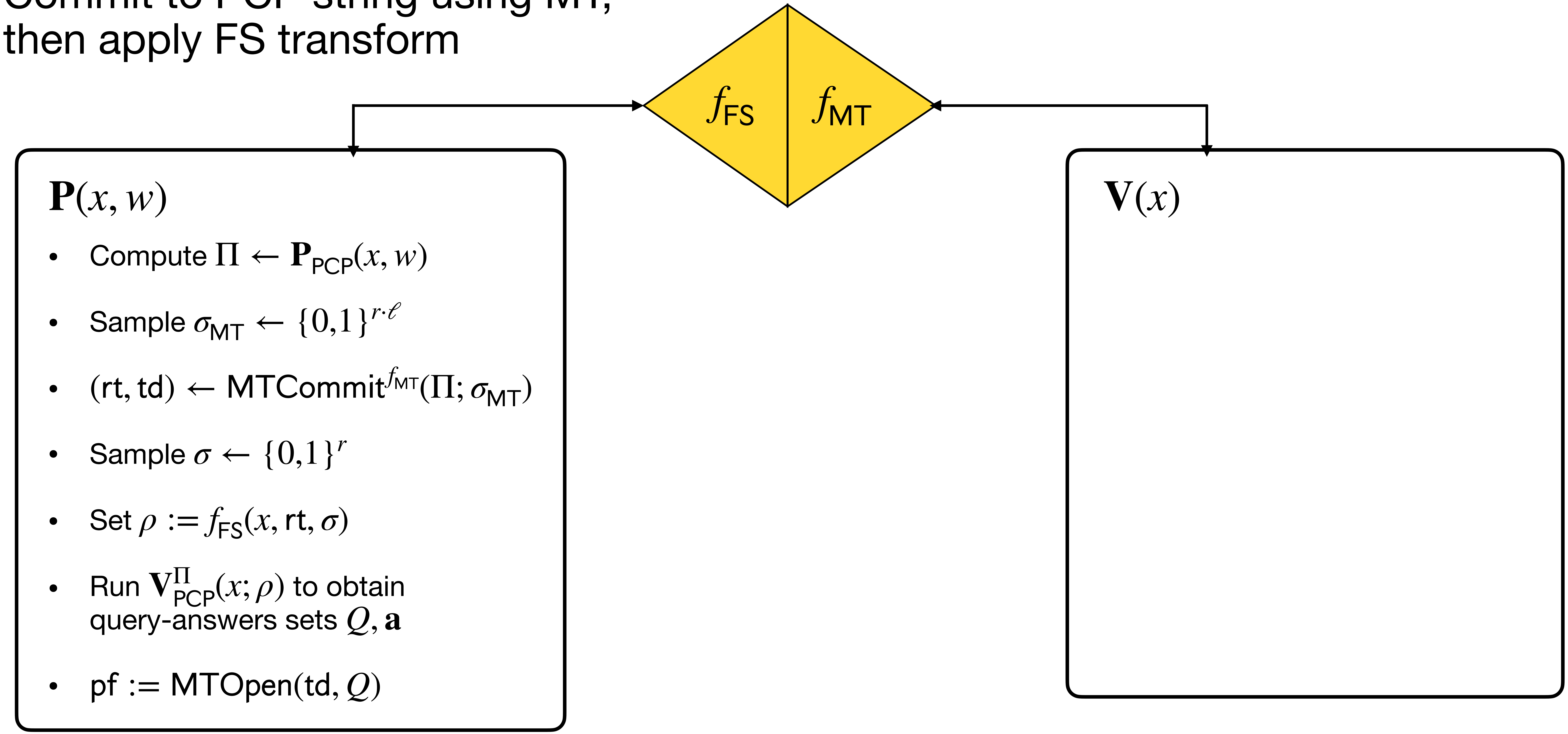
- Sample $\sigma_{\mathsf{MT}} \leftarrow \{0,1\}^{r \cdot \ell}$
- $(\mathsf{rt}, \mathsf{td}) \leftarrow \mathsf{MTCommit}^{f_{\mathsf{MT}}}(\Pi; \sigma_{\mathsf{MT}})$
- Sample $\sigma \leftarrow \{0,1\}^r$
- Set $\rho := f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma)$
- Run $\mathbf{V}_{\mathsf{PCP}}^{\Pi}(x; \rho)$ to obtain query-answers sets $Q, \mathbf{a}$

$\mathbf{V}(x)$

Micali’s construction III

Commit to PCP string using MT,
then apply FS transform



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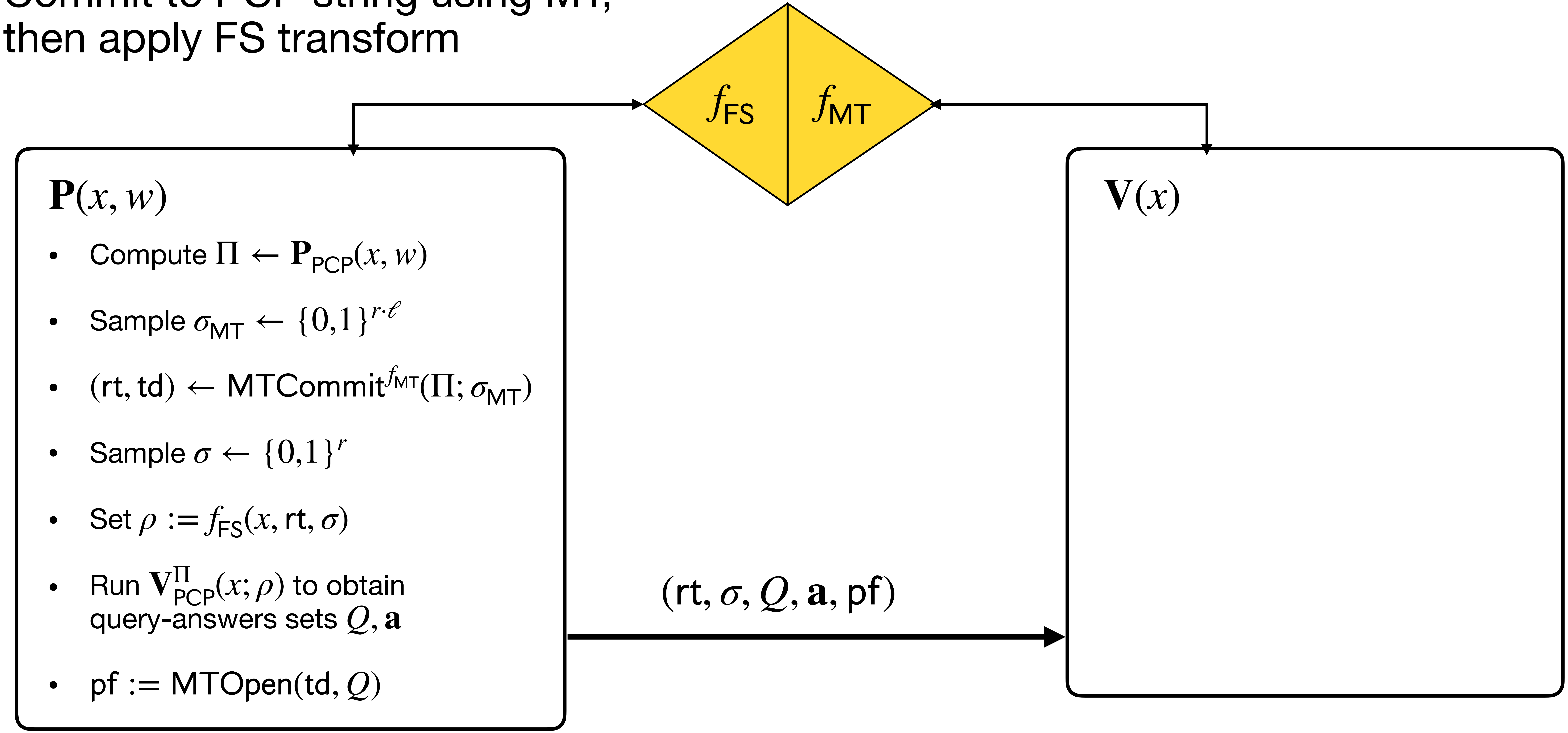
- Sample $\sigma \leftarrow \{0,1\}^{r}$
- Set $\rho := f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma)$
- Run $\mathbf{V}^{\Pi}_{\mathsf{PCP}}(x; \rho)$ to obtain query-answers sets $Q, \mathbf{a}$
- $\mathsf{pf} := \mathsf{MTOpen}(\mathsf{td}, Q)$

$\mathbf{V}(x)$

Micali's construction III

Commit to PCP string using MT,
then apply FS transform



f_{FS} f_{MT}

$\mathbf{P}(x, w)$

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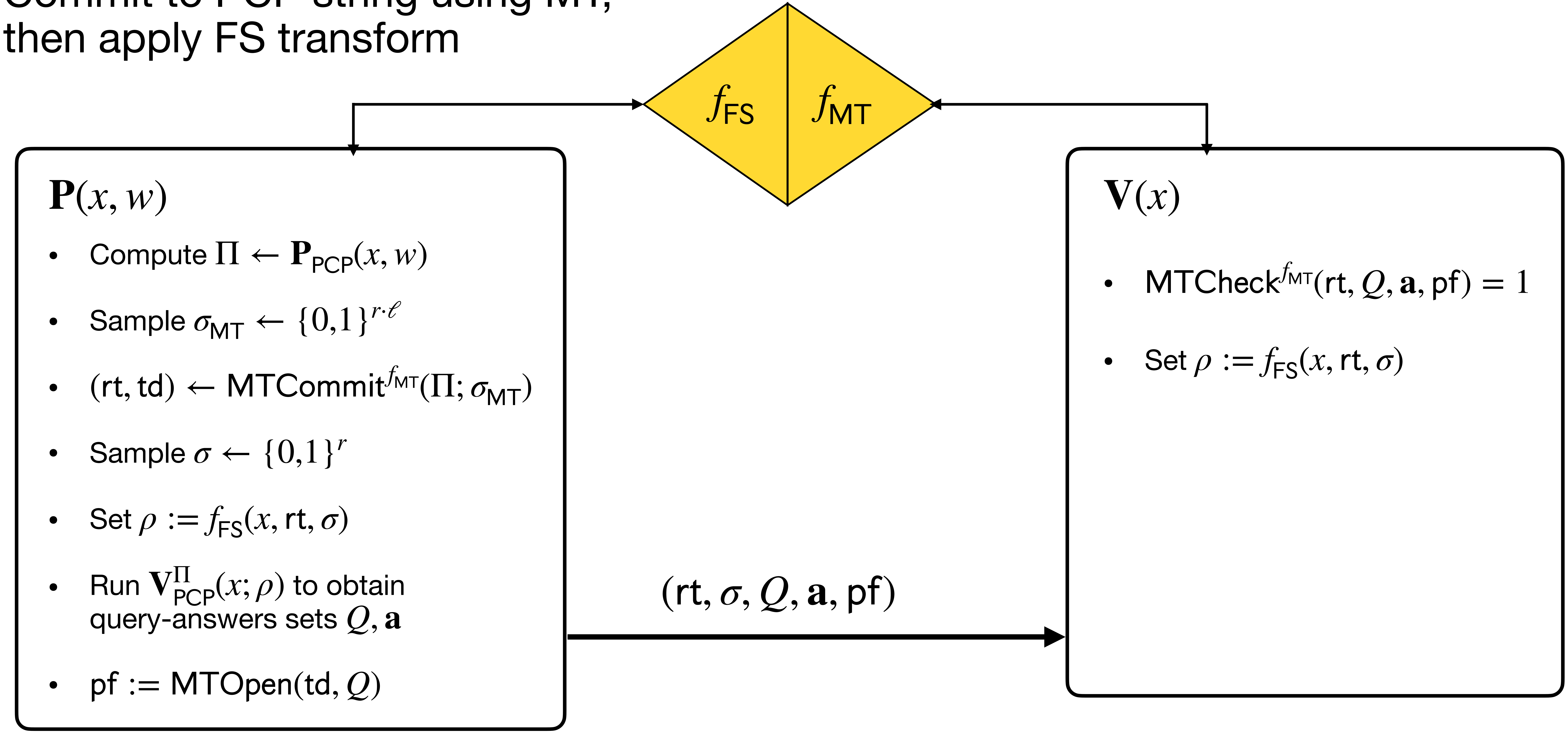
$(\mathsf{rt}, \sigma, Q, \mathbf{a}, \mathsf{pf})$

$\mathbf{V}(x)$

Micali’s construction III

Commit to PCP string using MT,
then apply FS transform



$\mathbf{P}(x, w)$

- Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$
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- Run $\mathbf{V}^{\Pi}_{\mathsf{PCP}}(x; \rho)$ to obtain query-answers sets $Q, \mathbf{a}$
- $\mathsf{pf} := \mathsf{MTOpen}(\mathsf{td}, Q)$

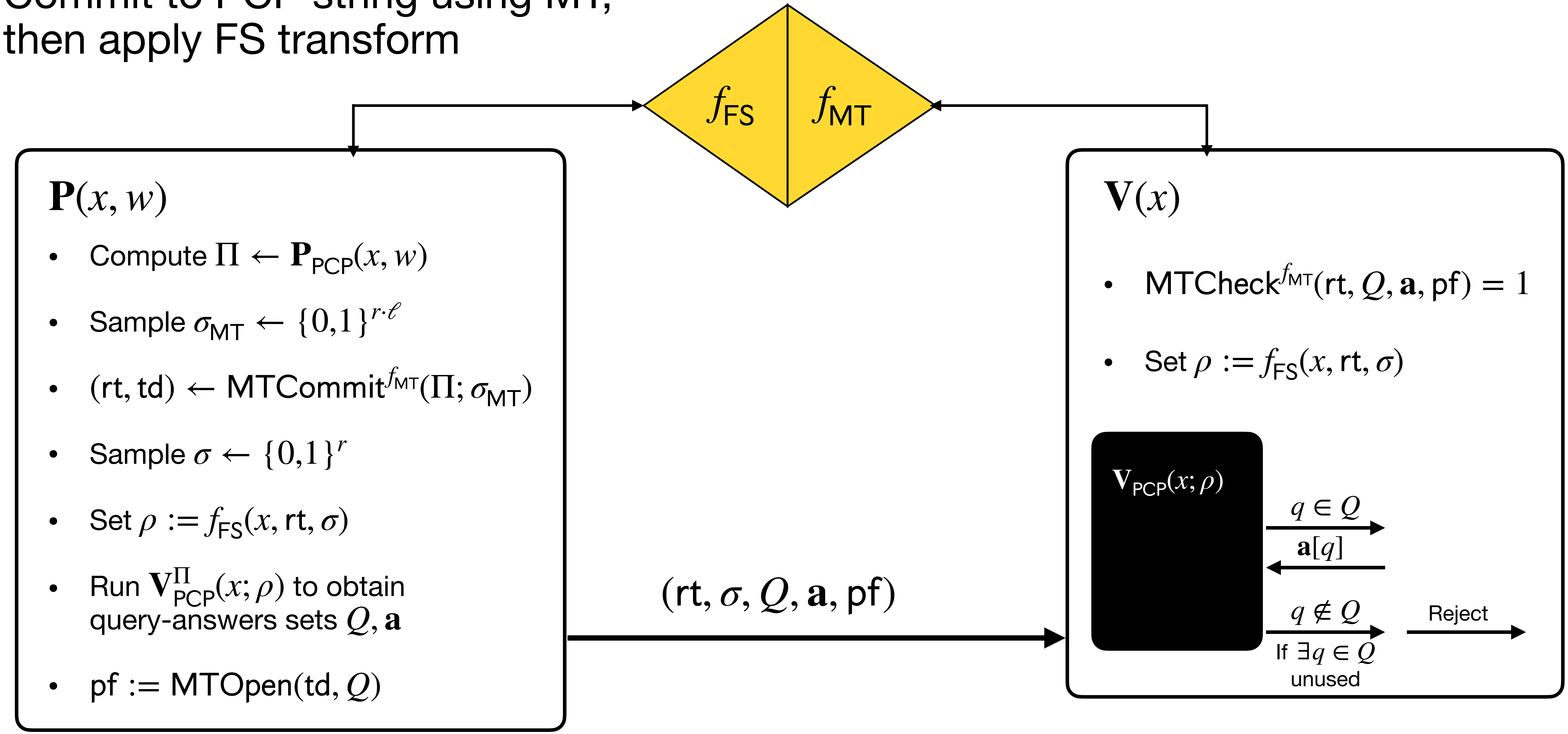
$(\mathsf{rt}, \sigma, Q, \mathbf{a}, \mathsf{pf})$

$\mathbf{V}(x)$

- $\mathsf{MTCheck}^{f_{\mathsf{MT}}}(\mathsf{rt}, Q, \mathbf{a}, \mathsf{pf}) = 1$
- Set $\rho := f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma)$

Micali's construction III

Commit to PCP string using MT,
then apply FS transform



$\mathbf{P}(x, w)$

- Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$
- Sample $\sigma_{\mathsf{MT}} \leftarrow \{0,1\}^{r \cdot \ell}$
- $(\mathsf{rt}, \mathsf{td}) \leftarrow \mathsf{MTCommit}^{f_{\mathsf{MT}}}(\Pi; \sigma_{\mathsf{MT}})$
- Sample $\sigma \leftarrow \{0,1\}^{r}$
- Set $\rho := f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma)$
- Run $\mathbf{V}^{\Pi}_{\mathsf{PCP}}(x; \rho)$ to obtain query-answers sets $Q, \mathbf{a}$
- $\mathsf{pf} := \mathsf{MTOpen}(\mathsf{td}, Q)$

$(\mathsf{rt}, \sigma, Q, \mathbf{a}, \mathsf{pf})$

$\mathbf{V}(x)$

- $\mathsf{MTCheck}^{f_{\mathsf{MT}}}(\mathsf{rt}, Q, \mathbf{a}, \mathsf{pf}) = 1$
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$\mathbf{V}_{\mathsf{PCP}}(x; \rho)$
$q \in Q$
$\mathbf{a}[q]$
$q \notin Q$
Reject
If $\exists q \in Q$ unused

UC Security I

[Canetti 2001]

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- Motivation: Modular security analysis of protocols

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Composition Theorem

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π : protocol

φ : ideal functionality

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$$\pi \approx_{\text{UC}} \varphi$$

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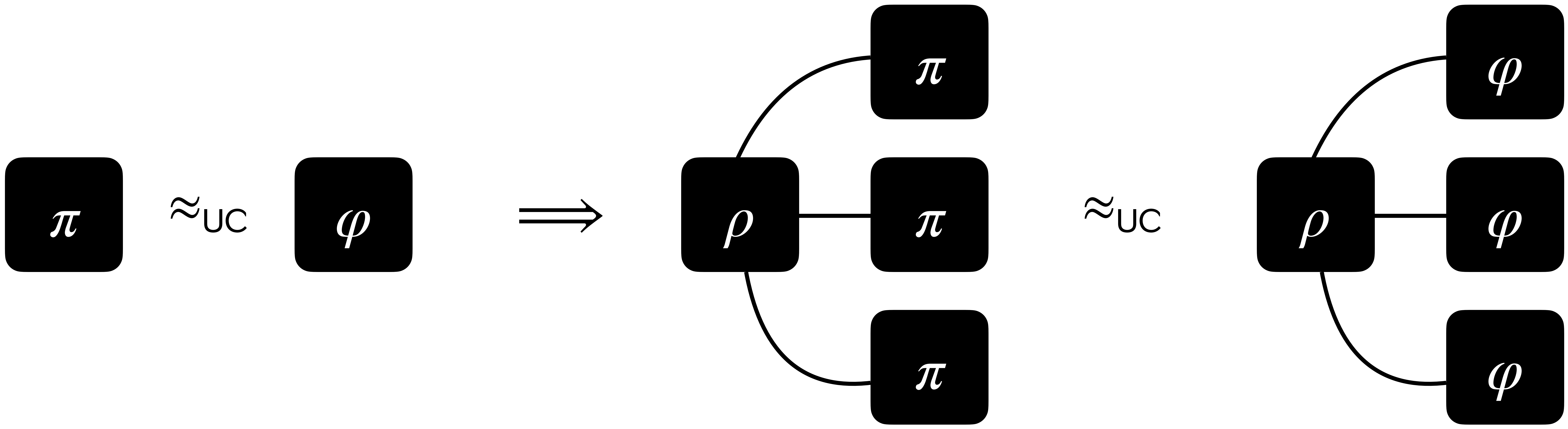

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Real

$\approx$

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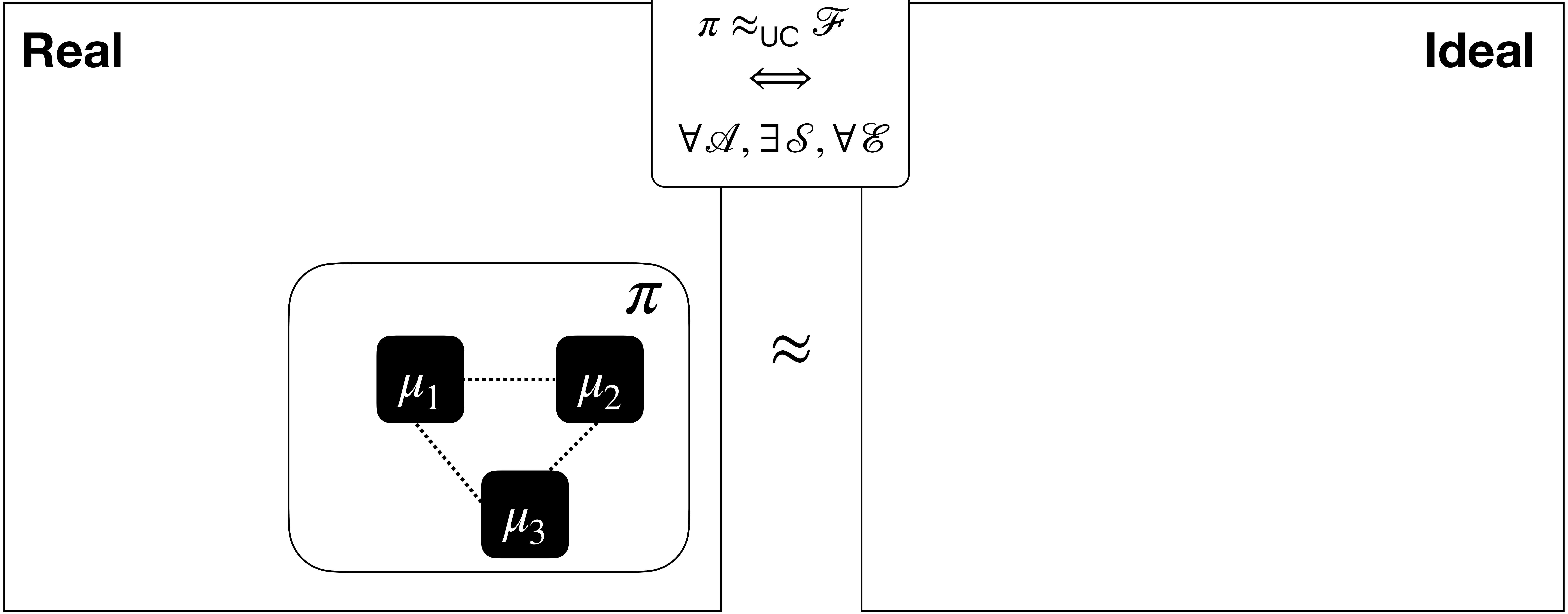

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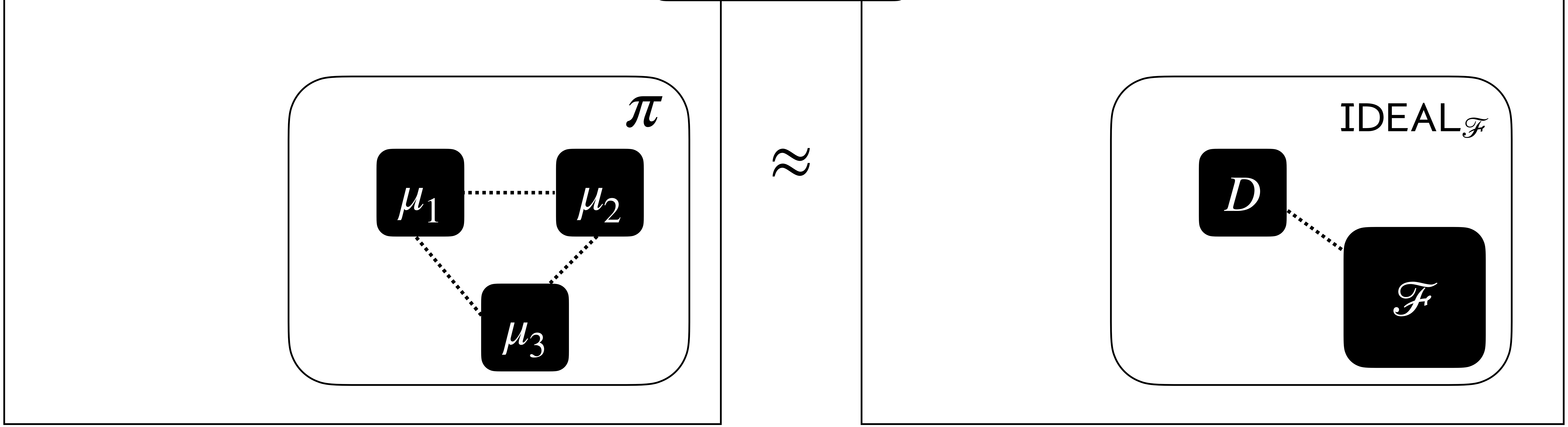

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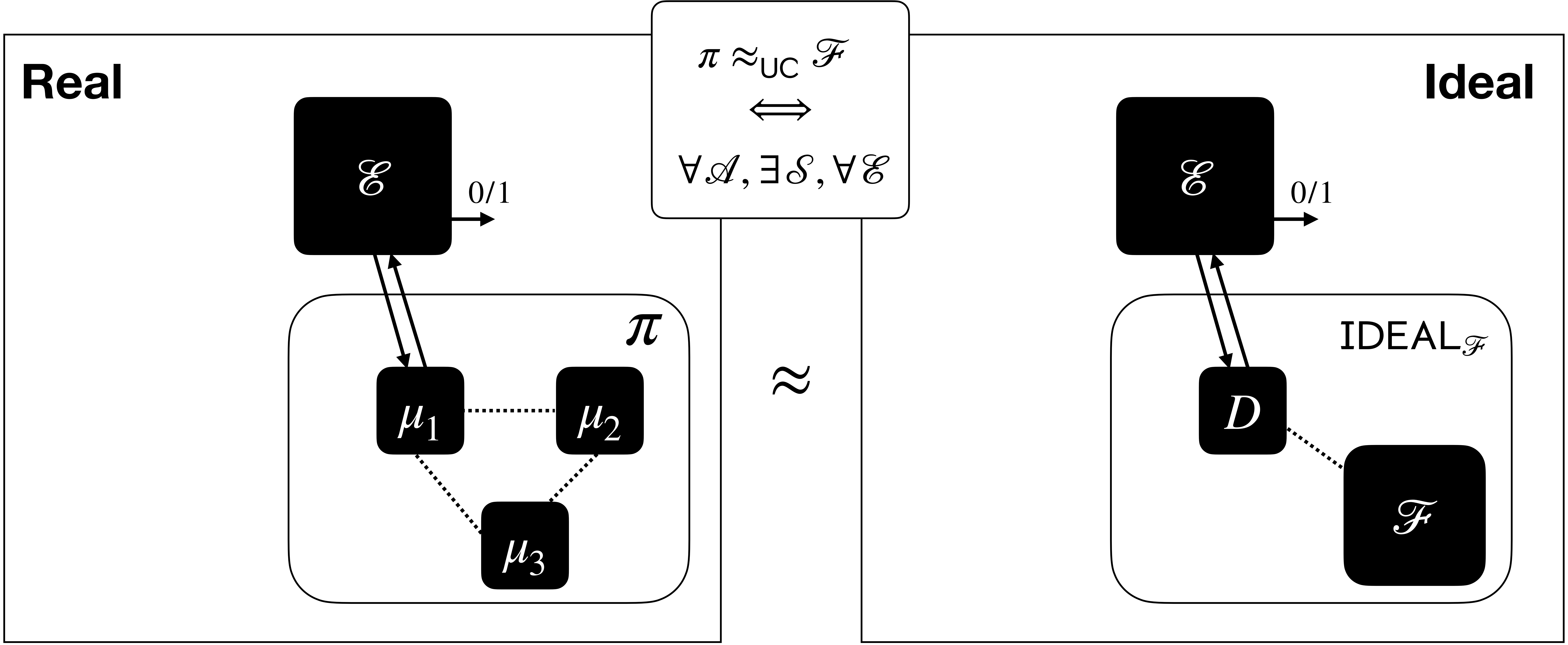

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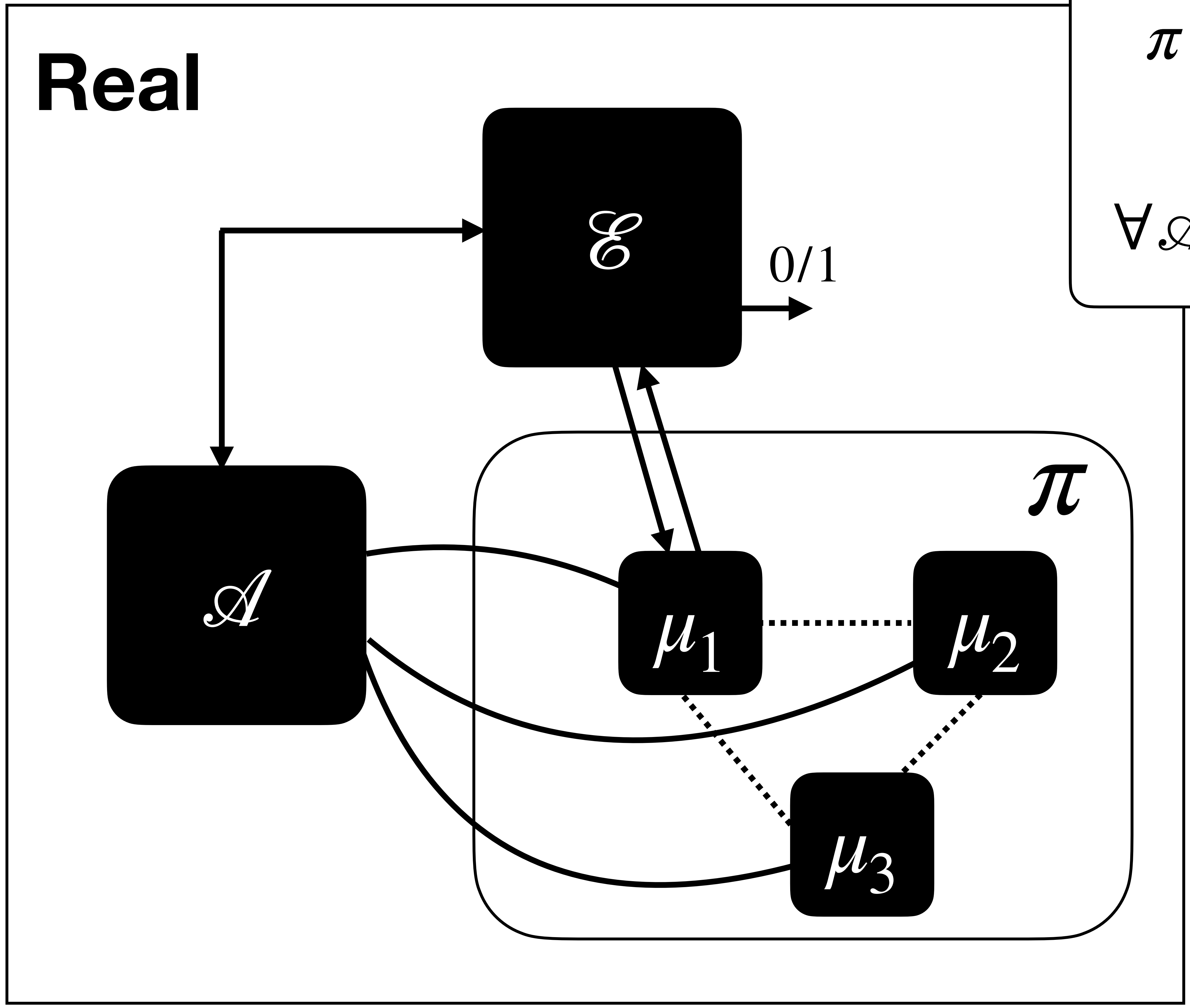

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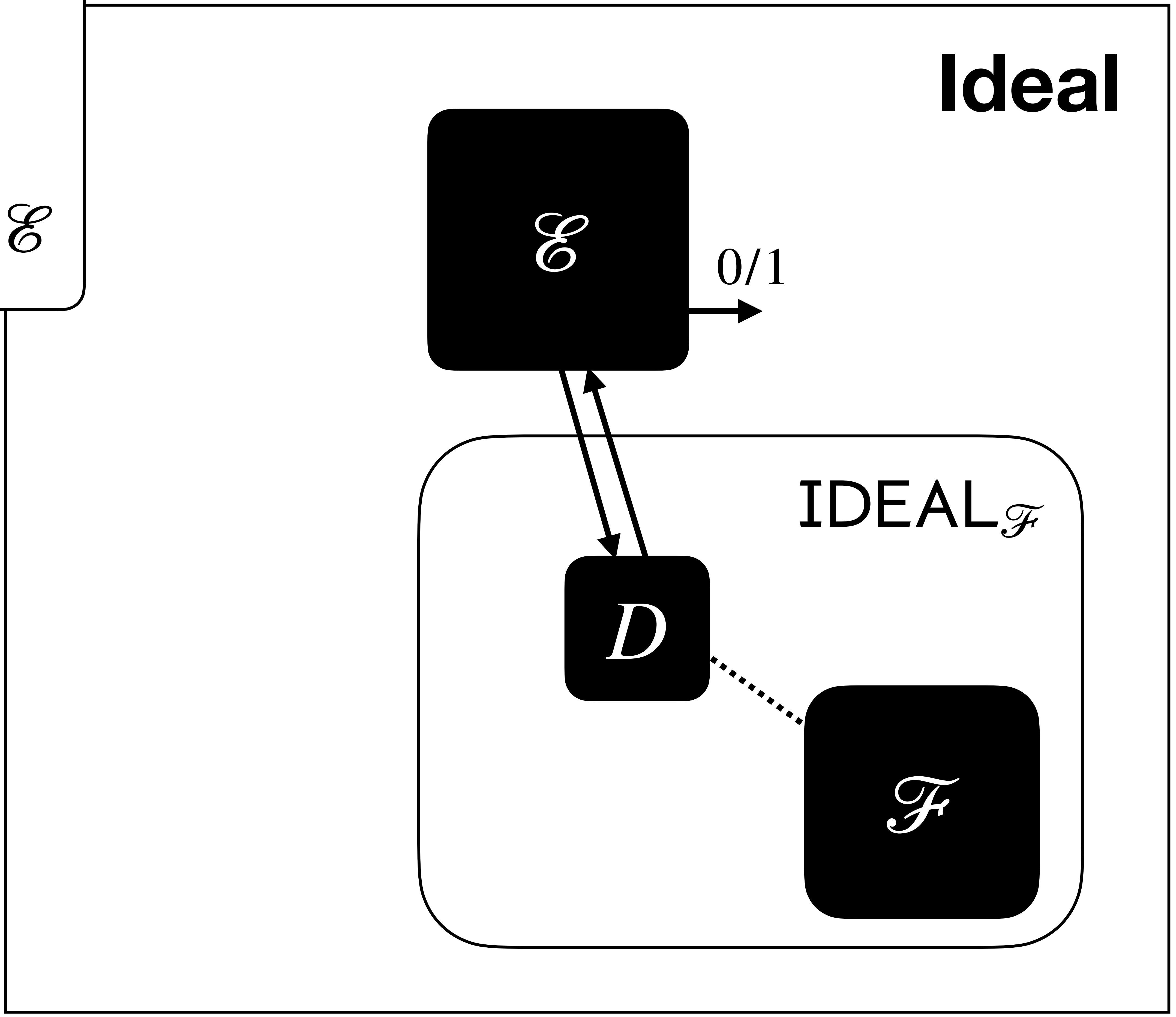

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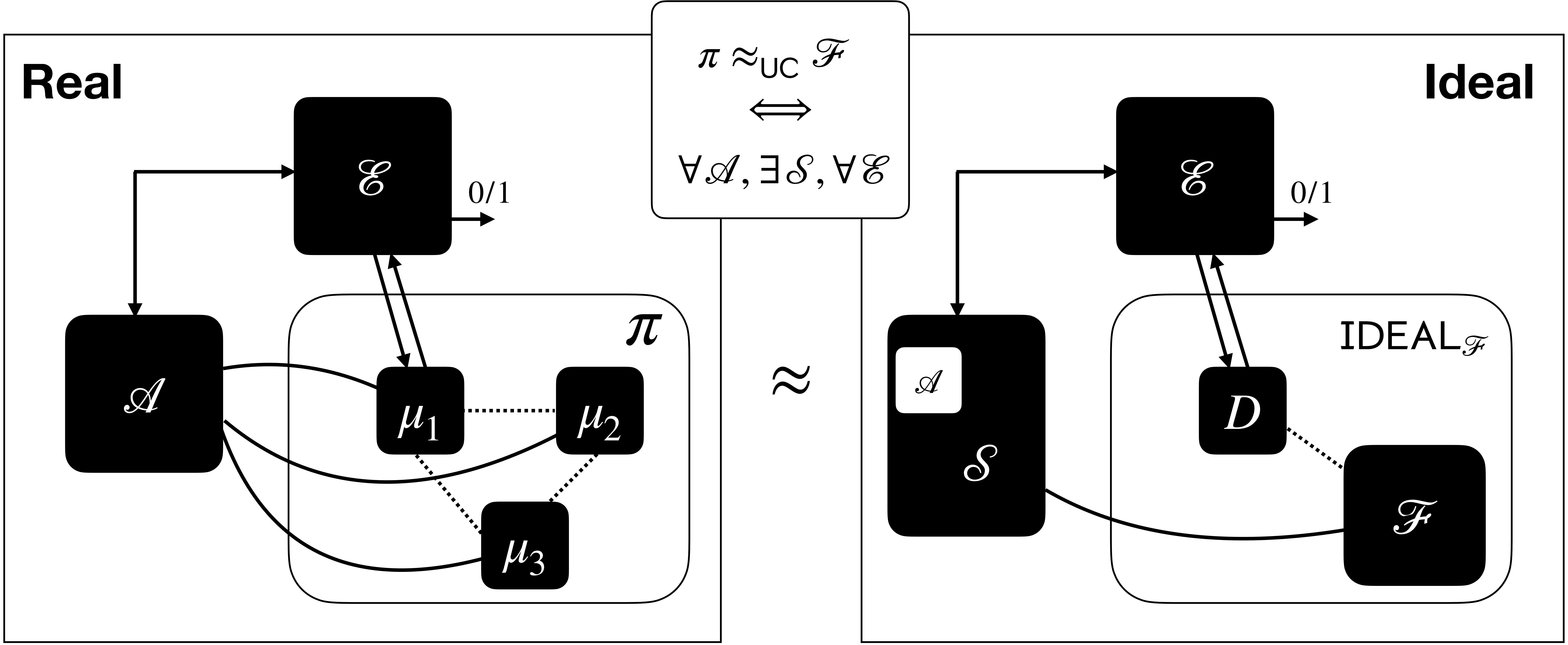

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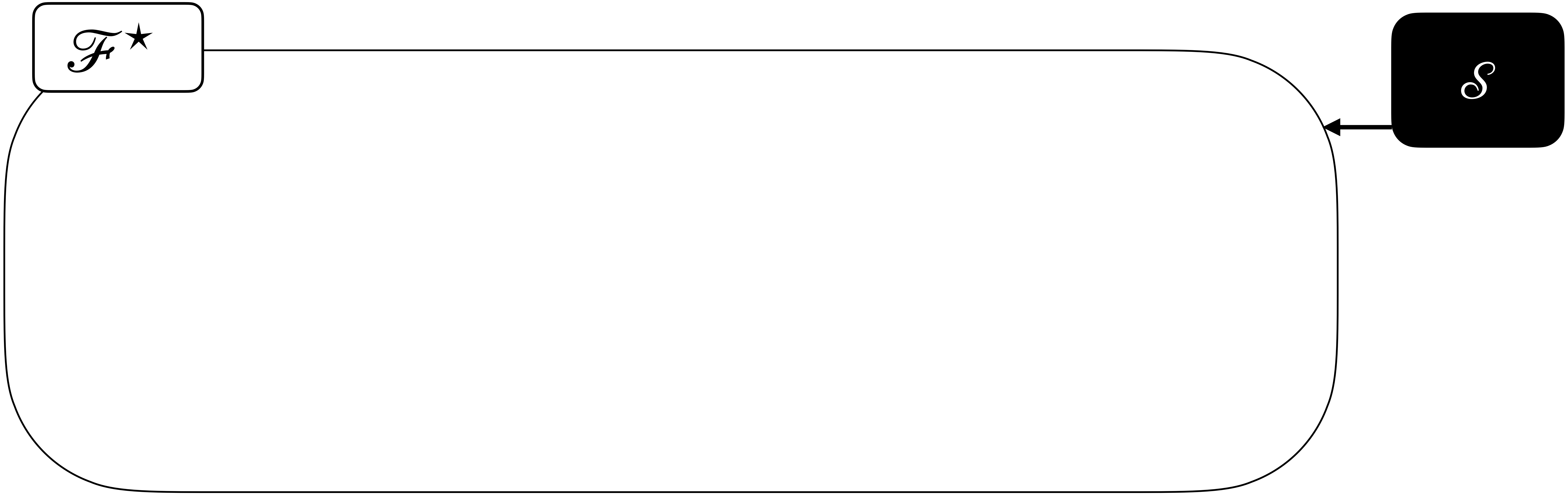

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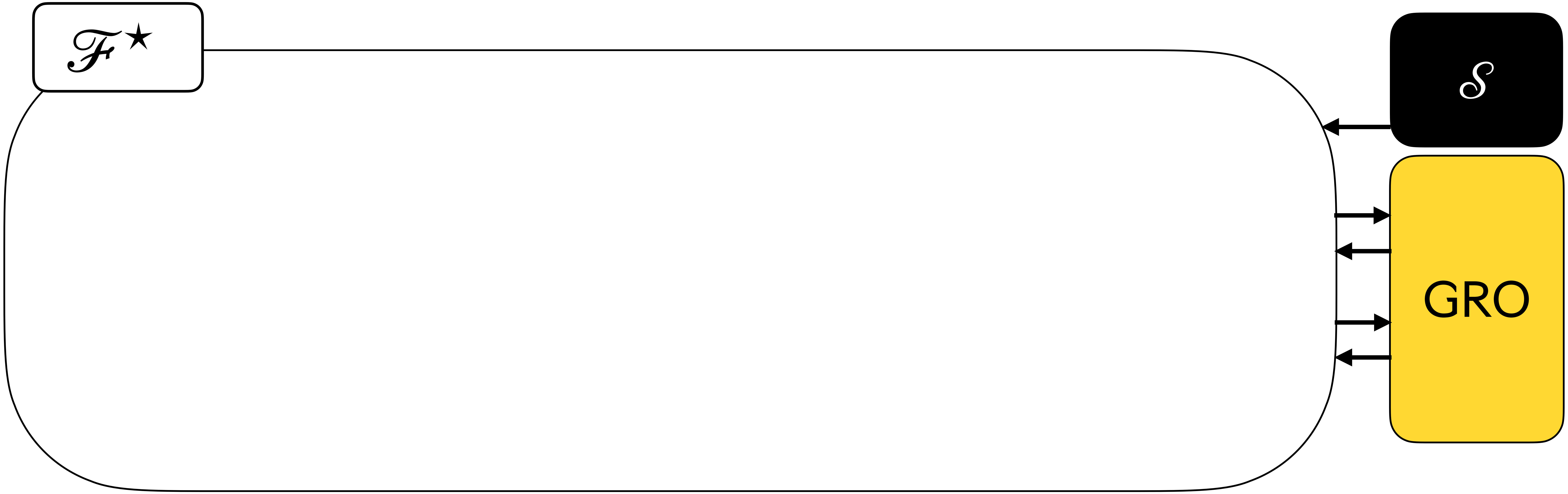

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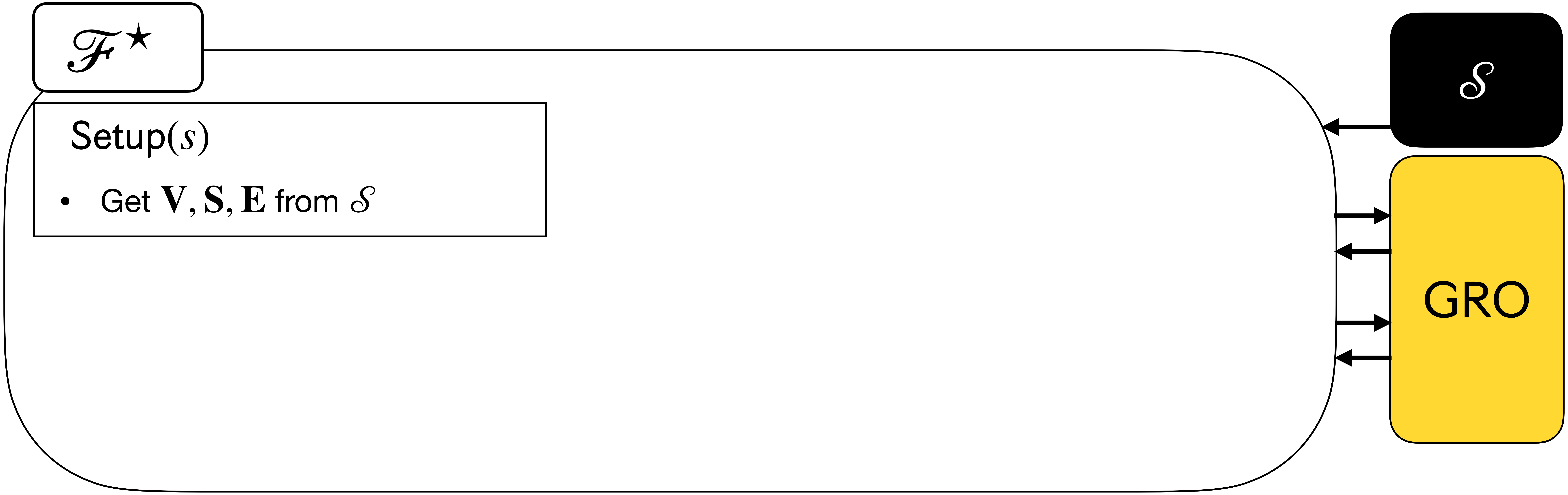

$\mathscr{F}^\star$

$\mathsf{Setup}(s)$

- Get $\mathbf{V}, \mathbf{S}, \mathbf{E}$ from $\mathscr{S}$

$\mathscr{S}$

GRO

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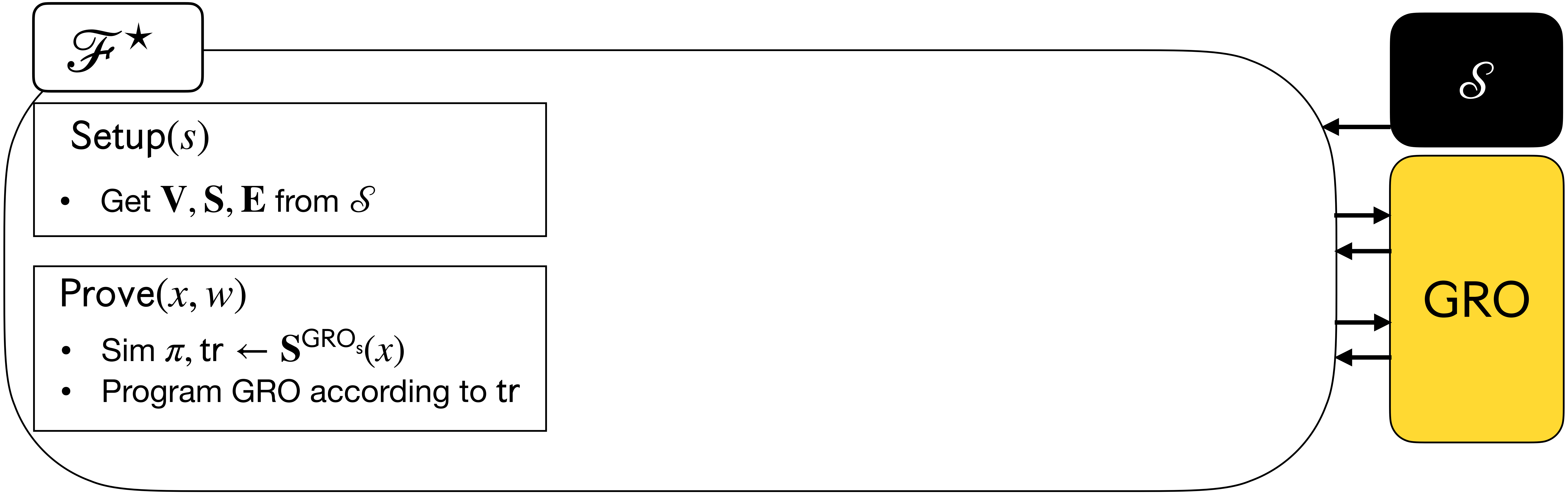

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- Sim π, tr $\leftarrow \mathbf{S}^{\mathsf{GRO}_s}(x)$
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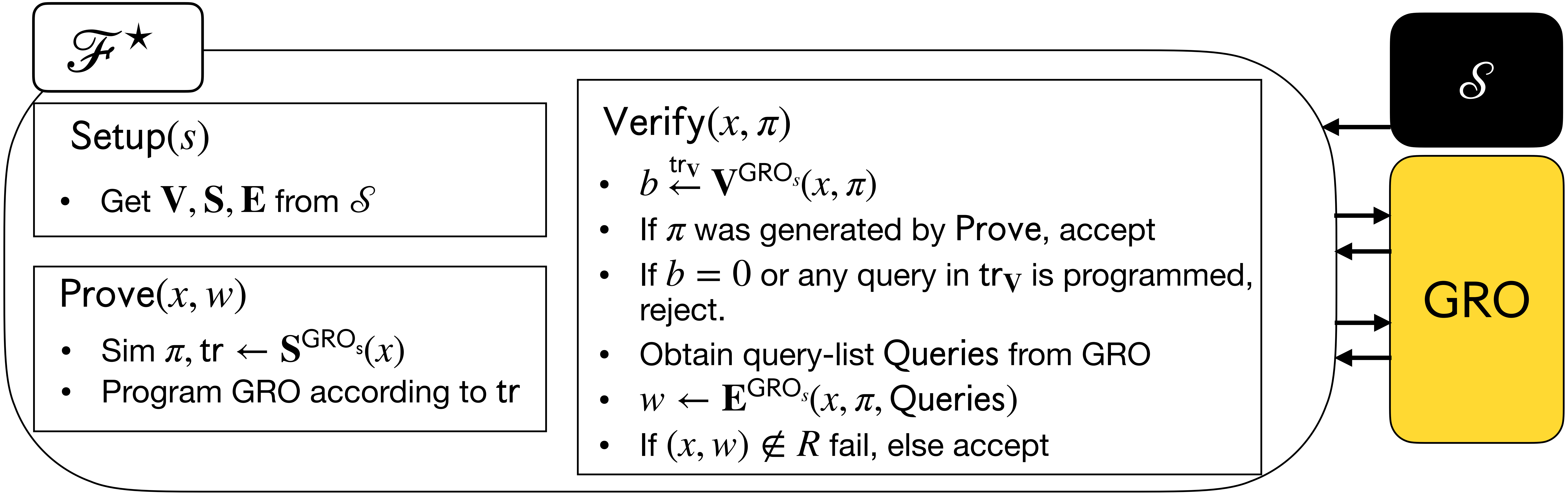

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Verify(x, π)

- $b \overset{\mathsf{tr}_\mathbf{V}}{\leftarrow} \mathbf{V}^{\mathsf{GRO}_s}(x, \pi)$
- If π was generated by Prove, accept
- If $b = 0$ or any query in tr$_\mathbf{V}$ is programmed, reject.
- Obtain query-list Queries from GRO
- $w \leftarrow \mathbf{E}^{\mathsf{GRO}_s}(x, \pi, \text{Queries})$
- If $(x, w) \notin R$ fail, else accept

Wrapper protocol

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Converts an argument $\mathsf{ARG} = (\mathbf{P}, \mathbf{V})$ in the ROM into a protocol in the GROM

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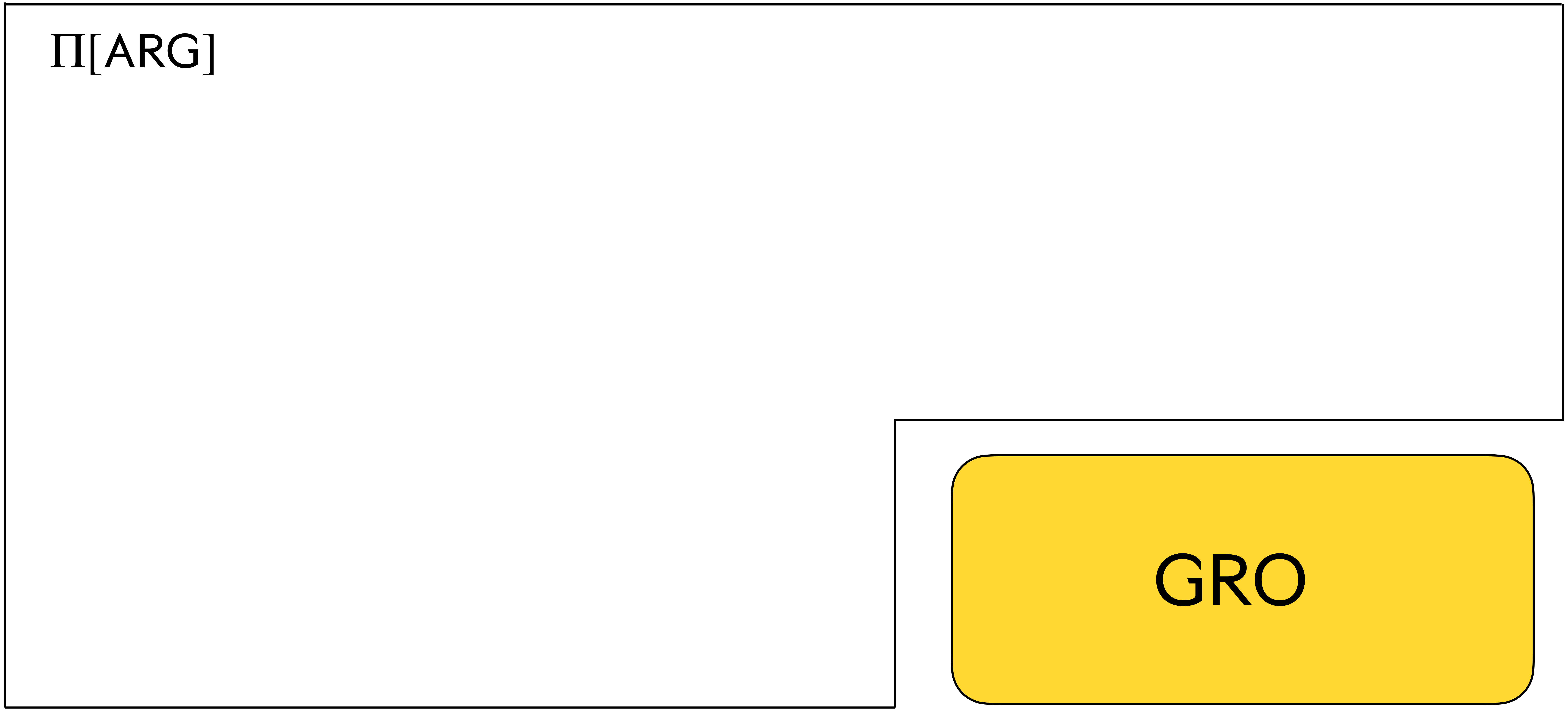

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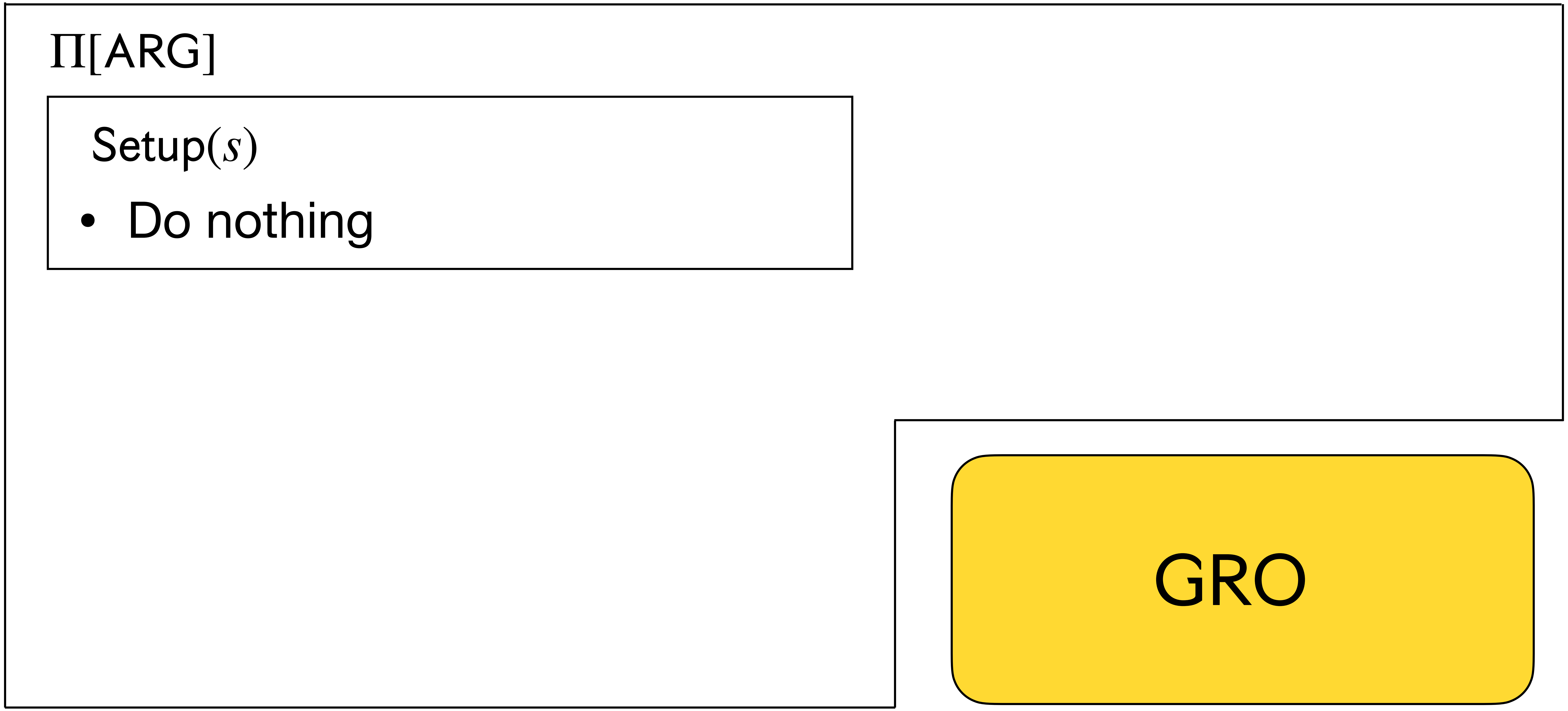

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Setup(s)

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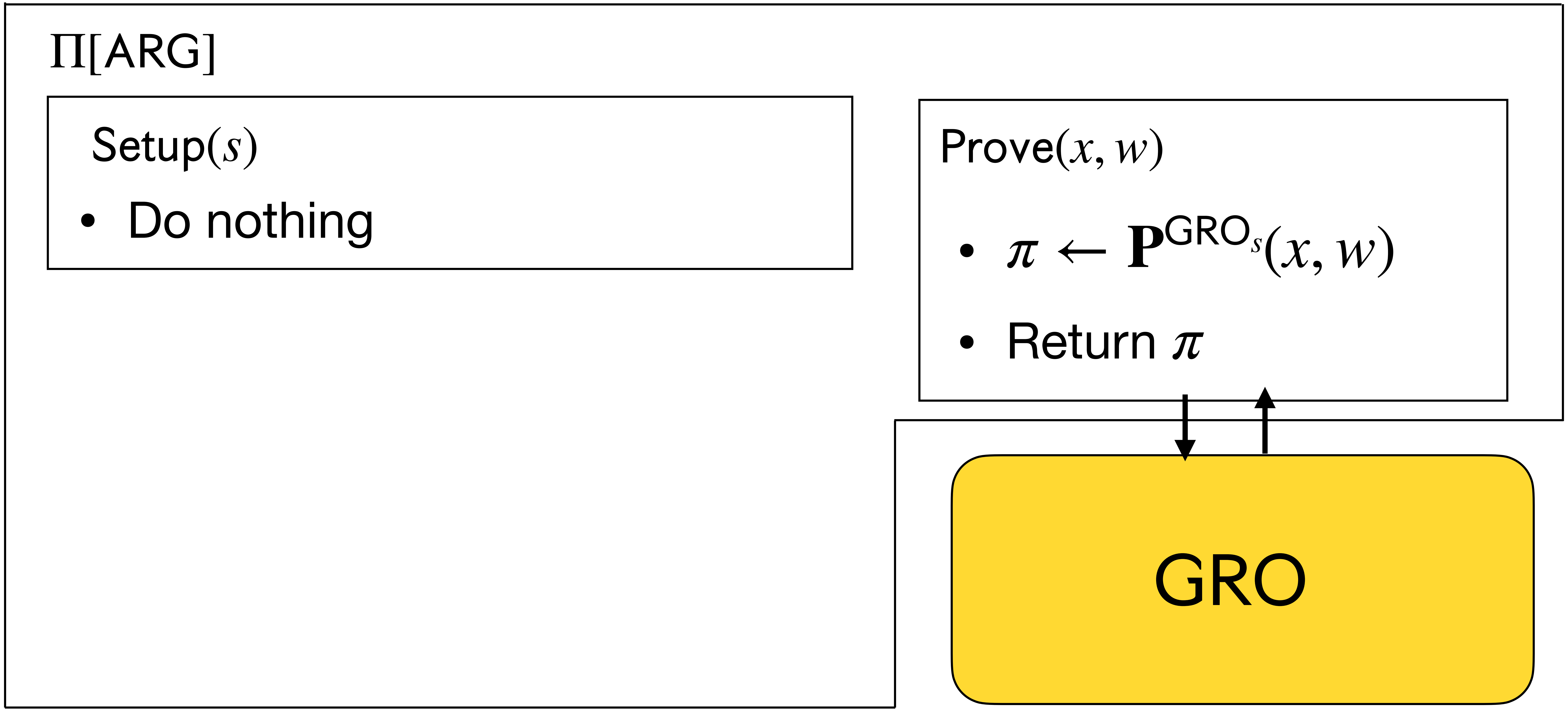

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Setup(s)

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Prove(x, w)

- $\pi \leftarrow \mathbf{P}^{\mathsf{GRO}_s}(x, w)$
- Return π

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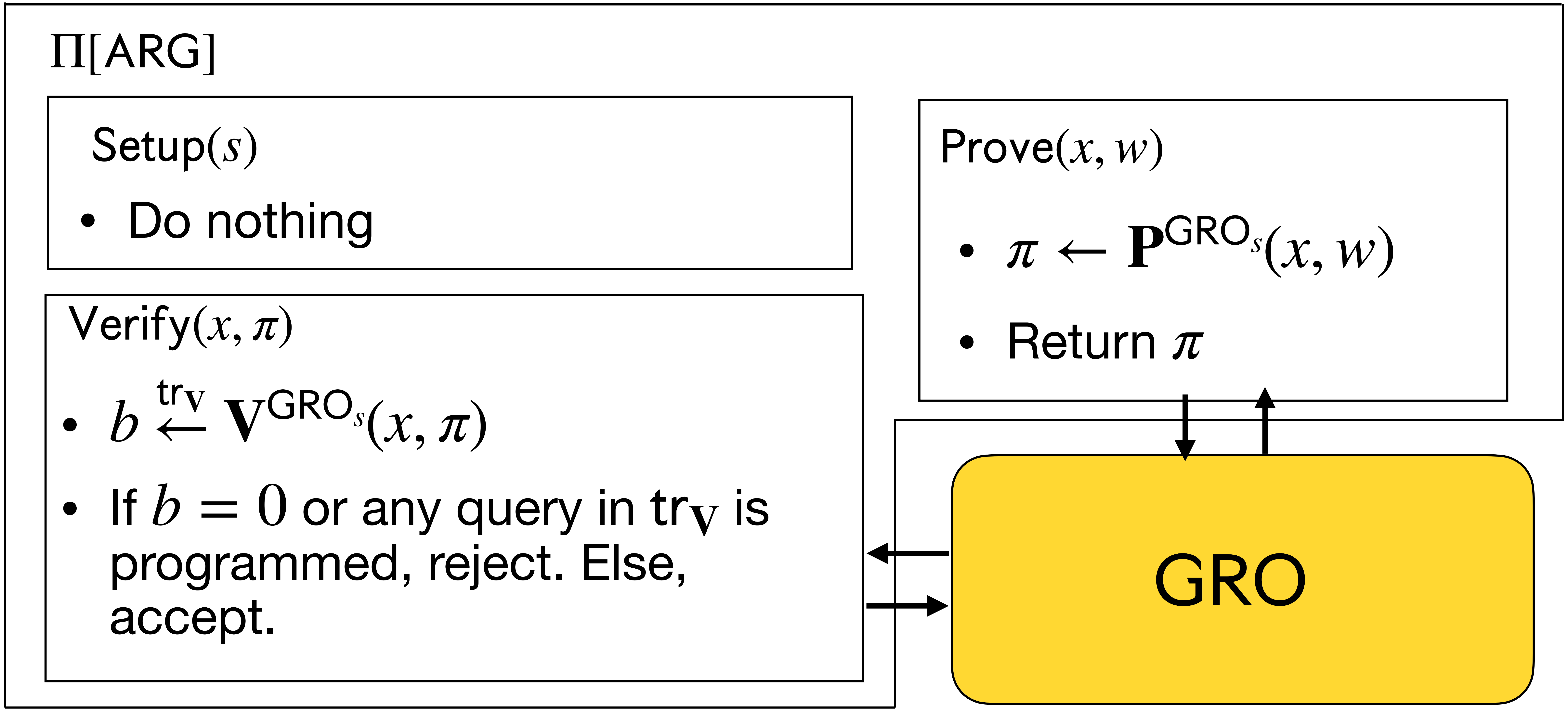

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Related works

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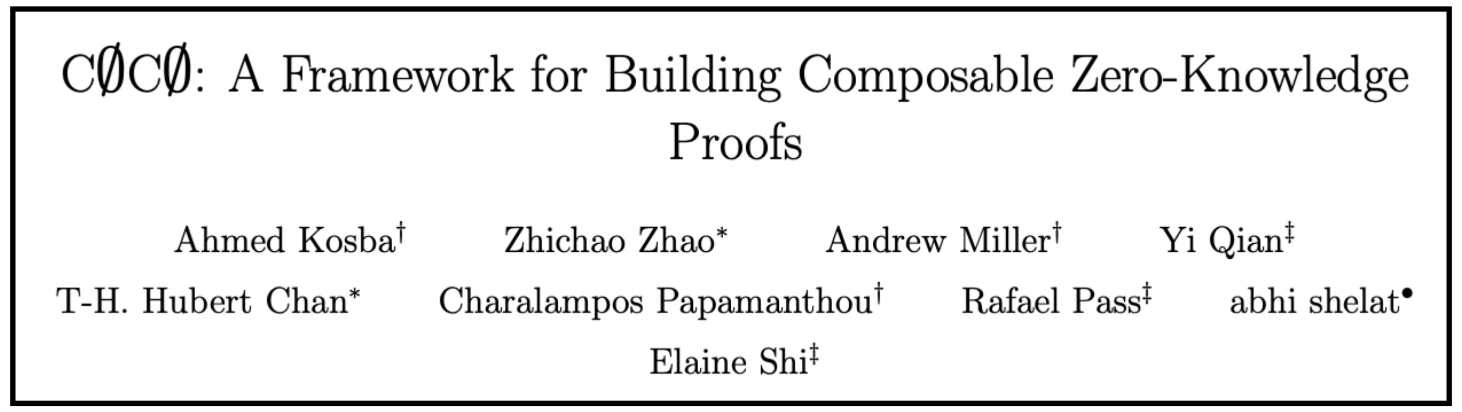

CØCØ: A Framework for Building Composable Zero-Knowledge Proofs

Ahmed Kosba[†] Zhichao Zhao[*] Andrew Miller[†] Yi Qian[‡]
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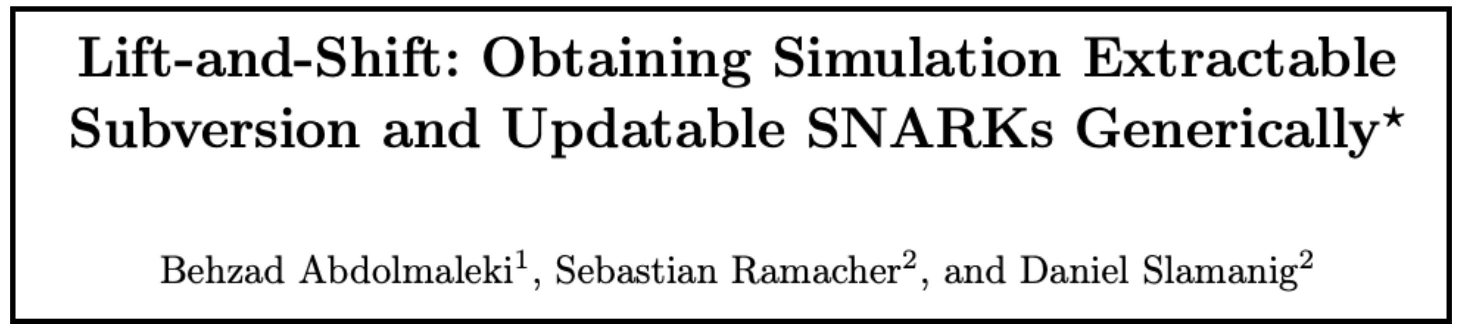

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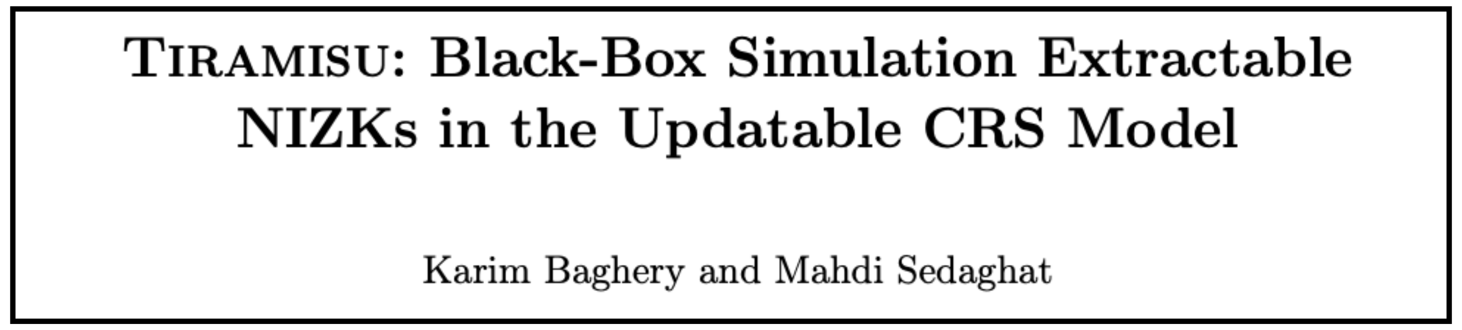
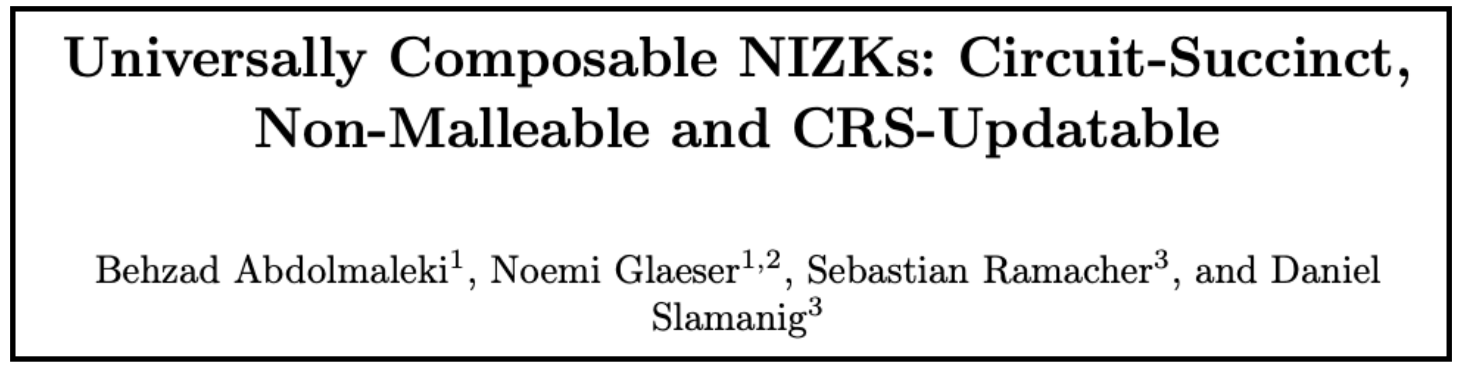


Tiramisu: Black-Box Simulation Extractable NIZKs in the Updatable CRS Model

Karim Baghery and Mahdi Sedaghat



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Behzad Abdolmaleki[1], Noemi Glaeser[1,2], Sebastian Ramacher[3], and Daniel Slamanig[3]

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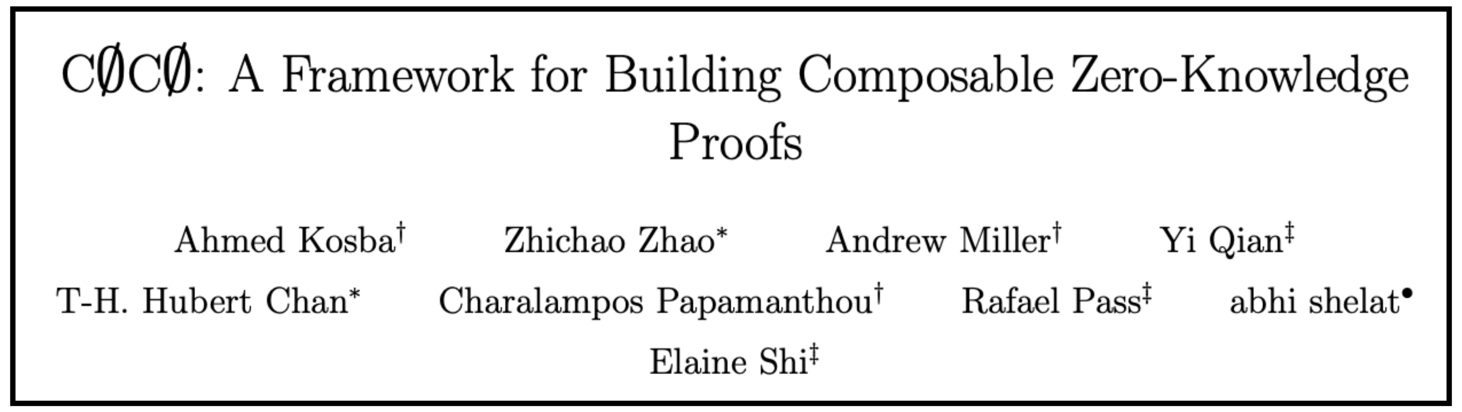
Append an encryption of the witness to the proof.

- Cannot be succinct $|\pi| \geq |w|$



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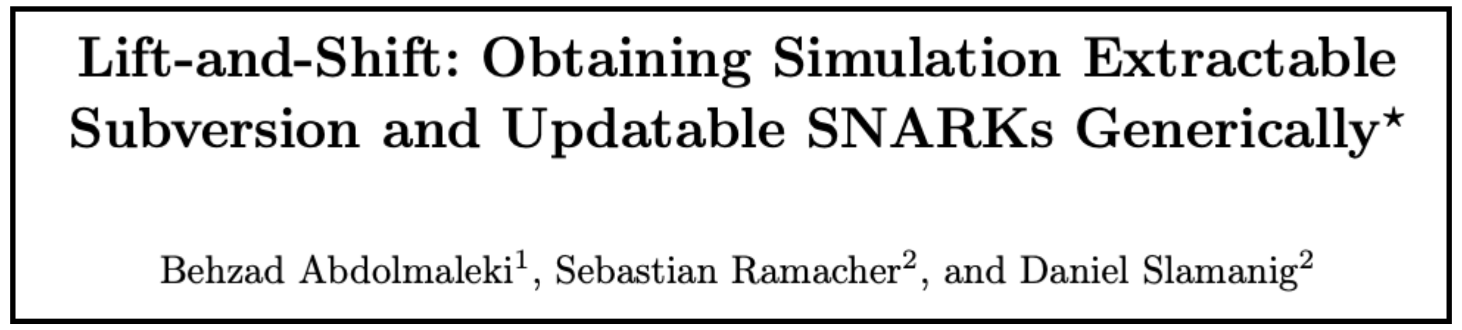

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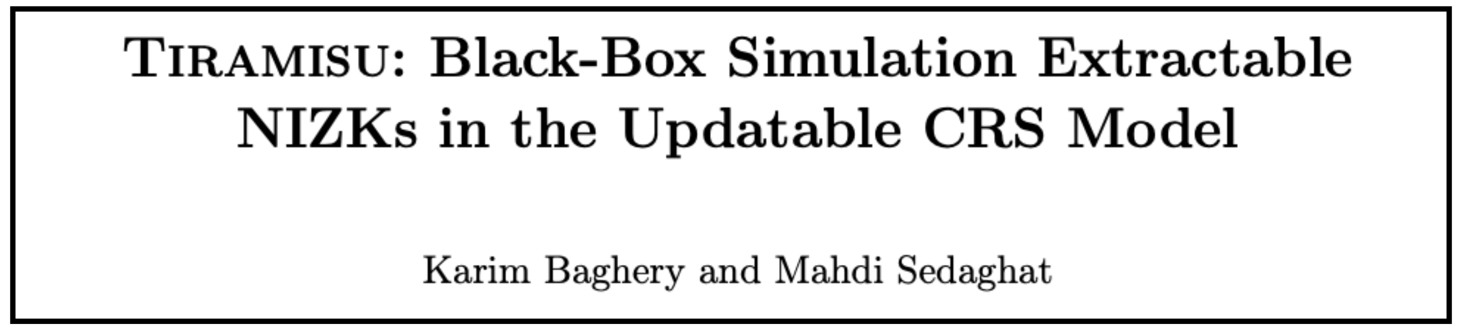

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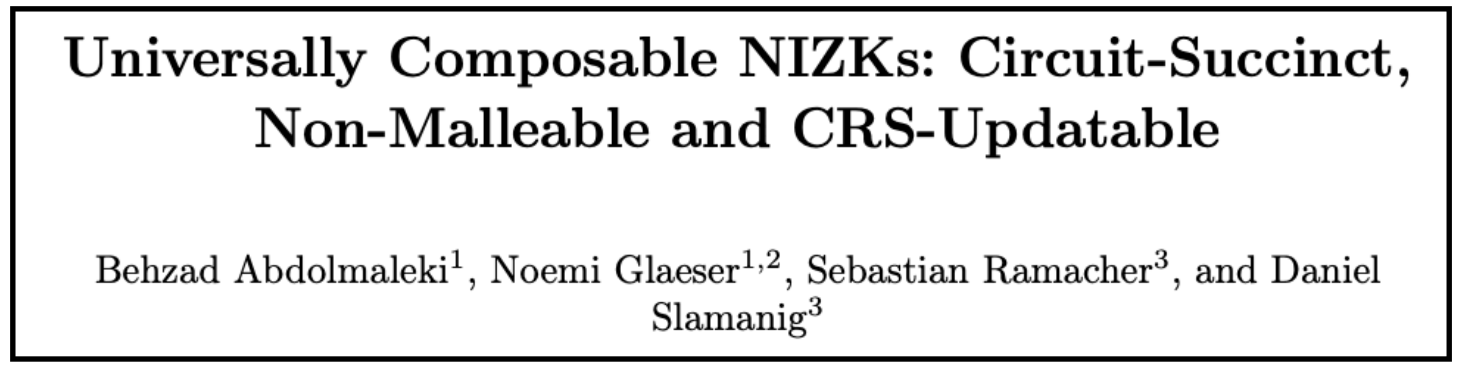

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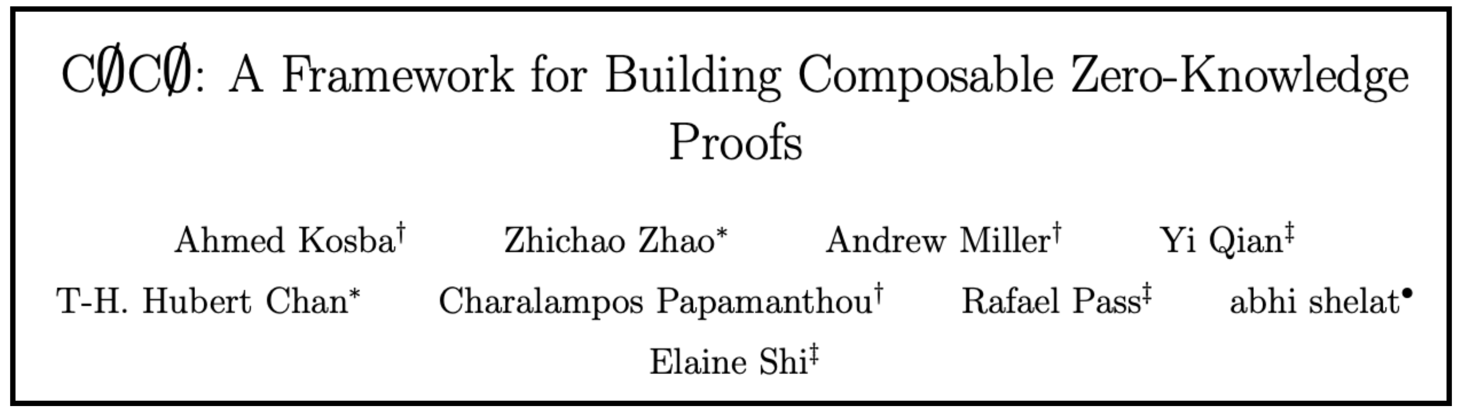

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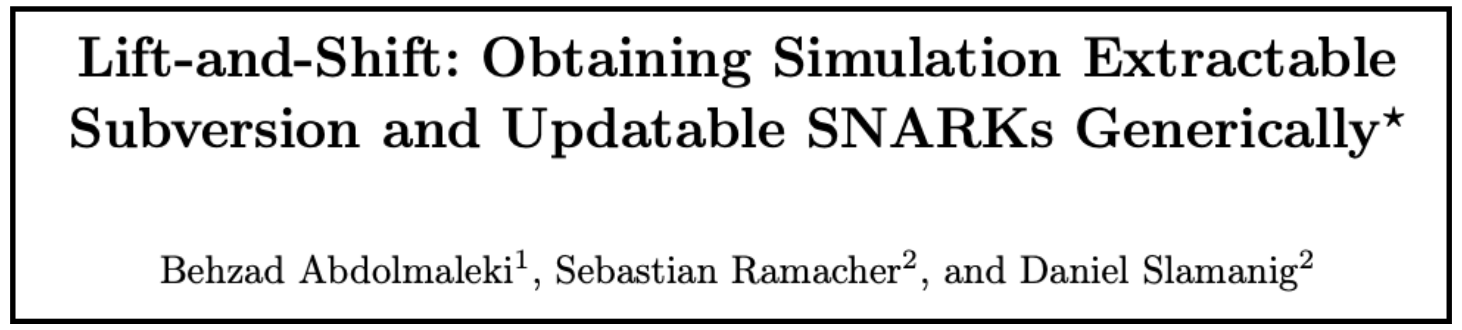

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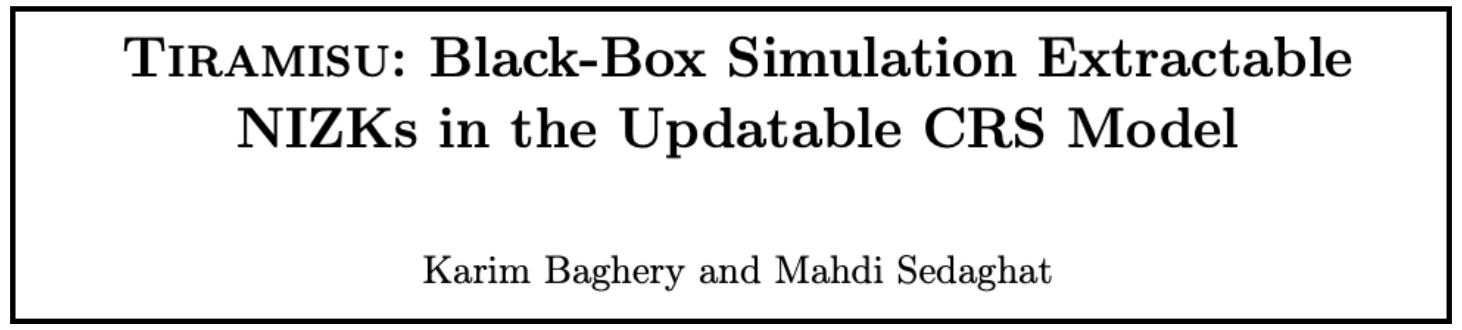

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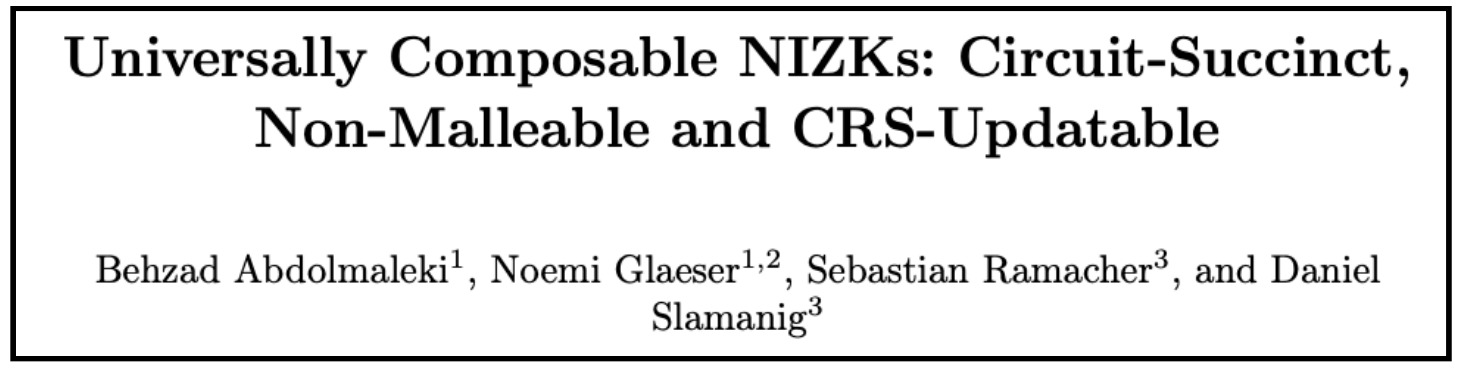

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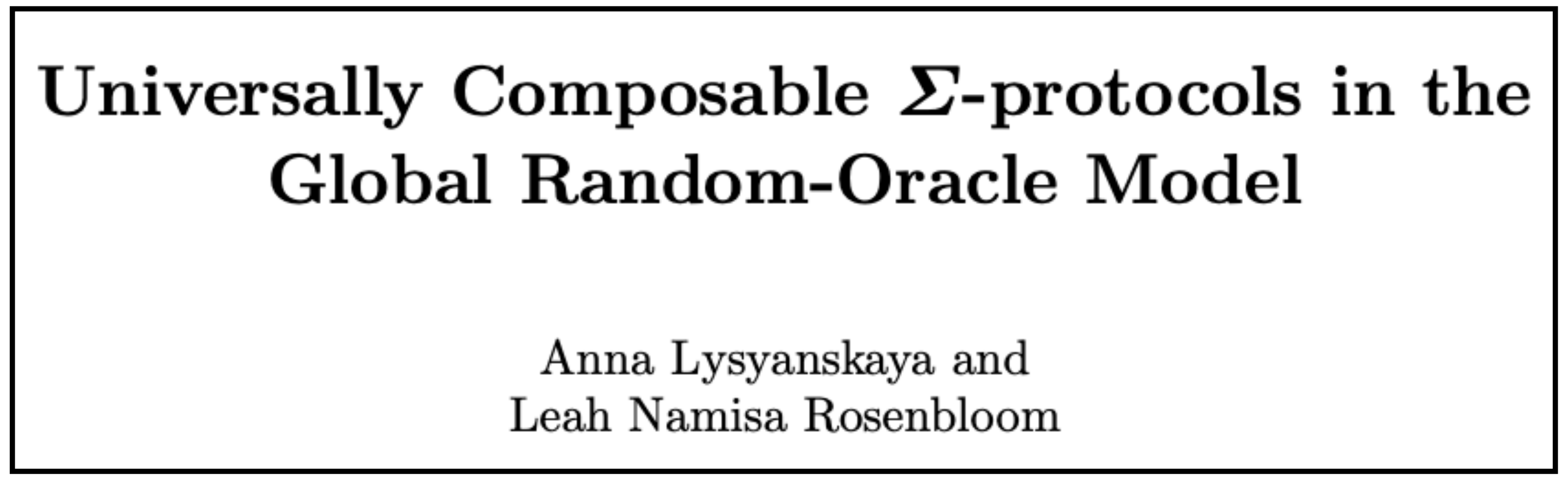
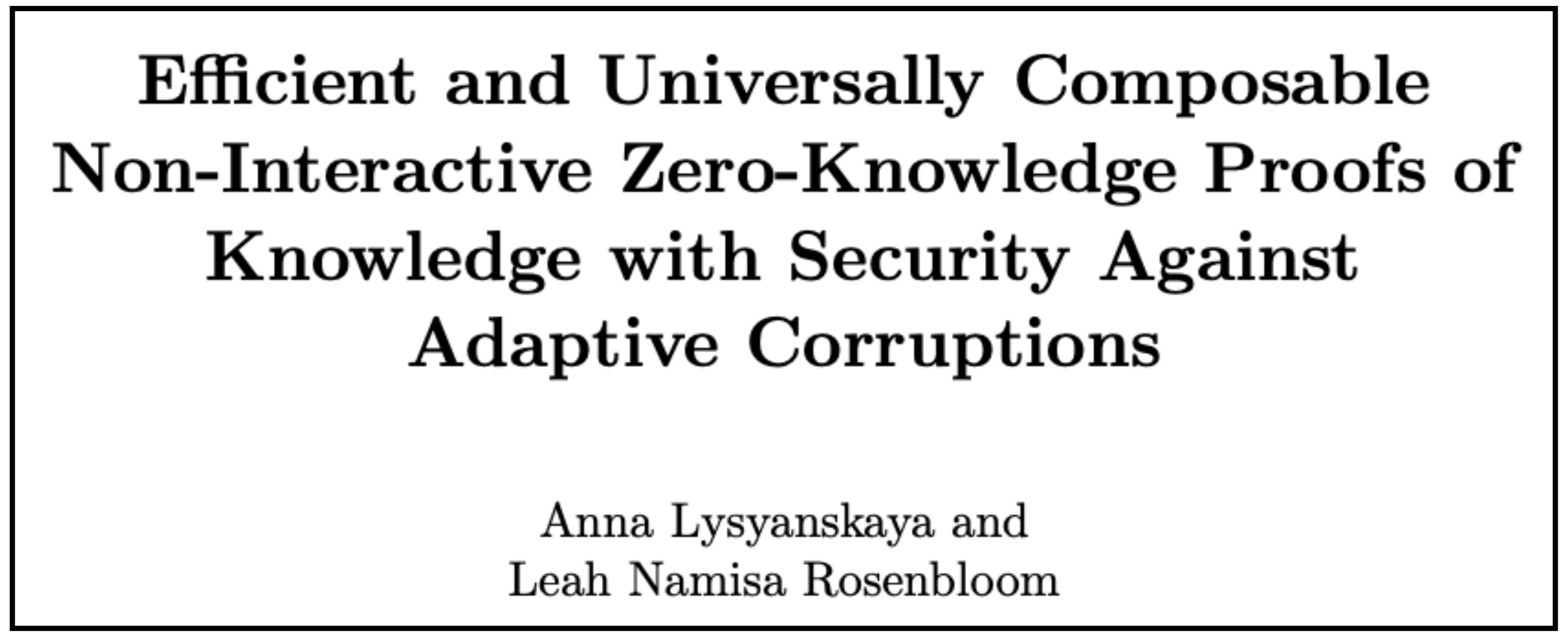


Universally Composable Σ-protocols in the Global Random-Oracle Model

Anna Lysyanskaya and
Leah Namisa Rosenbloom



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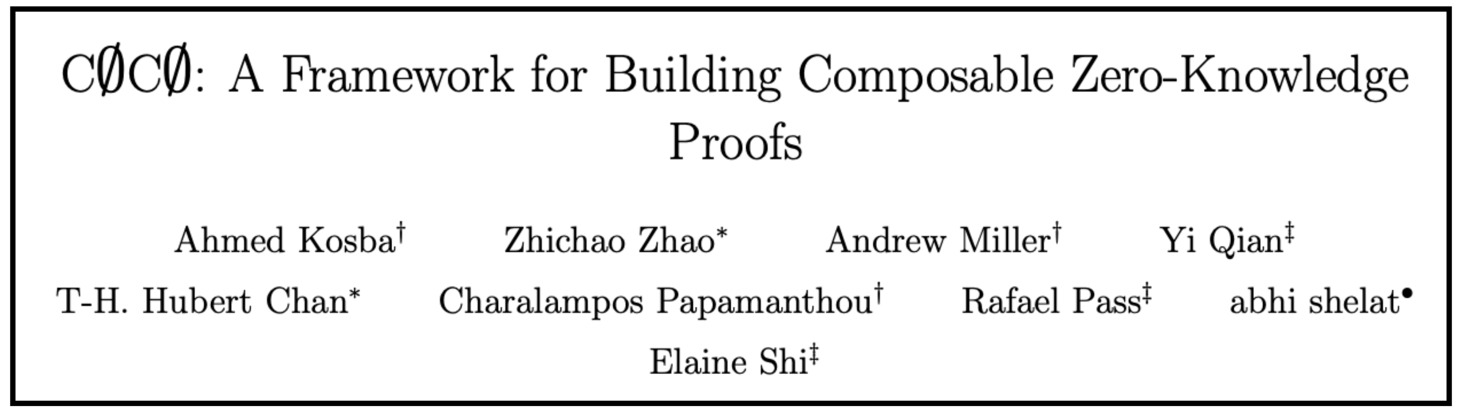

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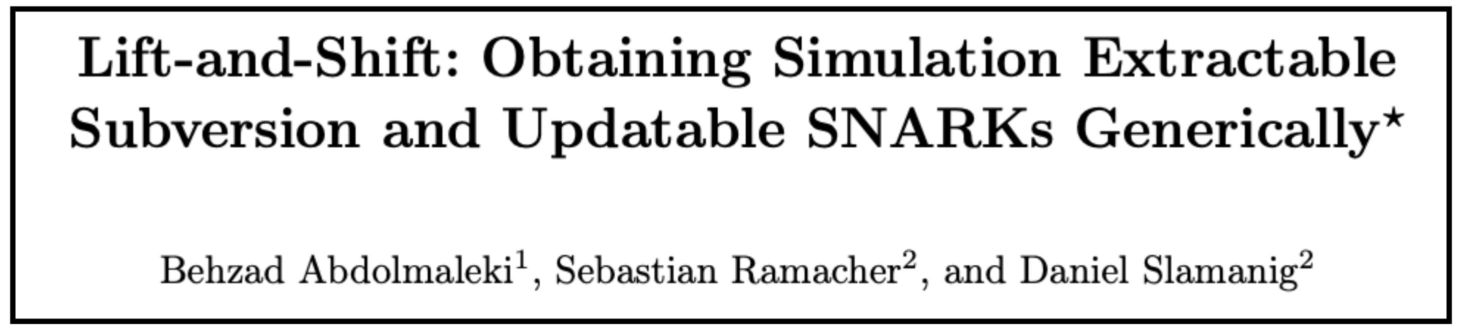

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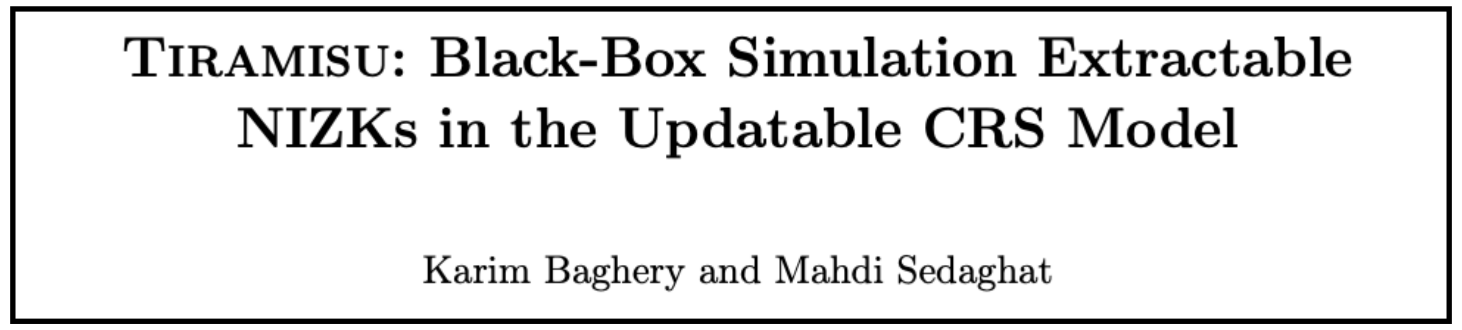

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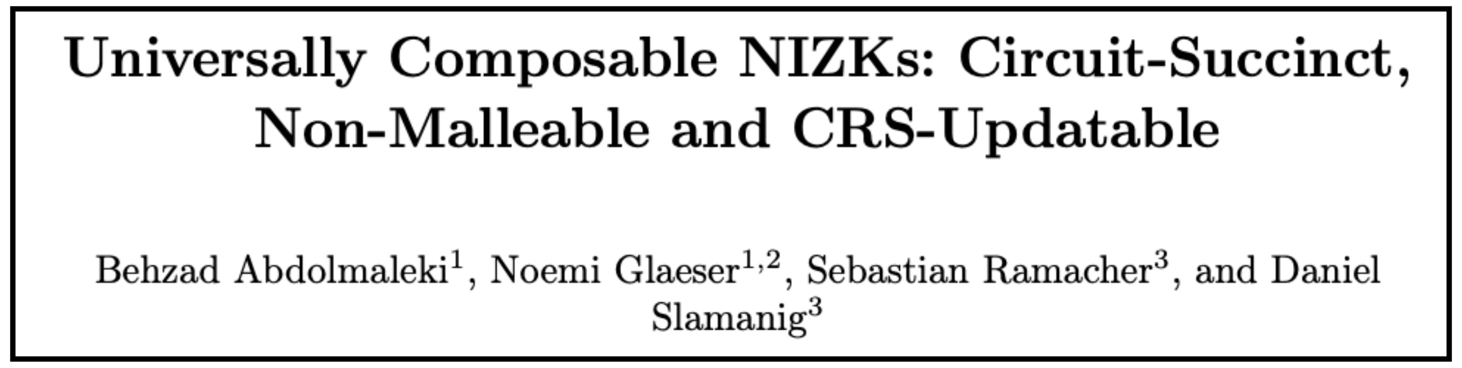


Universally Composable NIZKs: Circuit-Succinct, Non-Malleable and CRS-Updatable

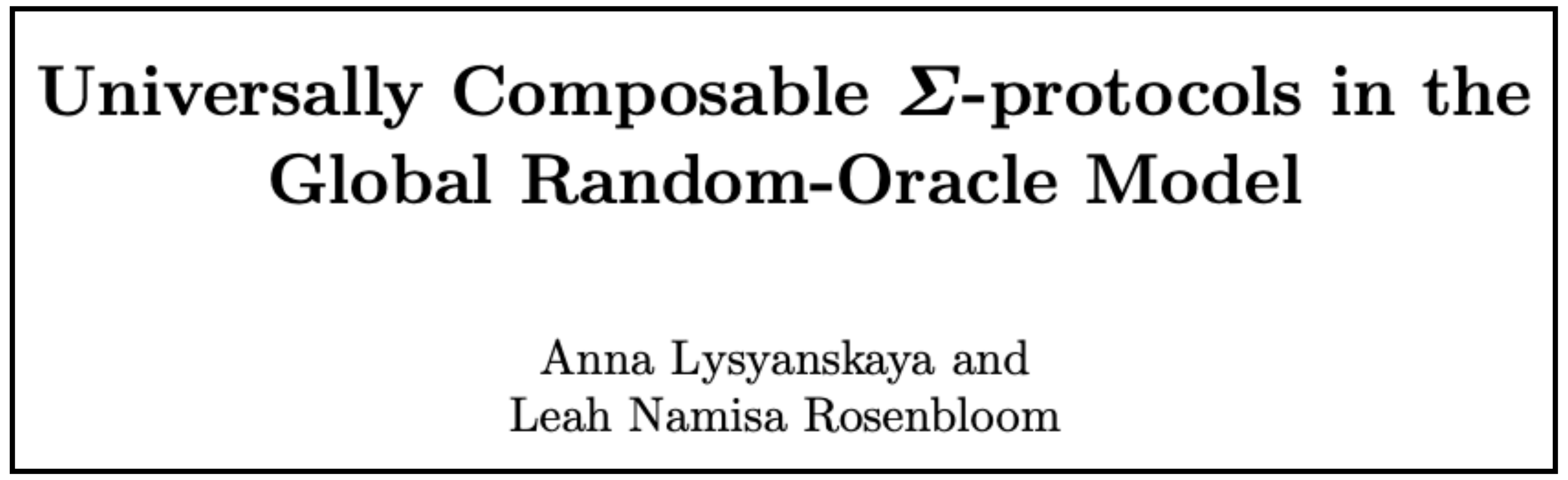
Behzad Abdolmaleki[1], Noemi Glaeser[1,2], Sebastian Ramacher[3], and Daniel Slamanig[3]

Compile Σ-protocol into NIZK

+ Techniques inspired this work

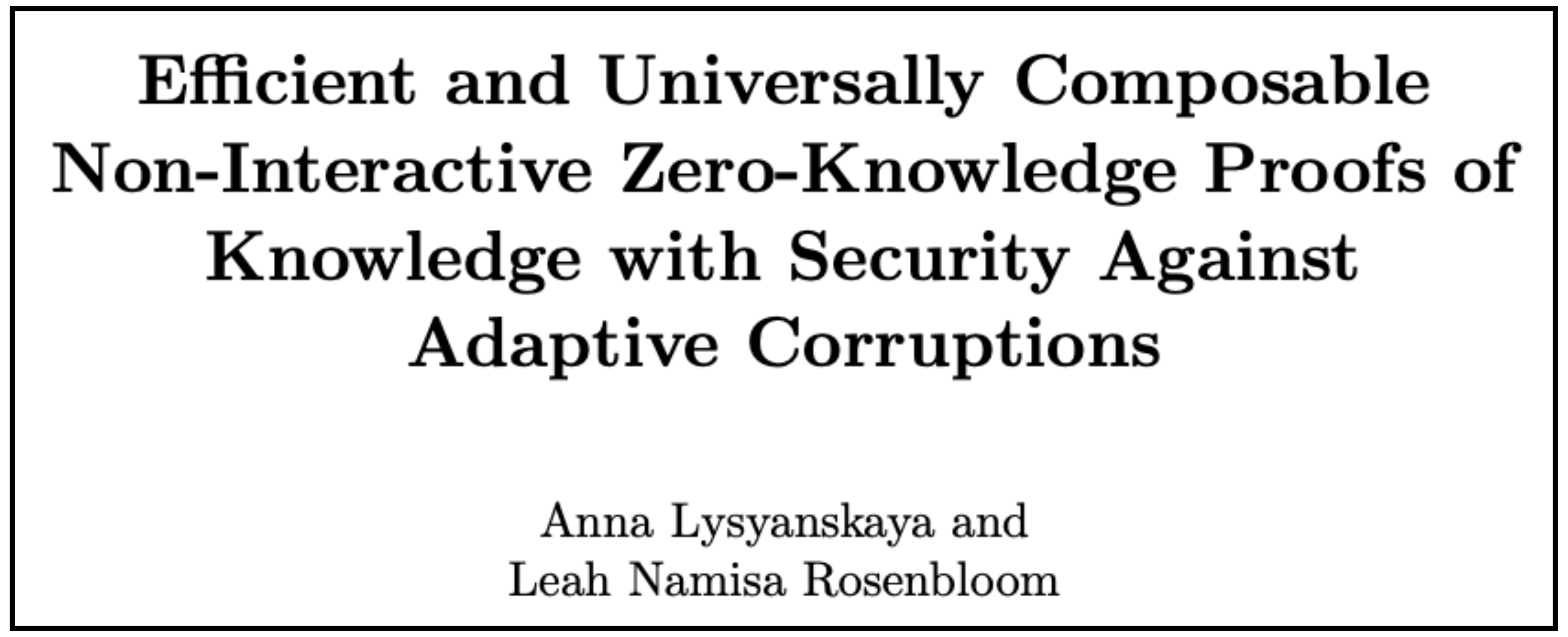
- Not succinct

- Expensive compilation (non-FS)



Universally Composable Σ-protocols in the Global Random-Oracle Model

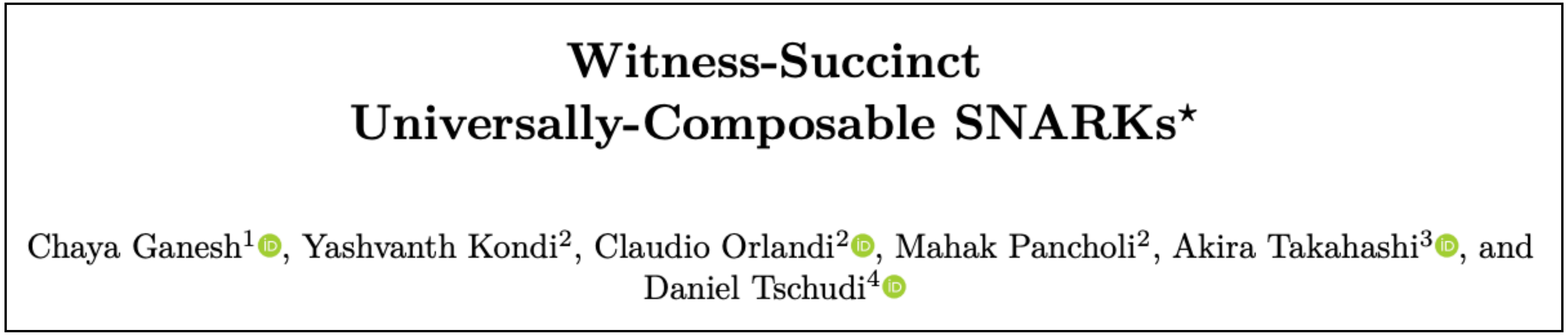
Anna Lysyanskaya and
Leah Namisa Rosenbloom



Efficient and Universally Composable Non-Interactive Zero-Knowledge Proofs of Knowledge with Security Against Adaptive Corruptions

Anna Lysyanskaya and
Leah Namisa Rosenbloom

Succinct UC-secure zkSNARKs



Witness-Succinct Universally-Composable SNARKs[*]

Chaya Ganesh[1], Yashvanth Kondi[2], Claudio Orlandi[2], Mahak Pancholi[2], Akira Takahashi[3], and Daniel Tschudi[4]

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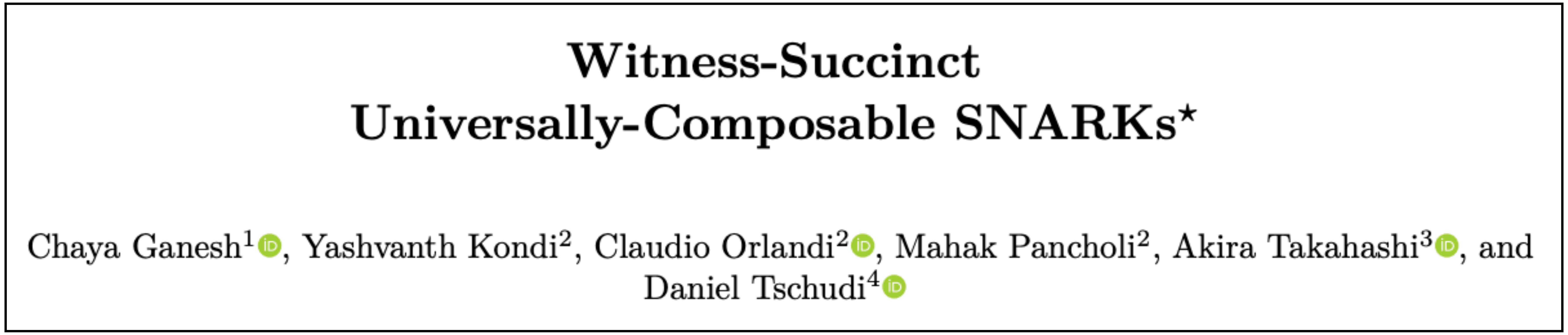

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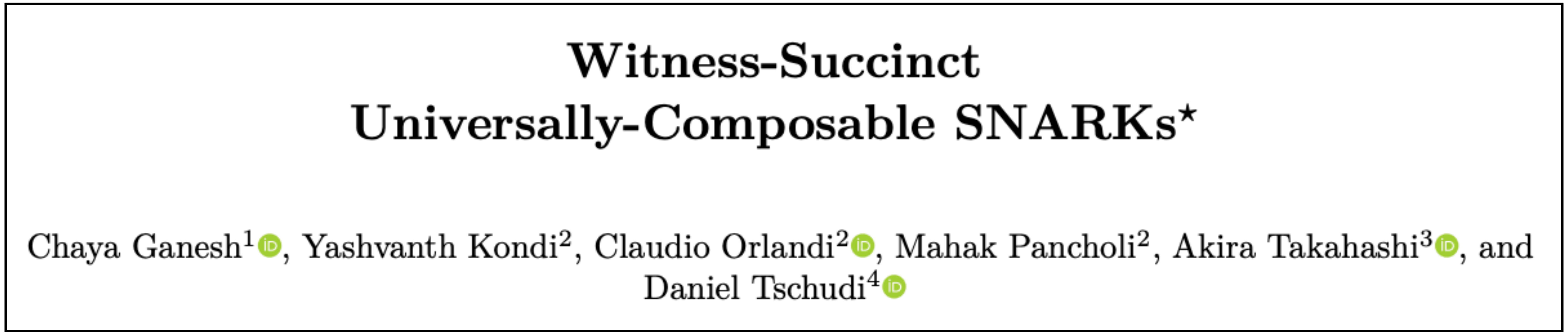

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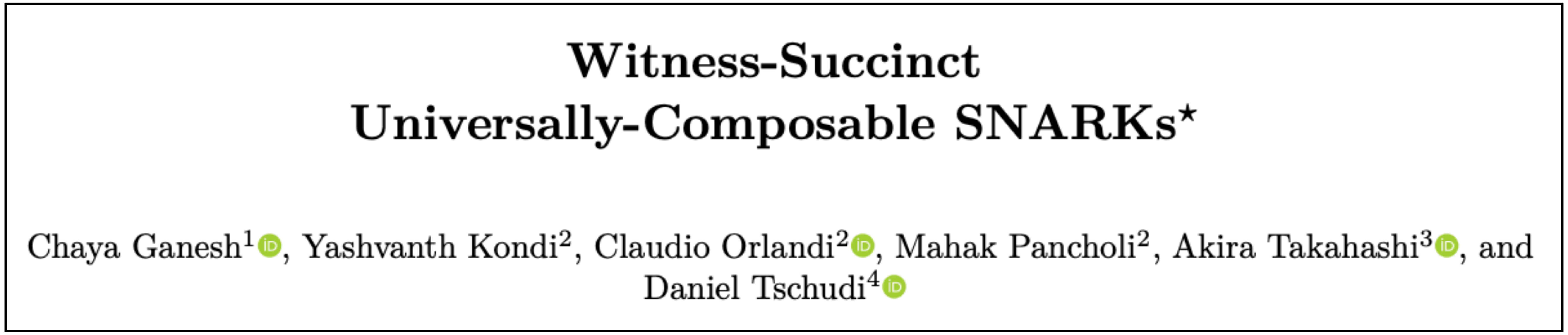
First UC-secure **S**NARK

Combines simulation-extractable zkSNARK with a PCS

Succinct UC-secure zkSNARKs



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Use Fischlin-like techniques to achieve straight-line extraction

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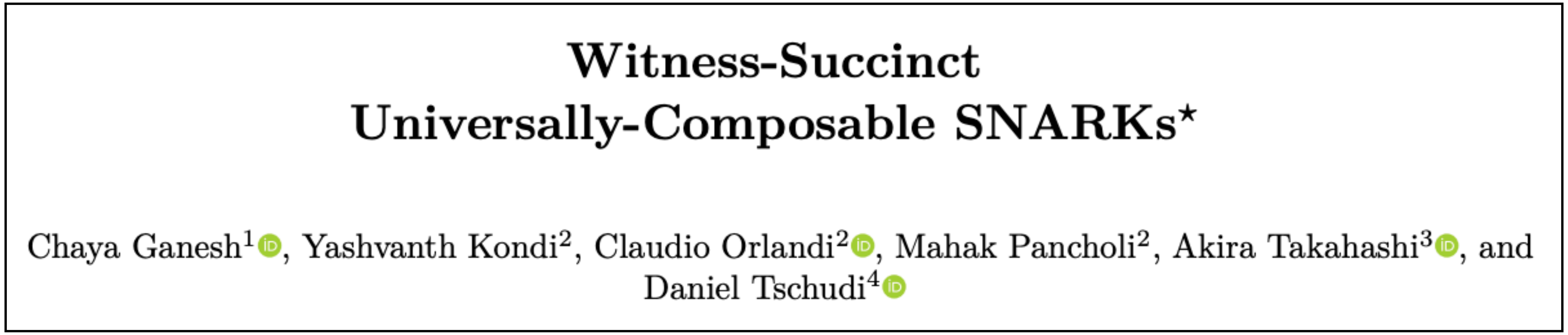

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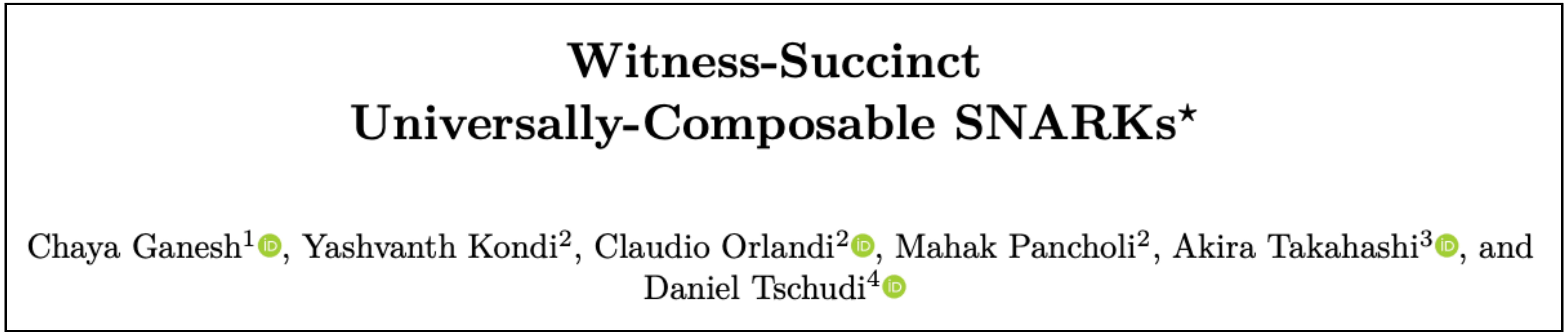

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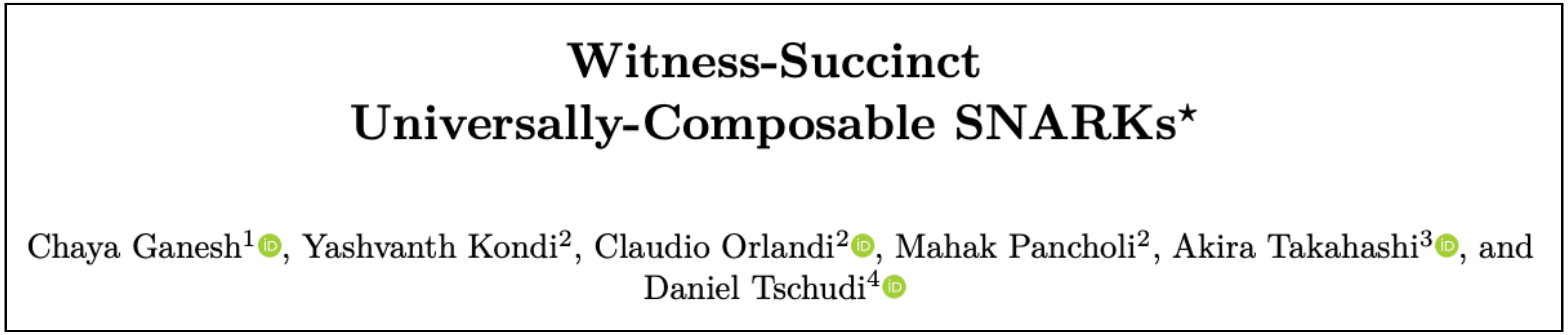
Succinct UC-secure zkSNARKs



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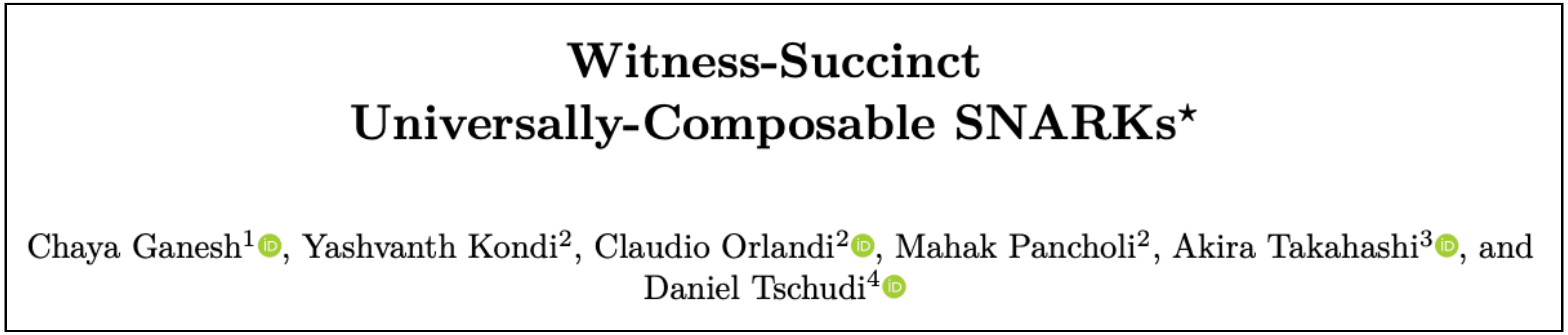
Succinct UC-secure zkSNARKs



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- Expensive non-standard construction

- Focuses on asymptotic security

zkSNARKs (in the ROM)

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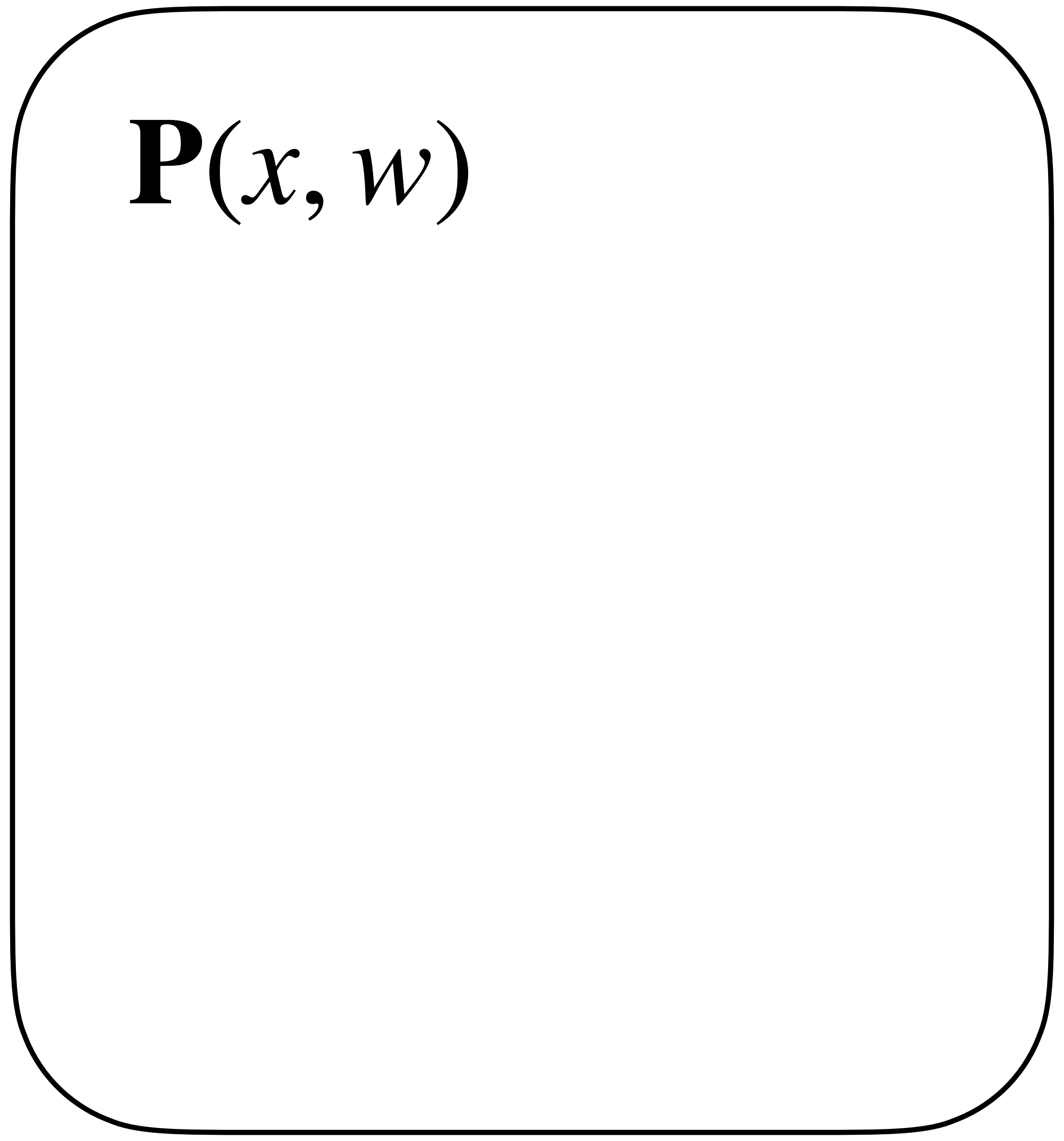
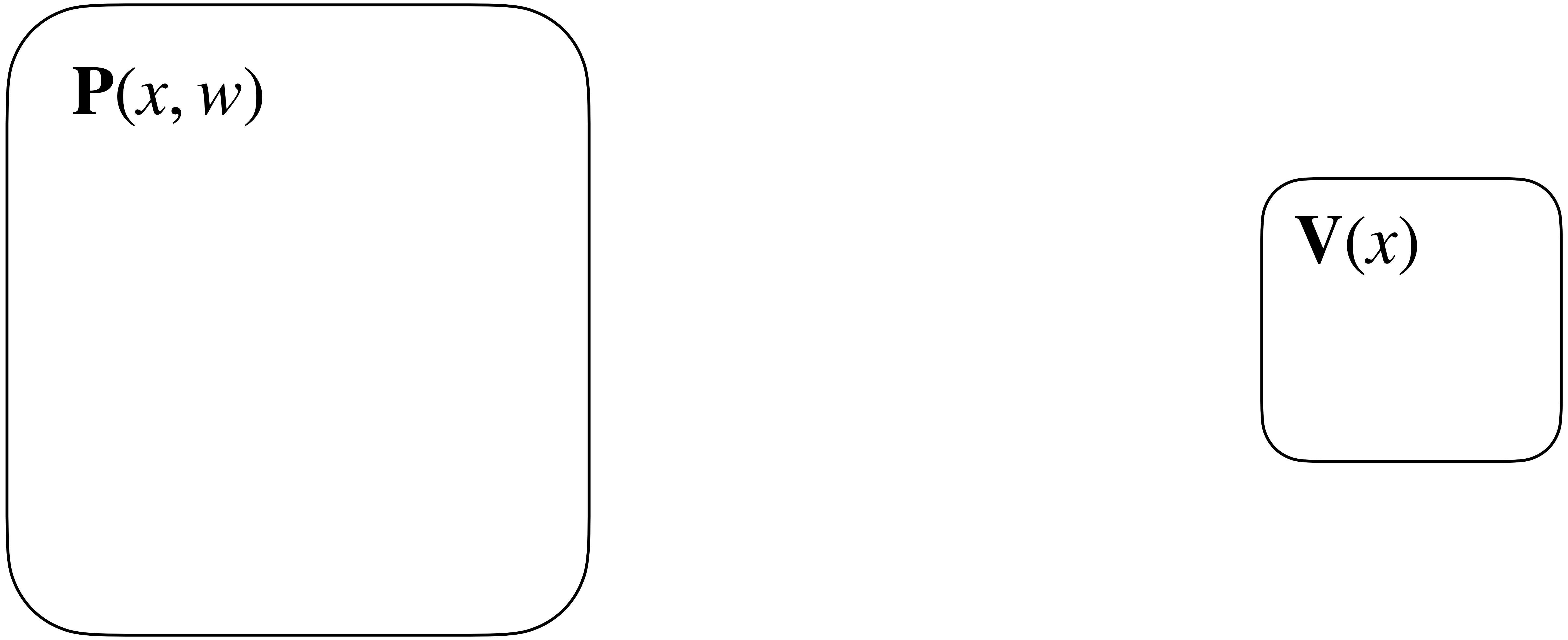


$\mathbf{P}(x, w)$

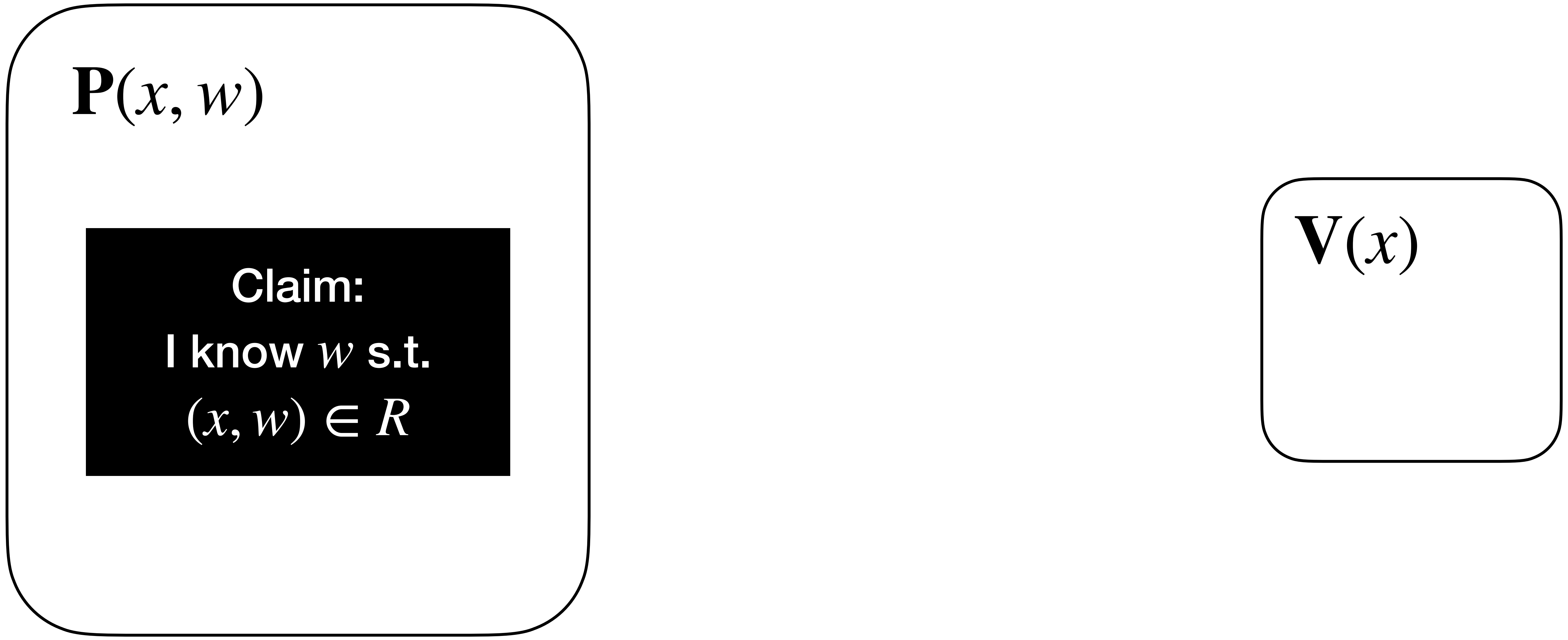
zkSNARKs (in the ROM)



$\mathbf{P}(x, w)$

$\mathbf{V}(x)$

zkSNARKs (in the ROM)

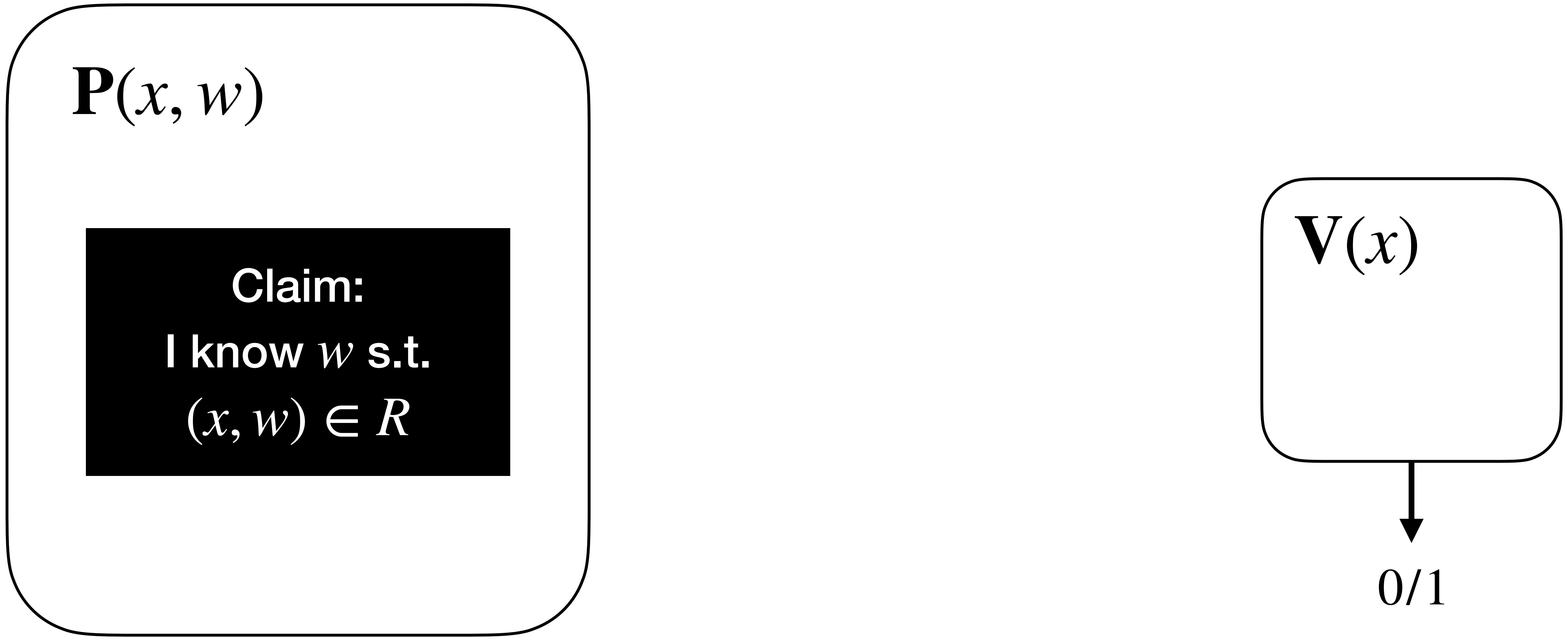


$\mathbf{P}(x, w)$

Claim:
I know w s.t.
$(x, w) \in R$

$\mathbf{V}(x)$

zkSNARKs (in the ROM)



$\mathbf{P}(x, w)$

Claim:
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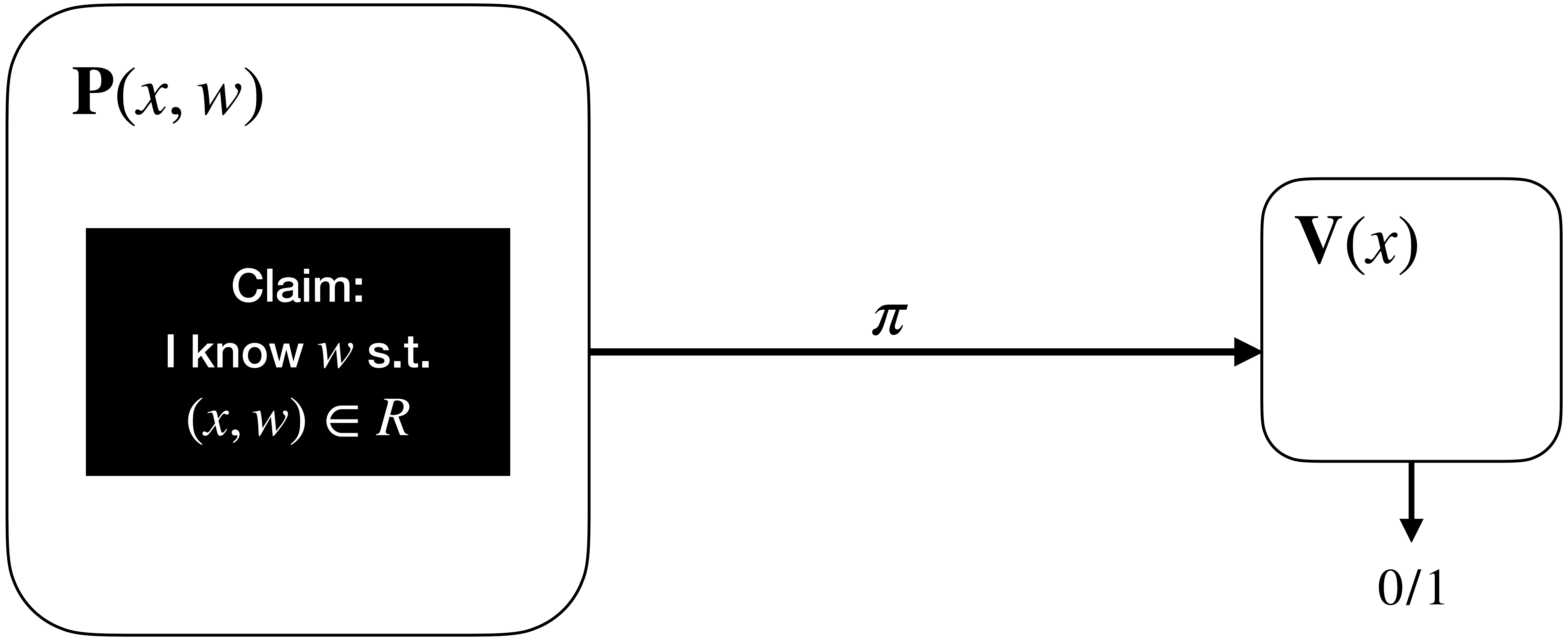
$\mathbf{V}(x)$

0/1

zkSNARKs (in the ROM)



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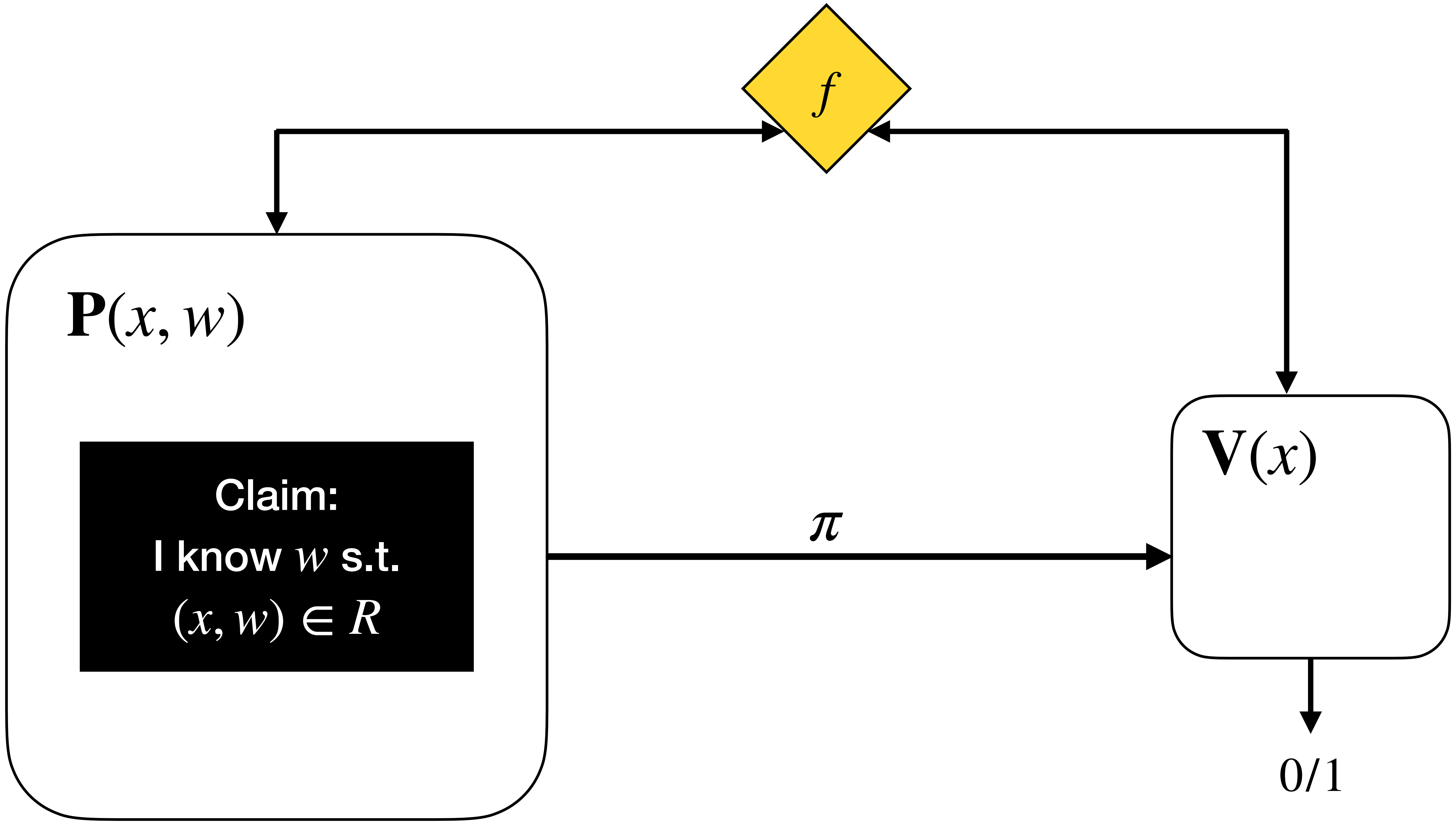

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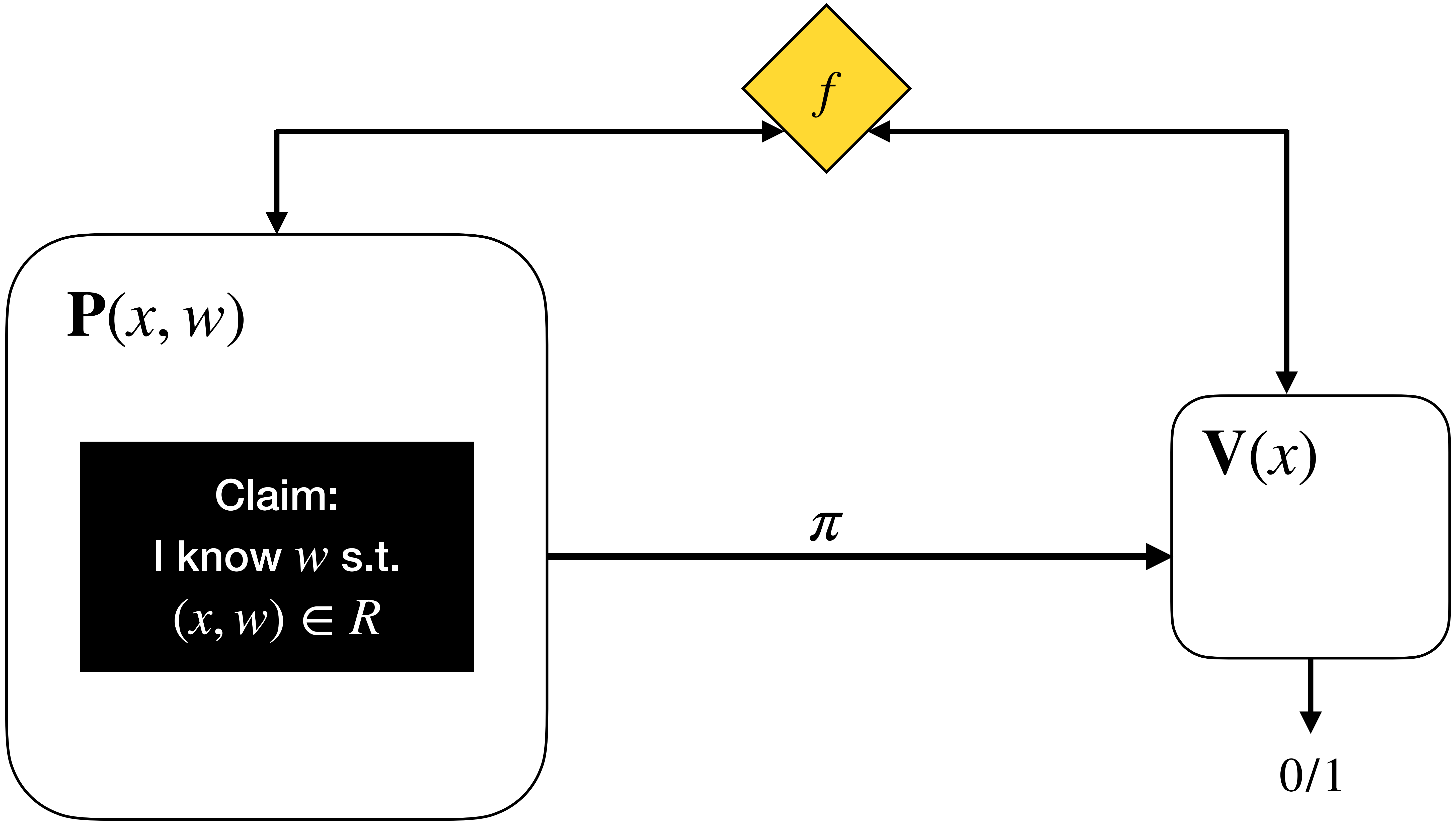
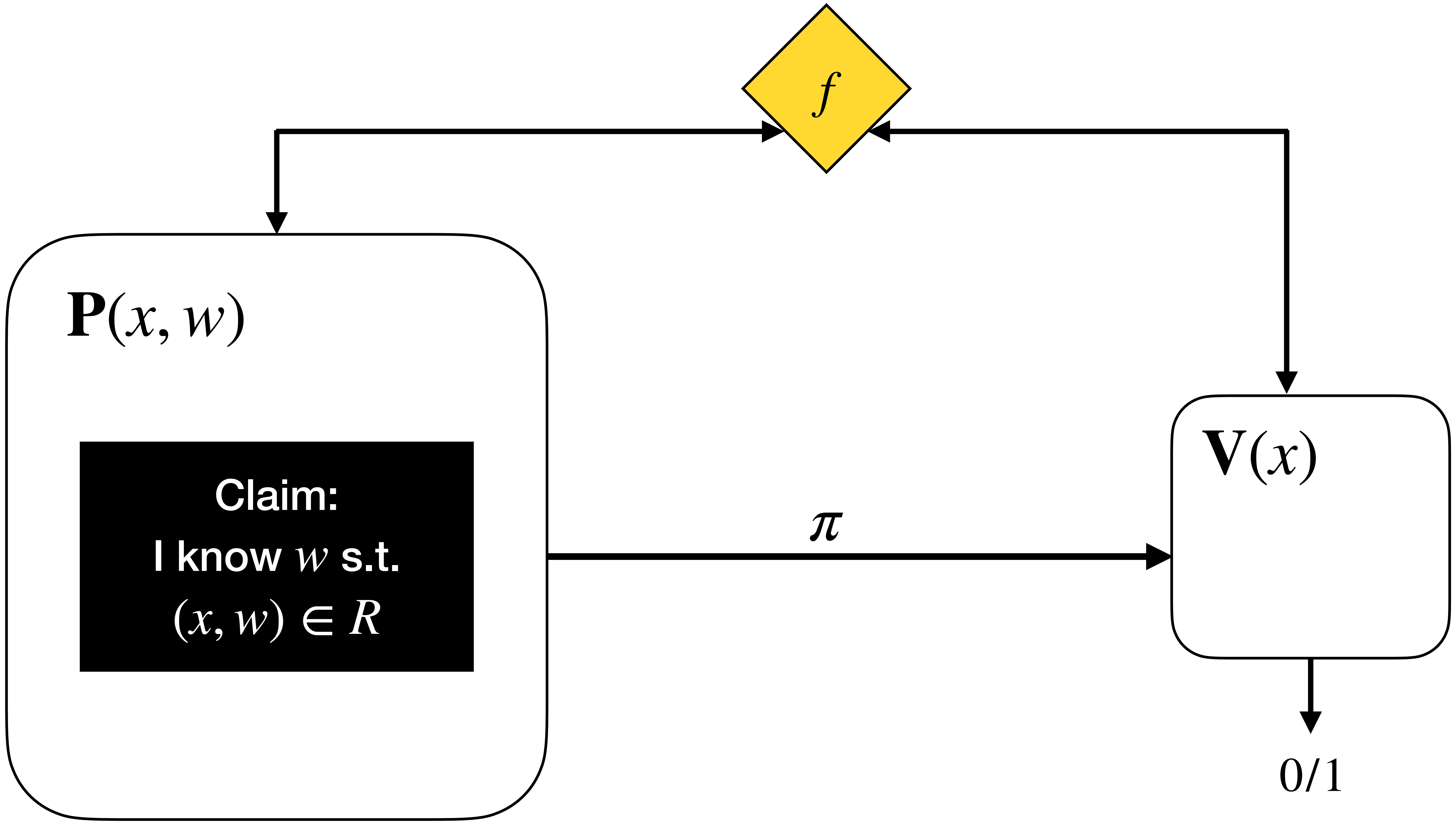


- Zero-Knowledge
  - $\exists \mathbf{S} : \ \mathbf{P}^f(x, w) \approx \mathbf{S}^f(x)$

zkSNARKs (in the ROM)



- Zero-Knowledge
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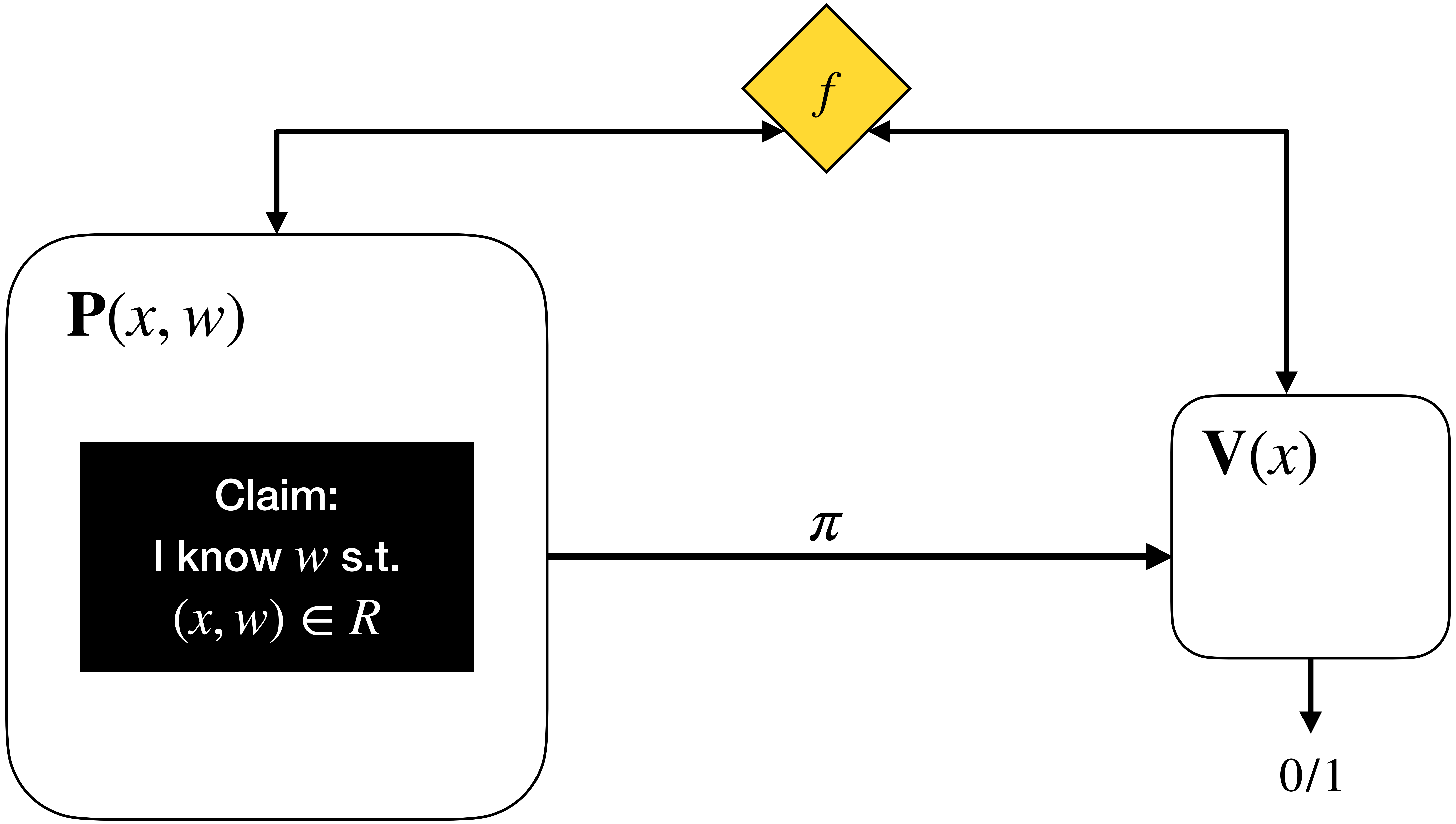
- Succinct
  - $|\pi| \ll |w|$

zkSNARKs (in the ROM)



- Zero-Knowledge
  - ○ $\exists \mathbf{S} : \mathbf{P}^f(x, w) \approx \mathbf{S}^f(x)$
- Succinct
  - ○ $|\pi| \ll |w|$
- Non-interactive

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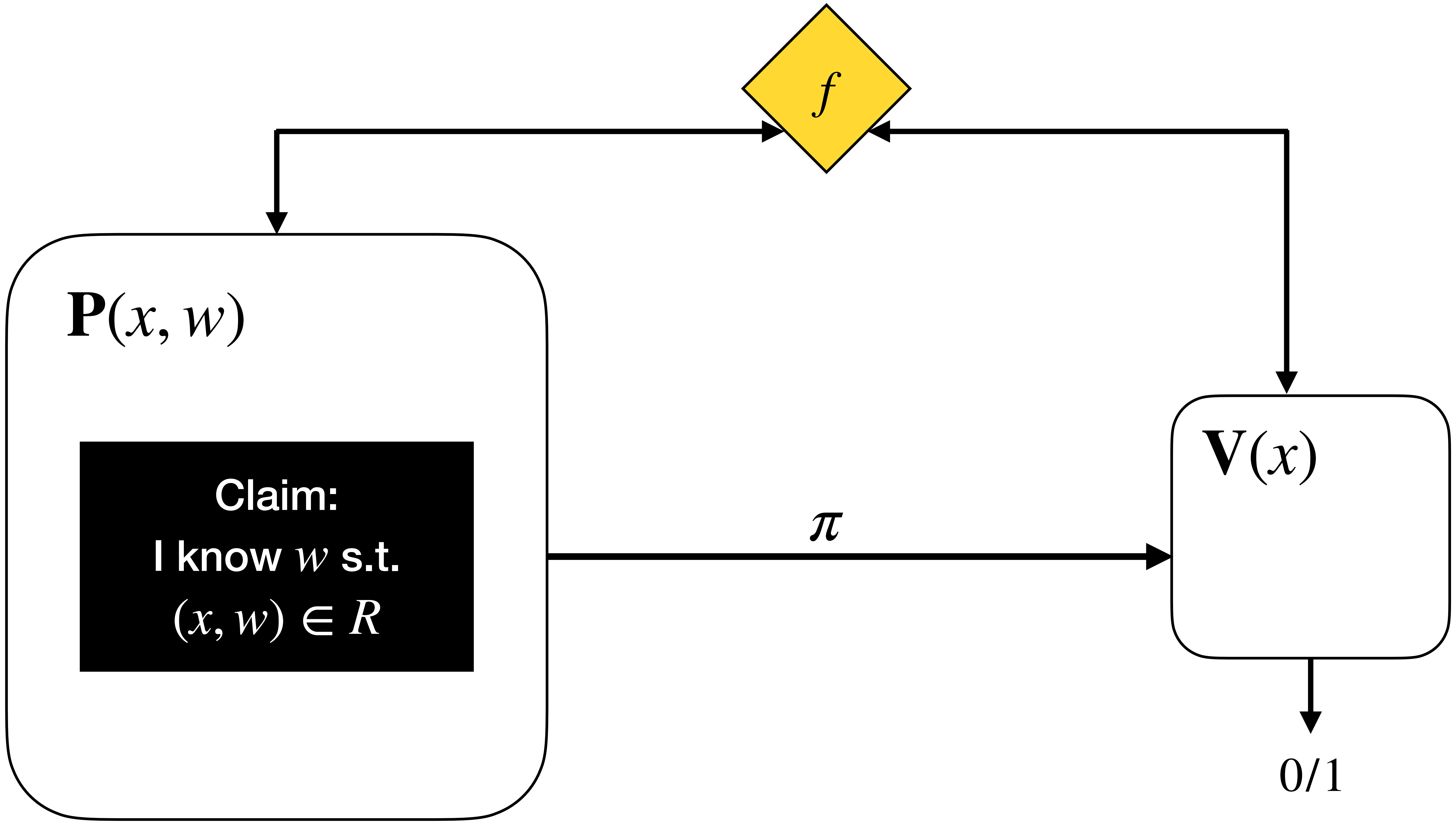

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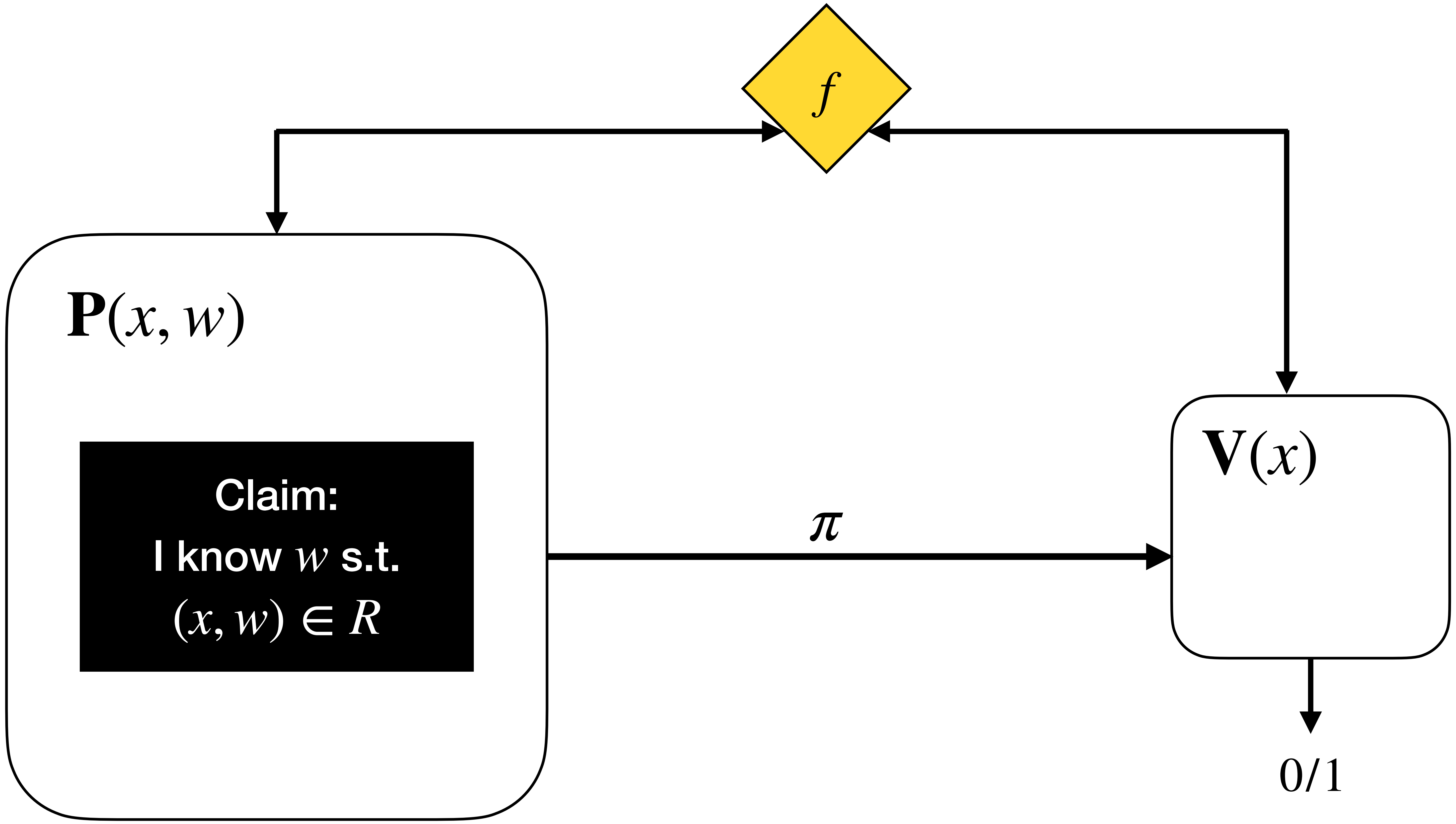

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  - $\exists \mathbf{E}: \ \mathbf{V}^f(x, \pi \leftarrow \tilde{\mathbf{P}}) = 1$

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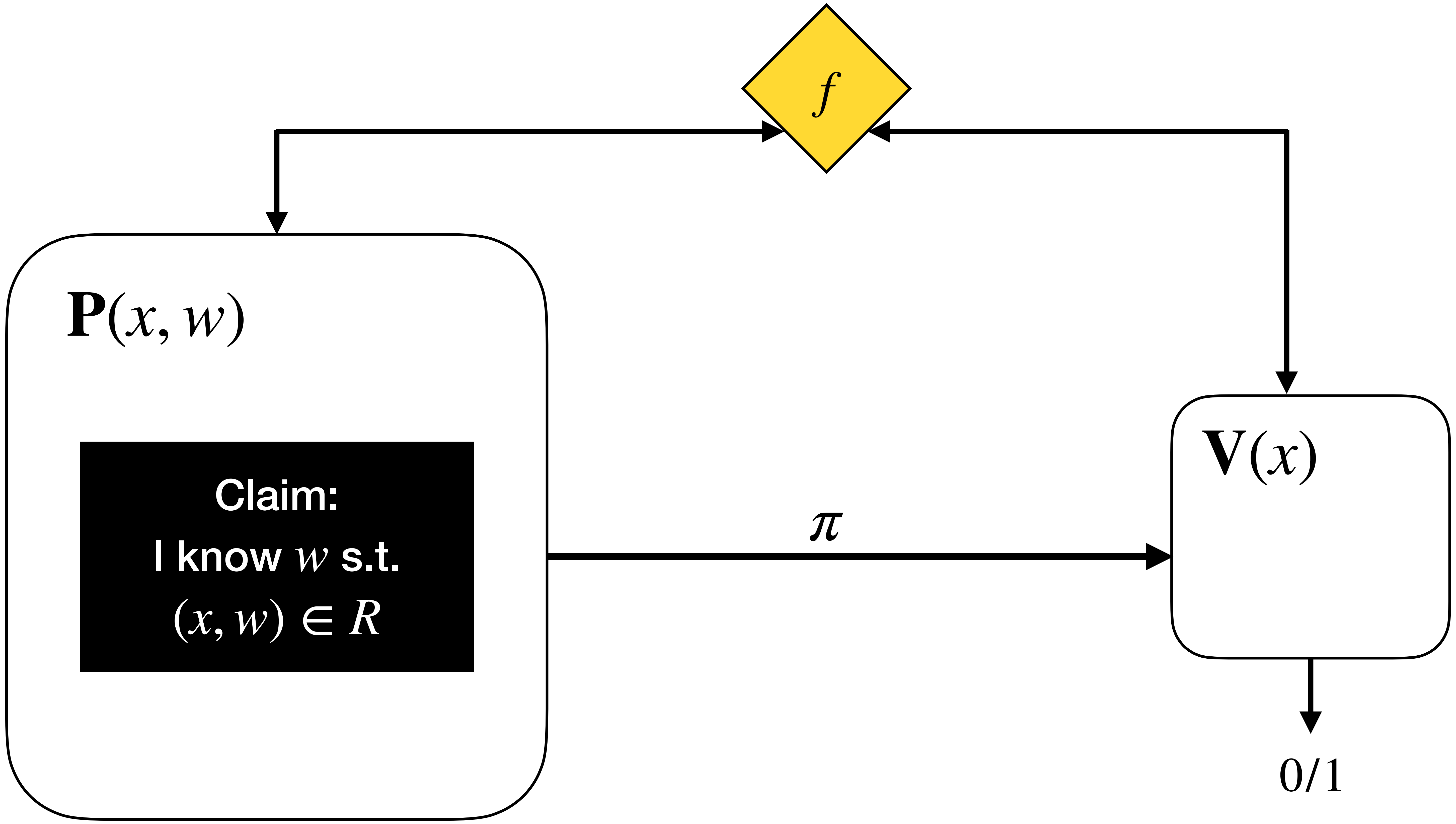

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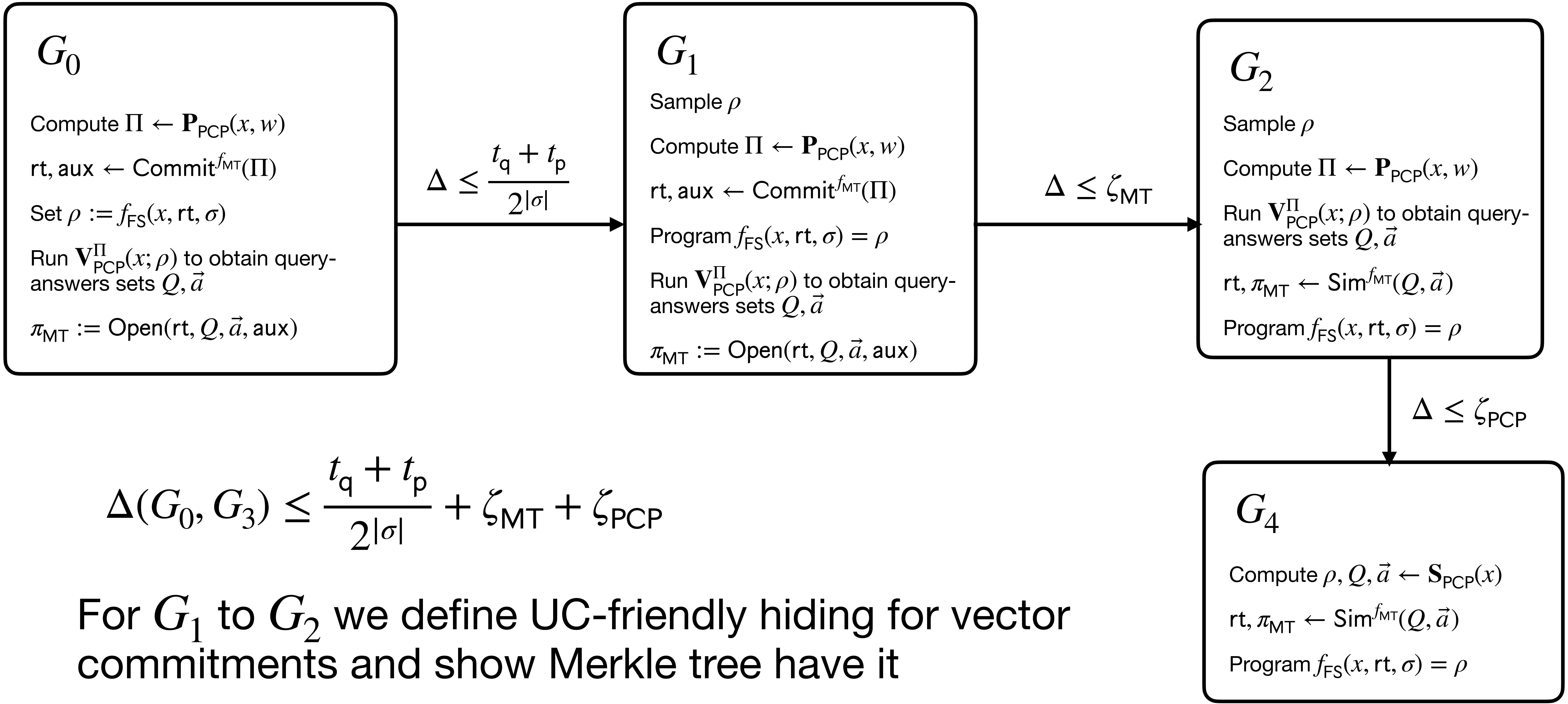
  - $|\pi| \ll |w|$
- Non-interactive
- Argument of Knowledge
  - $\exists \mathbf{E} : \ \mathbf{V}^f(x, \pi \leftarrow \tilde{\mathbf{P}}) = 1$ $\implies (x, \mathbf{E}(x, \pi, \mathrm{tr}_{\tilde{\mathbf{P}}})) \in R$

What if we only care about scalability?

Dropping ZK

- Often, SNARKs are deployed without ZK
- We consider this out of scope for this work but (at an high level) believe that:
    - The techniques here would still work and can be simplified.
    - Remove UC-friendly ZK and move to non-programmable GROM.
    - UC-completeness then reduces to perfect completeness.
    - Knowledge sound PCP/IOP suffices for Micali/BCS.

Micali has UC-friendly ZK



G_0

Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$

rt, aux $\leftarrow$ Commit$^{f_{\mathsf{MT}}}(\Pi)$

Set $\rho := f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma)$

Run $\mathbf{V}^{\Pi}_{\mathsf{PCP}}(x; \rho)$ to obtain query-answers sets $Q, \vec{a}$

$\pi_{\mathsf{MT}} :=$ Open(rt, $Q, \vec{a}$, aux)

$\Delta \leq \frac{t_{\mathsf{q}} + t_{\mathsf{p}}}{2^{|\sigma|}}$

G_1

Sample ρ

Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$

rt, aux $\leftarrow$ Commit$^{f_{\mathsf{MT}}}(\Pi)$

Program $f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma) = \rho$

Run $\mathbf{V}^{\Pi}_{\mathsf{PCP}}(x; \rho)$ to obtain query-answers sets $Q, \vec{a}$

$\pi_{\mathsf{MT}} :=$ Open(rt, $Q, \vec{a}$, aux)

$\Delta \leq \zeta_{\mathsf{MT}}$

G_2

Sample ρ

Compute $\Pi \leftarrow \mathbf{P}_{\mathsf{PCP}}(x, w)$

Run $\mathbf{V}^{\Pi}_{\mathsf{PCP}}(x; \rho)$ to obtain query-answers sets $Q, \vec{a}$

rt, $\pi_{\mathsf{MT}} \leftarrow$ Sim$^{f_{\mathsf{MT}}}(Q, \vec{a})$

Program $f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma) = \rho$

$\Delta \leq \zeta_{\mathsf{PCP}}$

G_4

Compute $\rho, Q, \vec{a} \leftarrow \mathbf{S}_{\mathsf{PCP}}(x)$

rt, $\pi_{\mathsf{MT}} \leftarrow$ Sim$^{f_{\mathsf{MT}}}(Q, \vec{a})$

Program $f_{\mathsf{FS}}(x, \mathsf{rt}, \sigma) = \rho$

$$\Delta(G_0, G_3) \leq \frac{t_{\mathsf{q}} + t_{\mathsf{p}}}{2^{|\sigma|}} + \zeta_{\mathsf{MT}} + \zeta_{\mathsf{PCP}}$$

For G_1 to G_2 we define UC-friendly hiding for vector commitments and show Merkle tree have it

Micali has UC-friendly completeness

Micali has UC-friendly completeness

UC-friendly completeness

Micali has UC-friendly completeness

- Assuming **PCP perfect completeness**, honest proof are rejected only if the verifier queries a previously programmed point.

UC-friendly completeness

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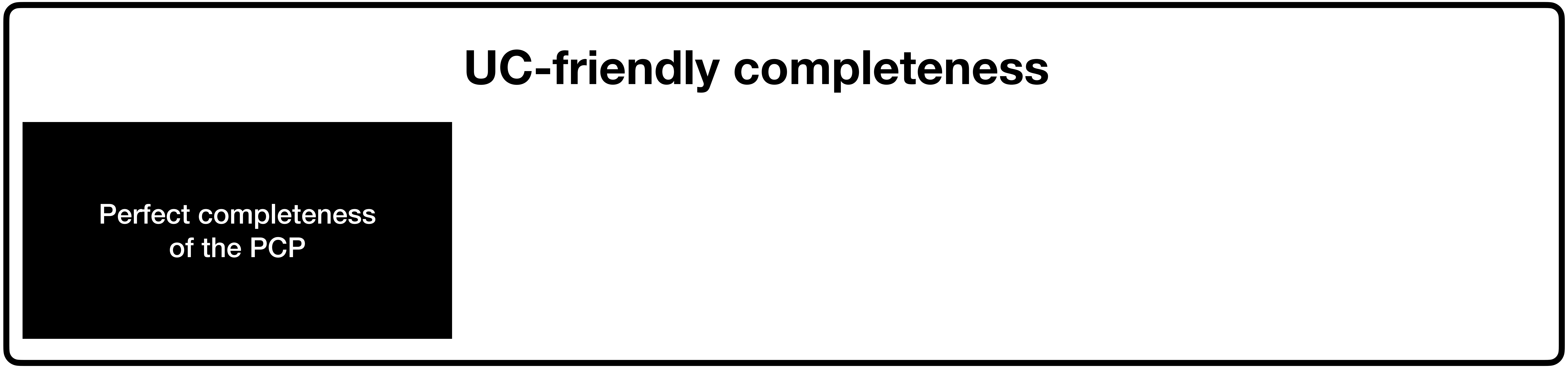

UC-friendly completeness

Perfect completeness of the PCP

Micali has UC-friendly completeness

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- Disallow this attack with two natural properties:

UC-friendly completeness

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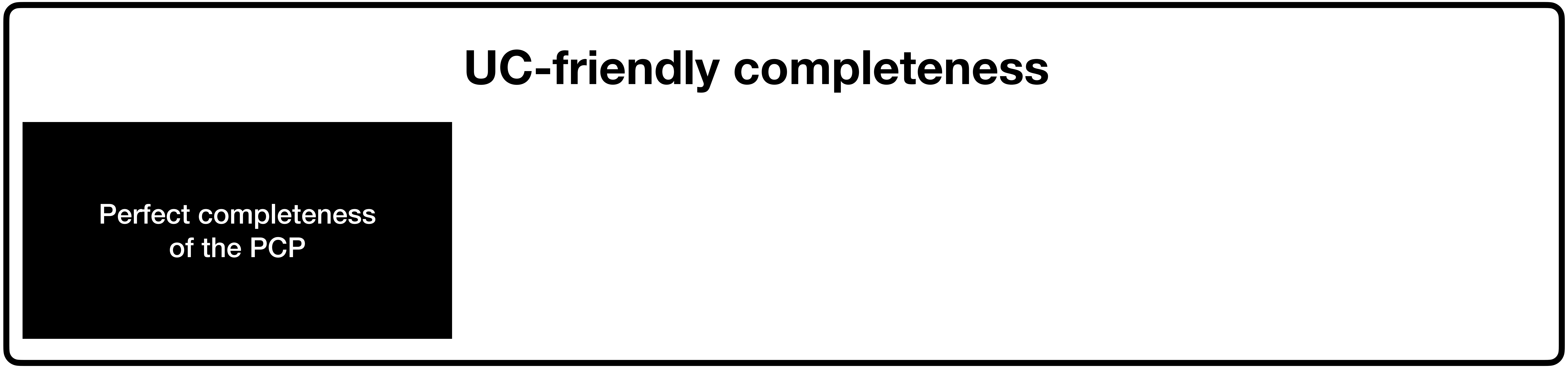

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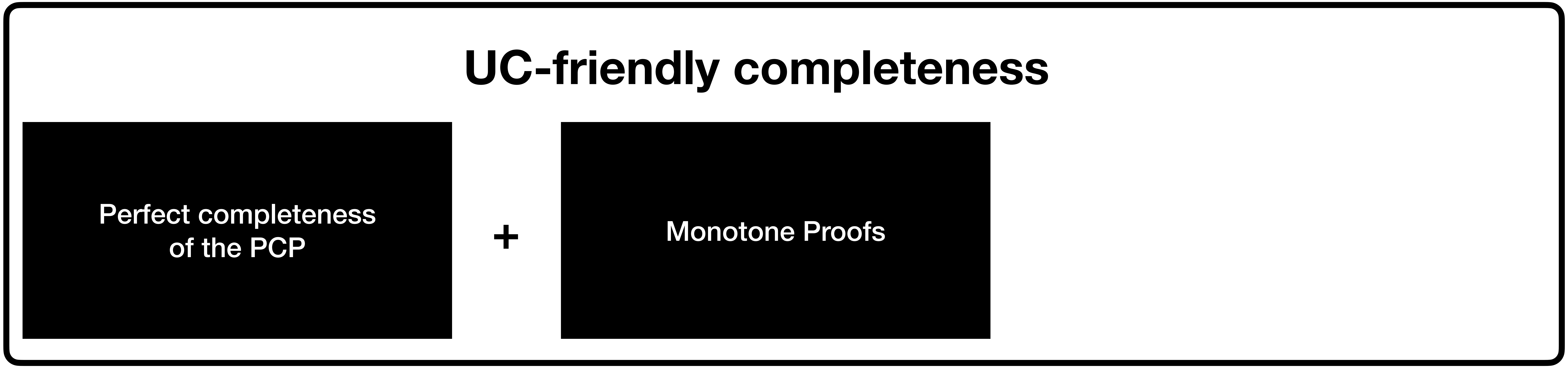

UC-friendly completeness

Perfect completeness of the PCP

+

Monotone Proofs

Micali has UC-friendly completeness

- Assuming **PCP perfect completeness**, honest proof are rejected only if the verifier queries a previously programmed point.

- Disallow this attack with two natural properties:

  - **Monotone proofs** (verifier does not query points not previously queried by the prover)

  - **Unpredictable queries** (hard to program points prover will query)

UC-friendly completeness

Perfect completeness of the PCP + Monotone Proofs

Micali has UC-friendly completeness

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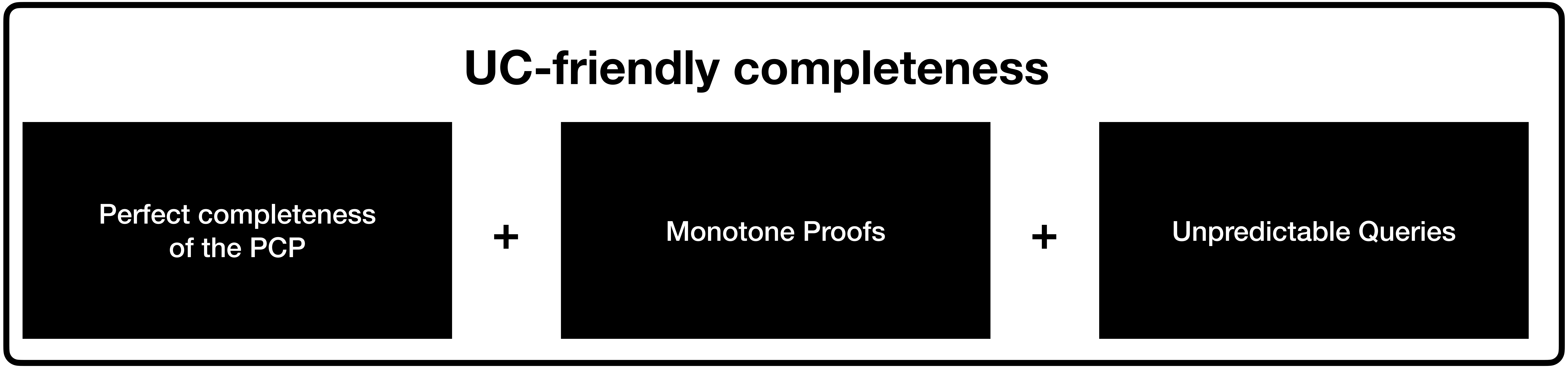

UC-friendly completeness

Perfect completeness of the PCP + Monotone Proofs + Unpredictable Queries

Micali has UC-friendly KS

Micali has UC-friendly KS

UC-friendly KS of Micali

Micali has UC-friendly KS

- UC-friendly KS implies simulation-extractability.

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- Reduce to **state-restoration KS** (implied by KS of PCP)

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Merkle trees are UC-friendly extractable

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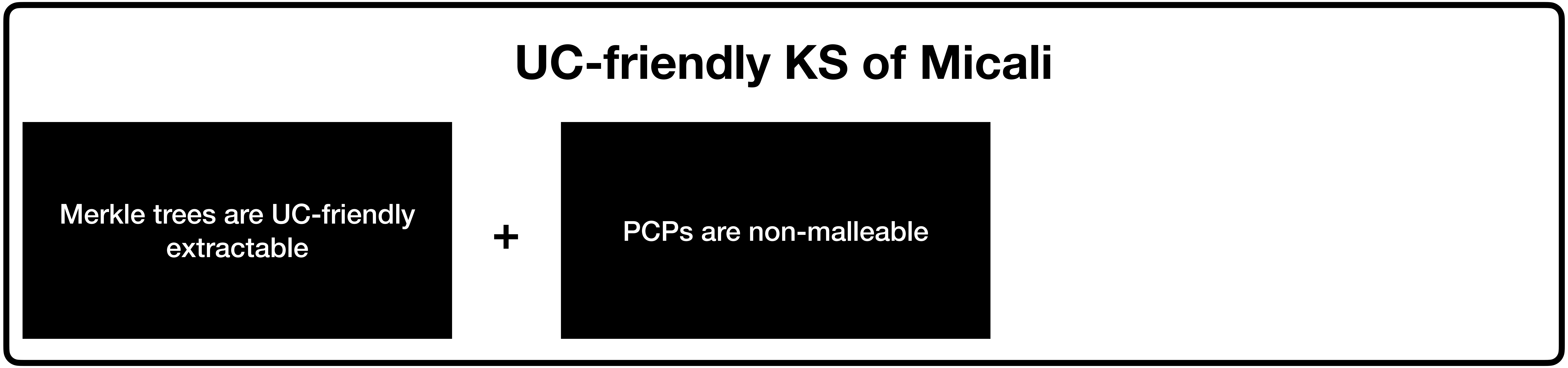

UC-friendly KS of Micali

Merkle trees are UC-friendly extractable

+

PCPs are non-malleable

Micali has UC-friendly KS

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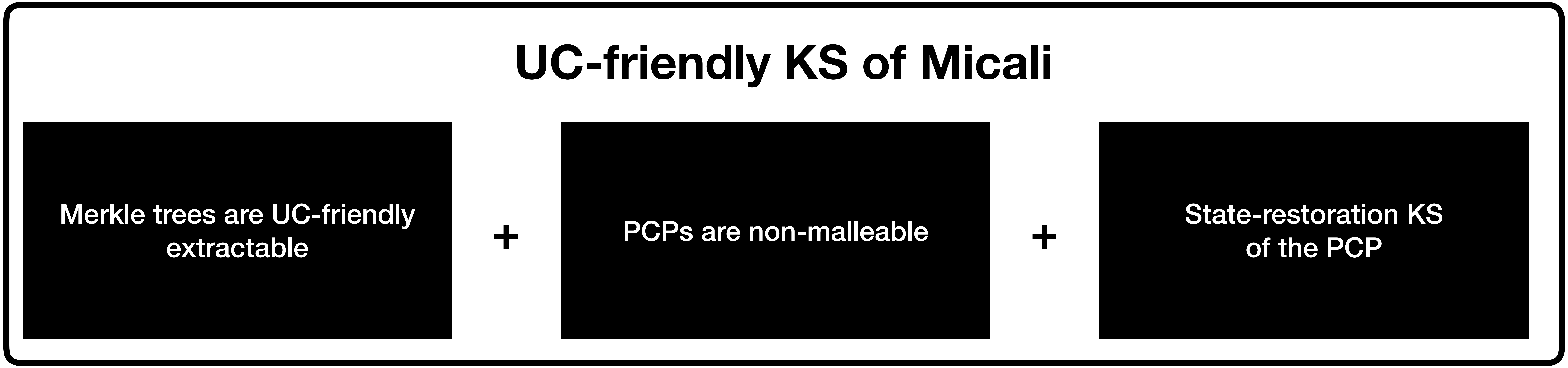

UC-friendly KS of Micali

Merkle trees are UC-friendly extractable + PCPs are non-malleable + State-restoration KS of the PCP

Related works

Known UC-secure zkSNARKs

Related works

Known UC-secure zkSNARKs

Non-Witness Succinct

Related works

Known UC-secure zkSNARKs

Non-Witness Succinct

Witness Succinct

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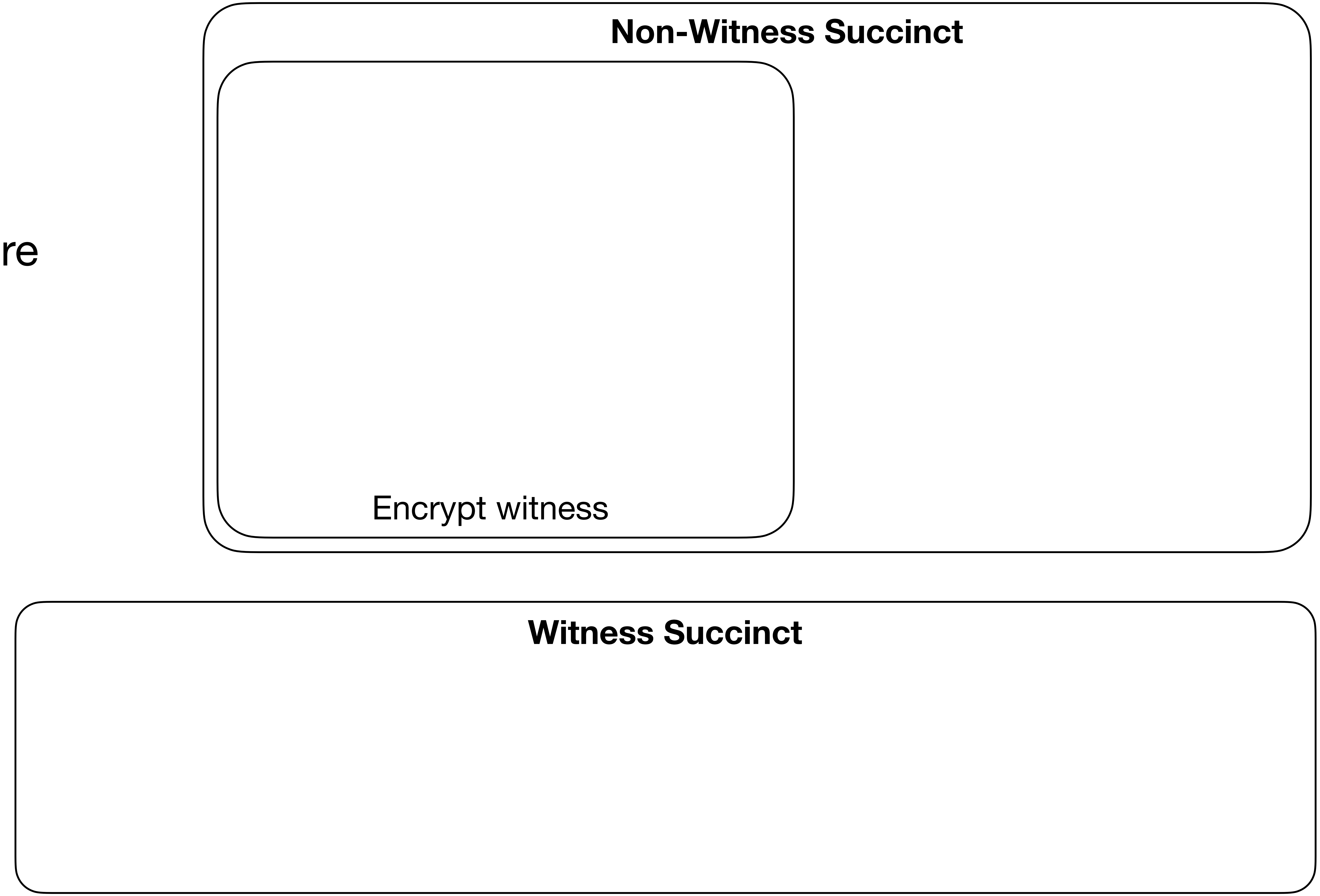


Non-Witness Succinct

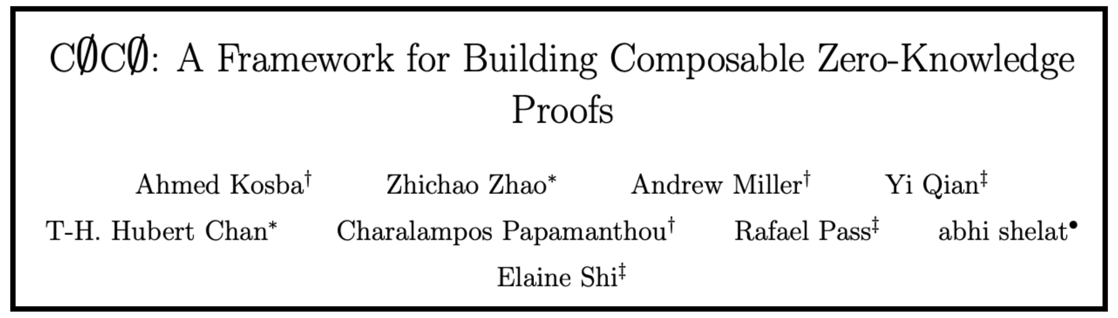
Encrypt witness

Witness Succinct

Related works

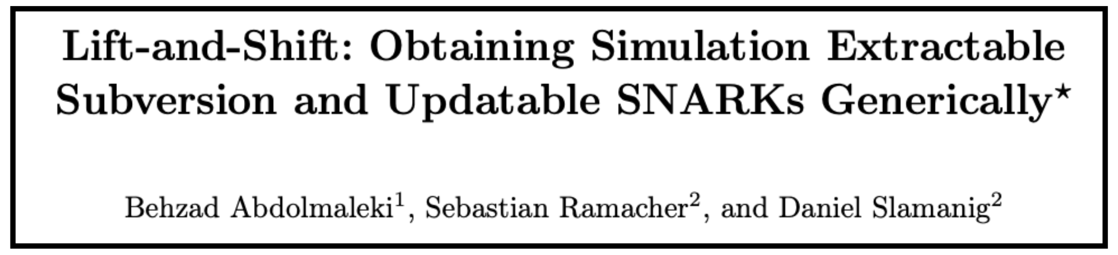
Known UC-secure zkSNARKs

Non-Witness Succinct



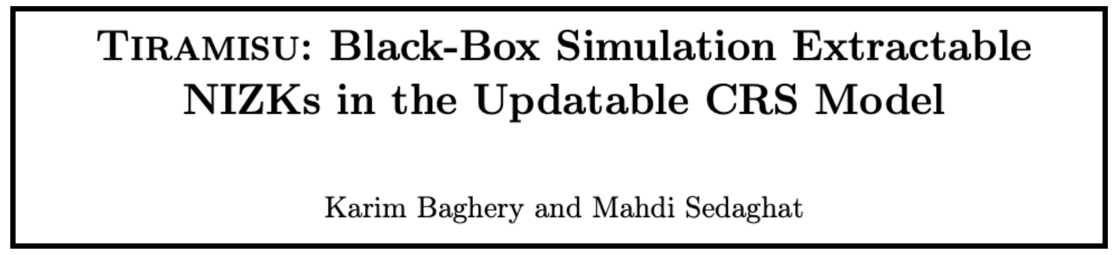
CØCØ: A Framework for Building Composable Zero-Knowledge Proofs

Ahmed Kosba[†] Zhichao Zhao[*] Andrew Miller[†] Yi Qian[‡]
T-H. Hubert Chan[*] Charalampos Papamanthou[†] Rafael Pass[‡] abhi shelat[•]
Elaine Shi[‡]



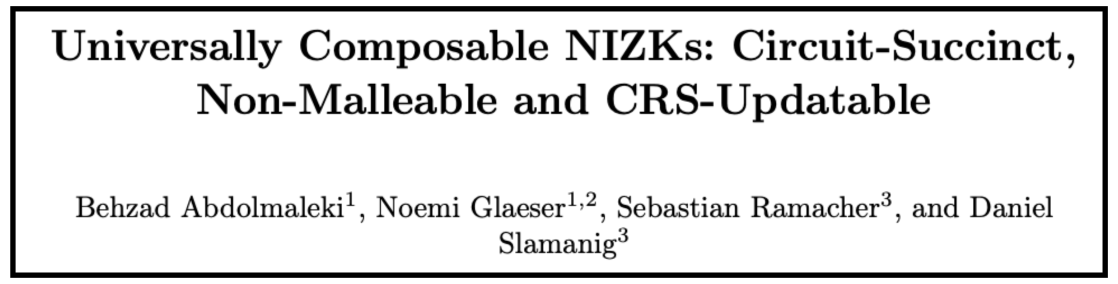
Lift-and-Shift: Obtaining Simulation Extractable Subversion and Updatable SNARKs Generically[⋆]

Behzad Abdolmaleki[1], Sebastian Ramacher[2], and Daniel Slamanig[2]



Tiramisu: Black-Box Simulation Extractable NIZKs in the Updatable CRS Model

Karim Baghery and Mahdi Sedaghat



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Encrypt witness

Witness Succinct

Related works

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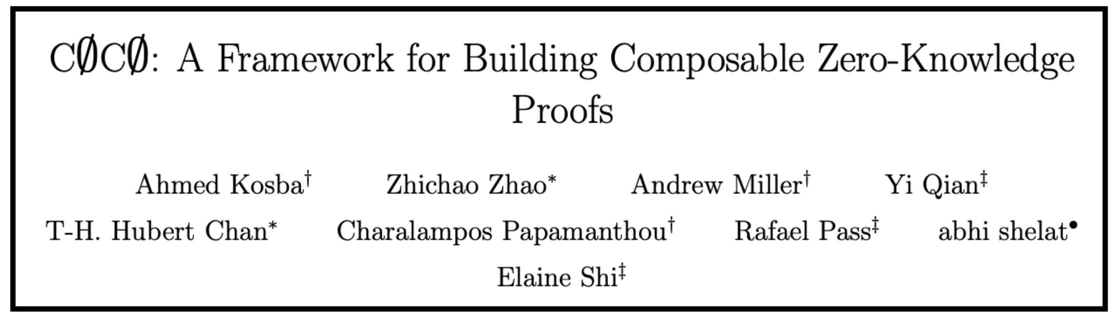
Non-Witness Succinct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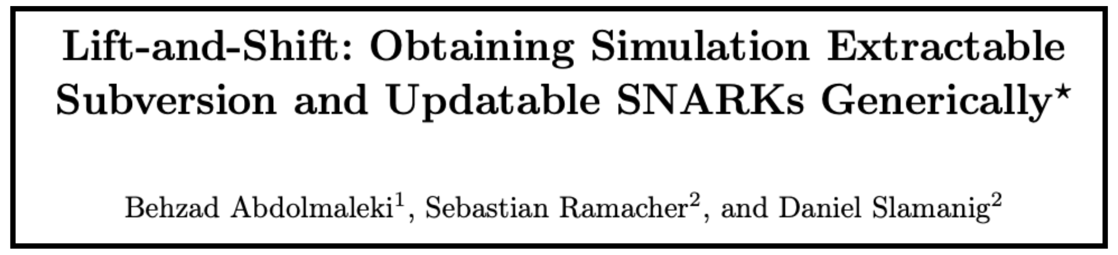
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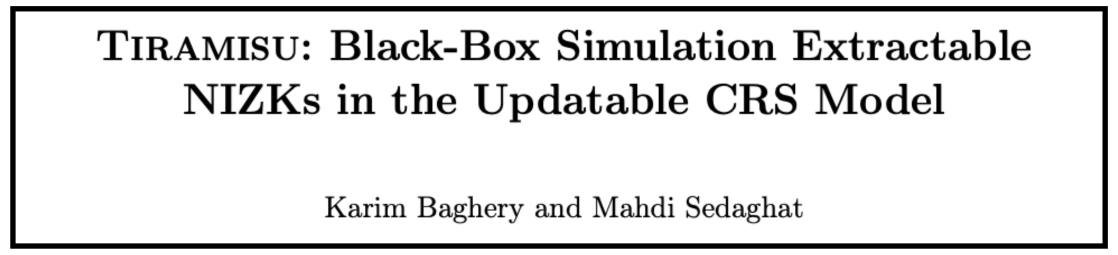
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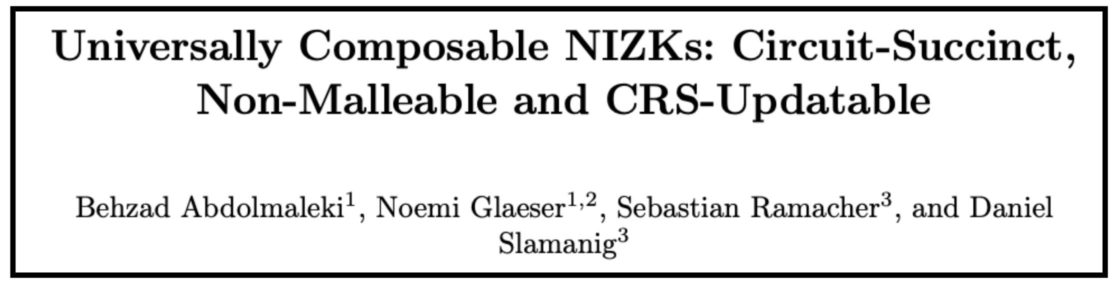
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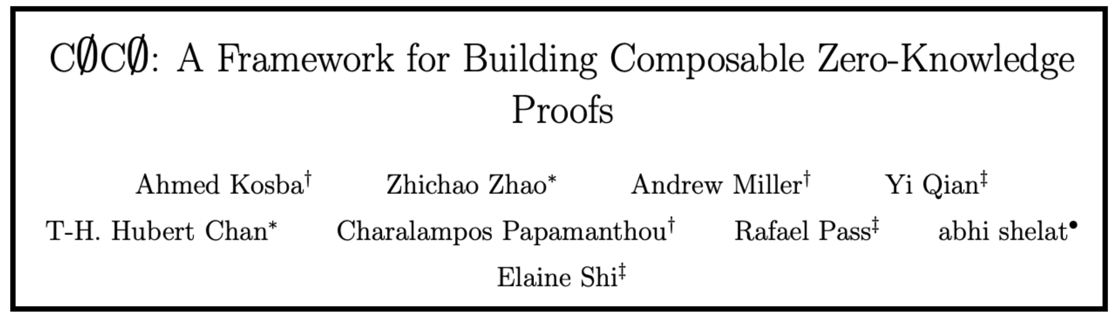

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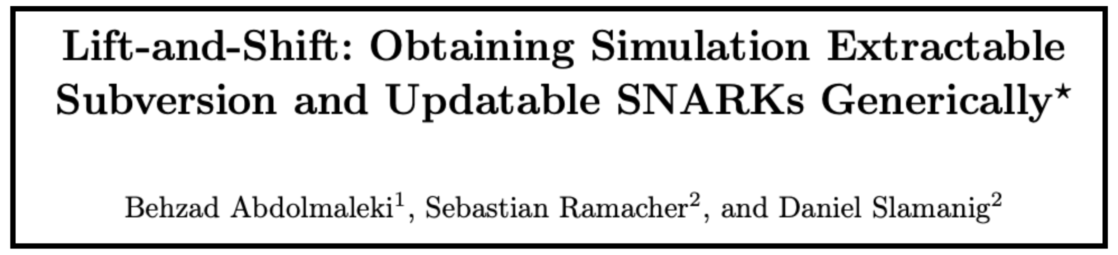

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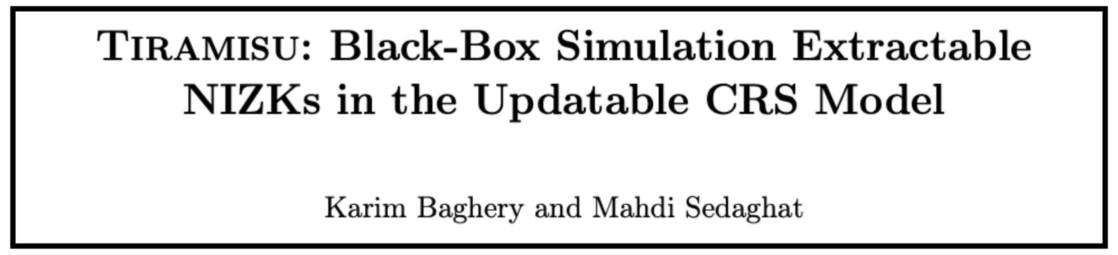

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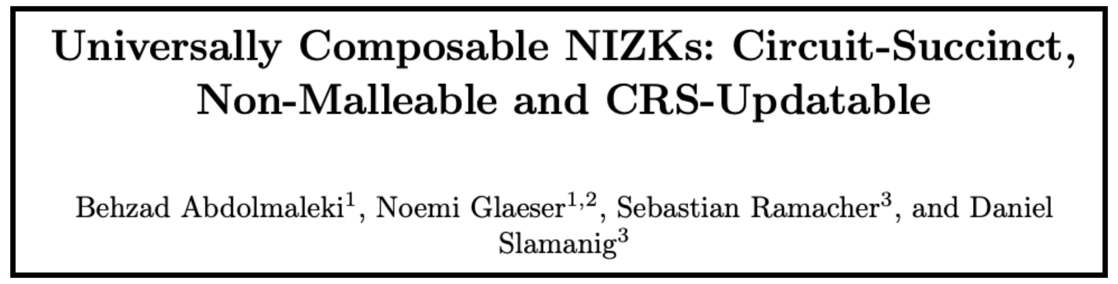

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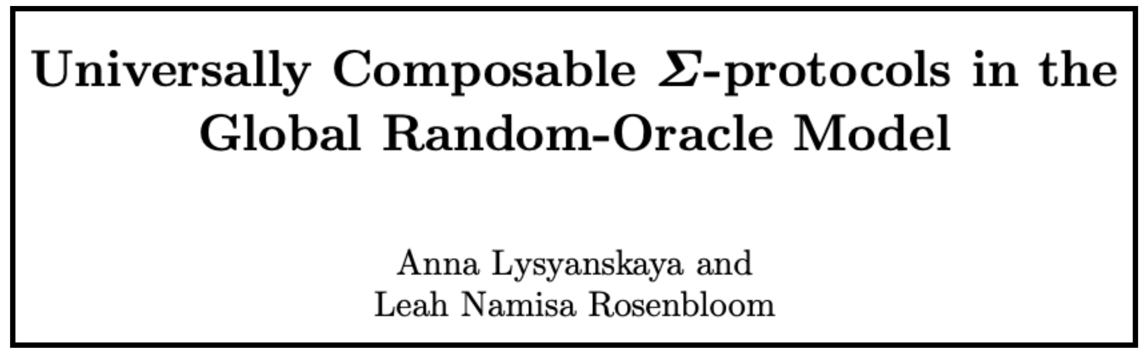

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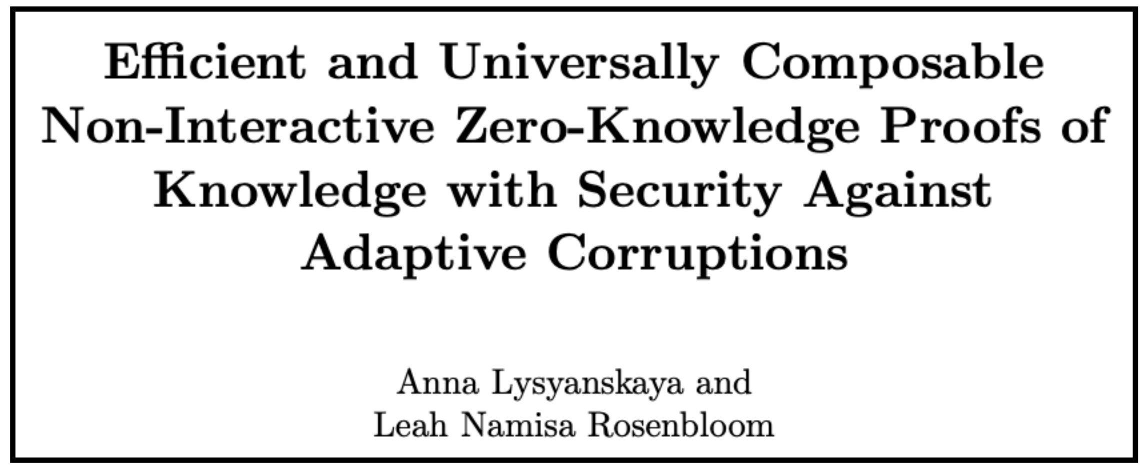

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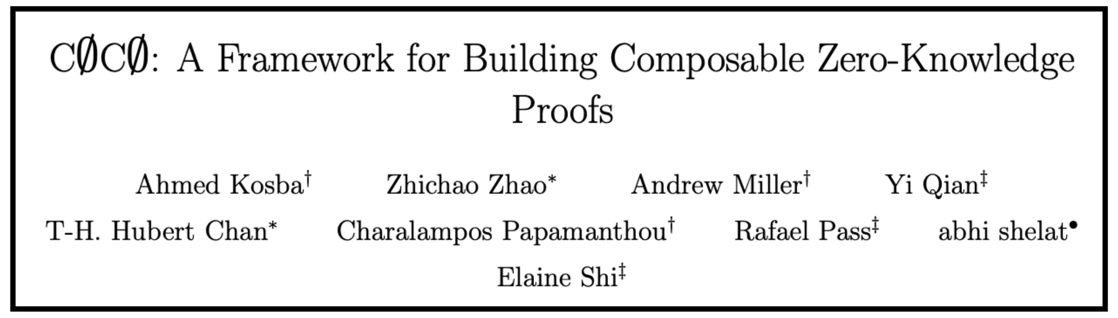

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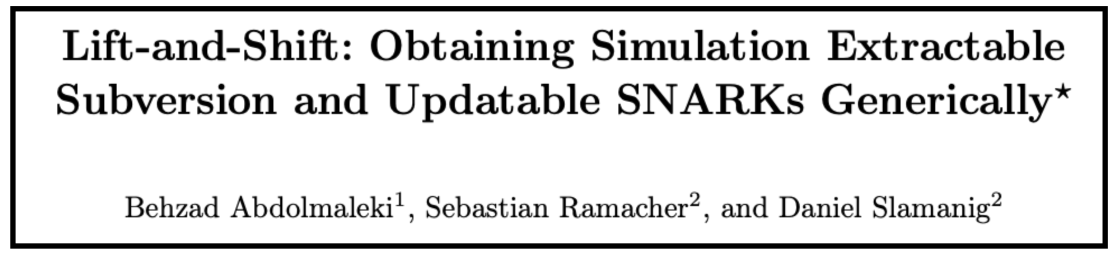

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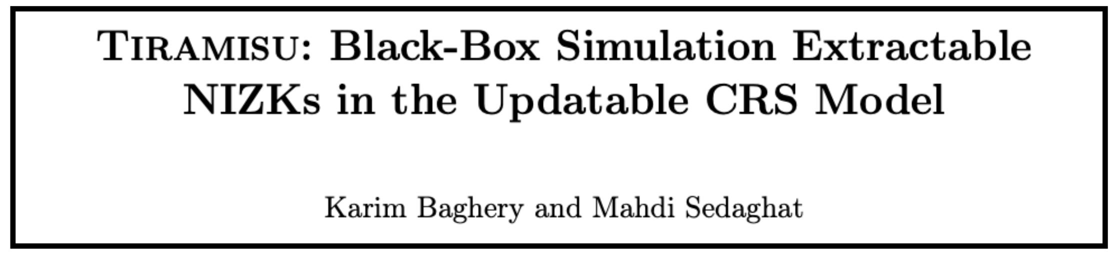

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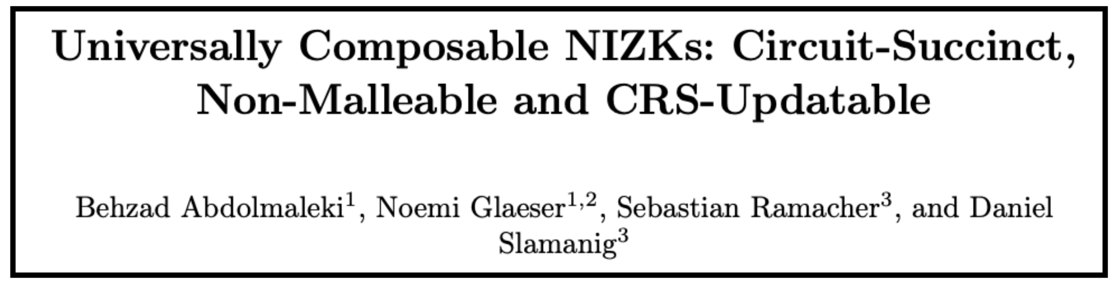

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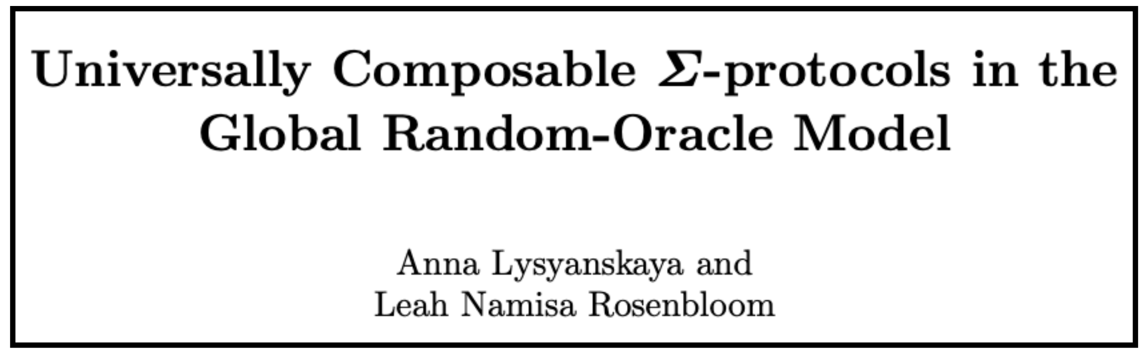

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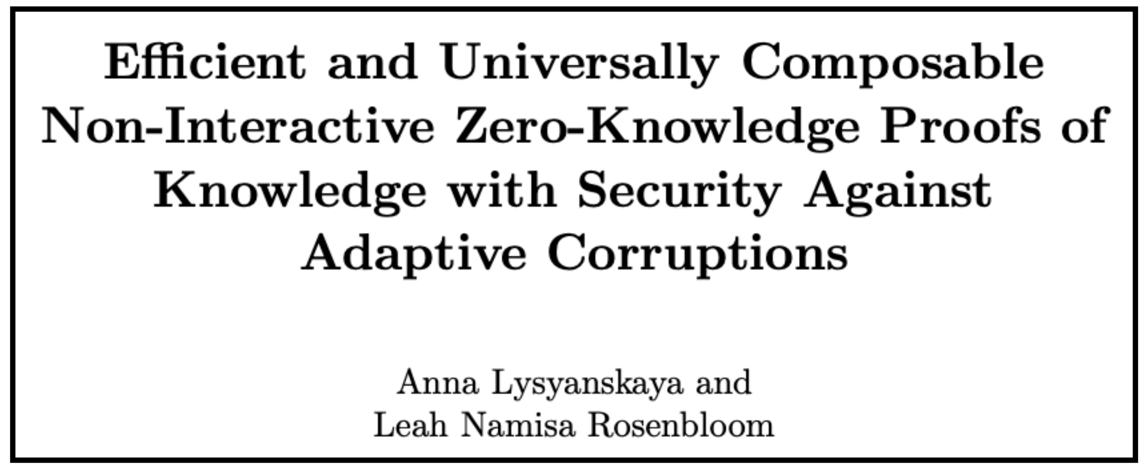

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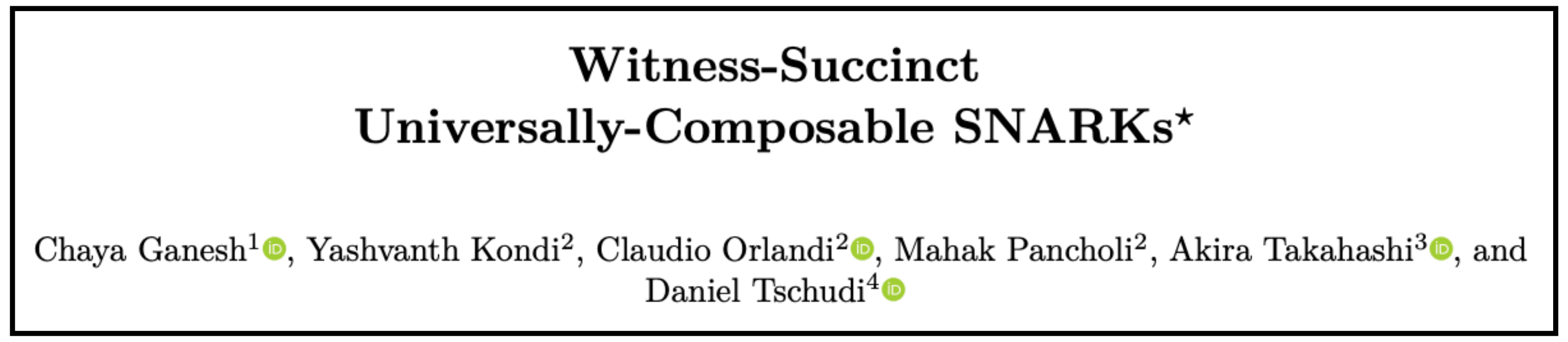

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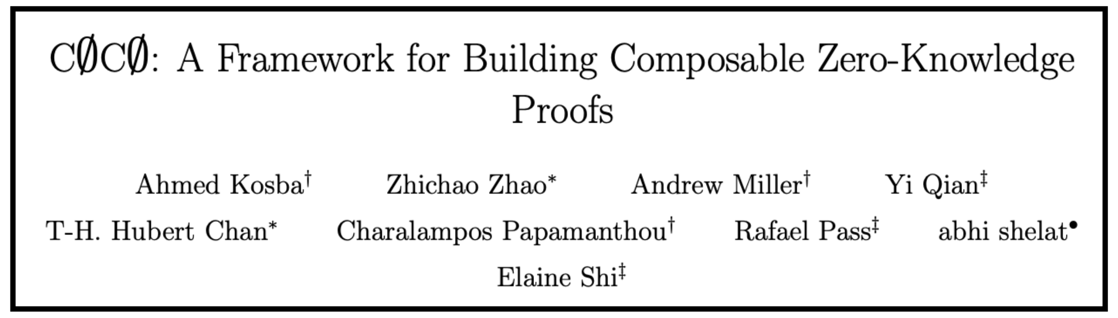

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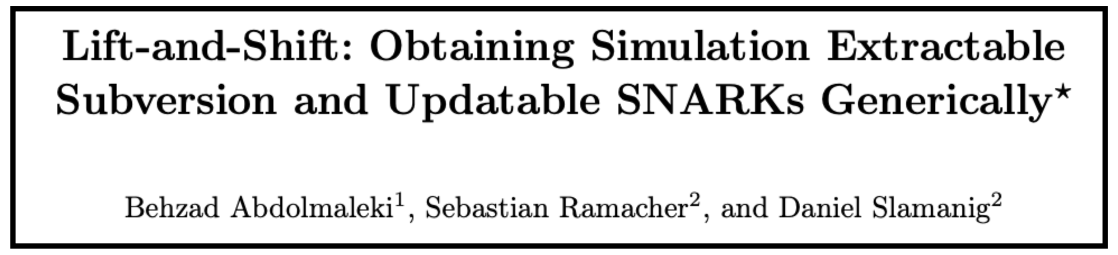

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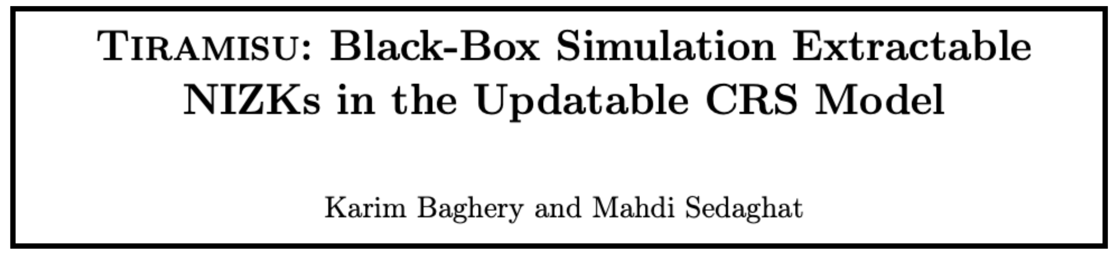

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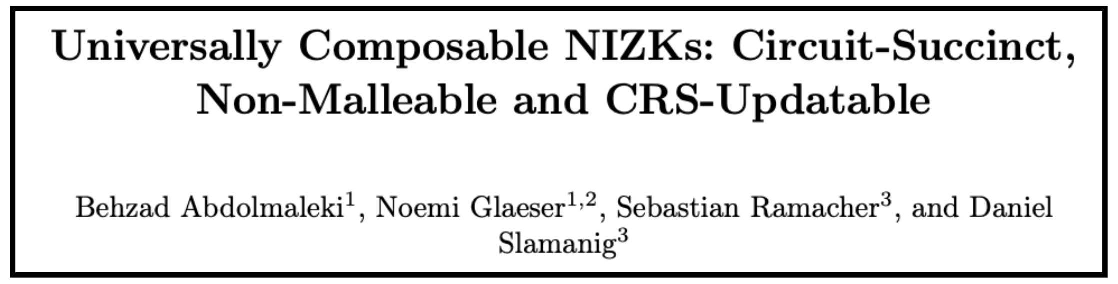

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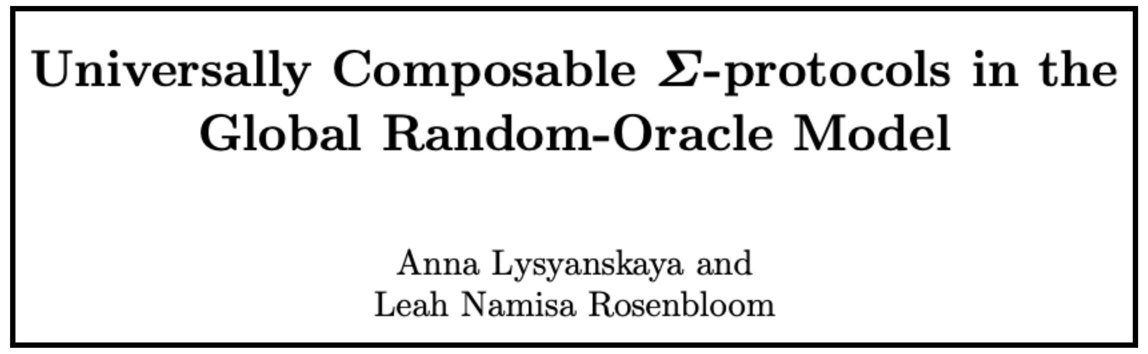

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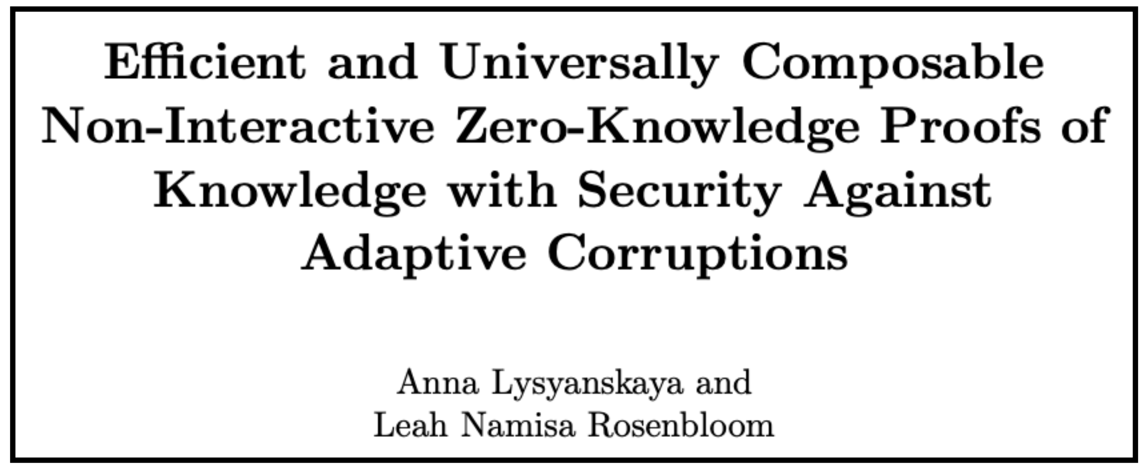

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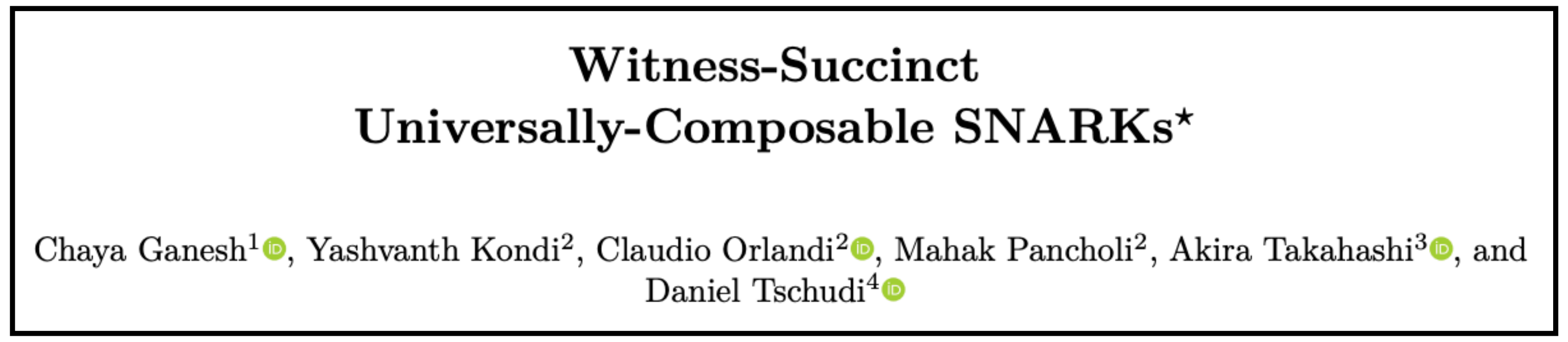

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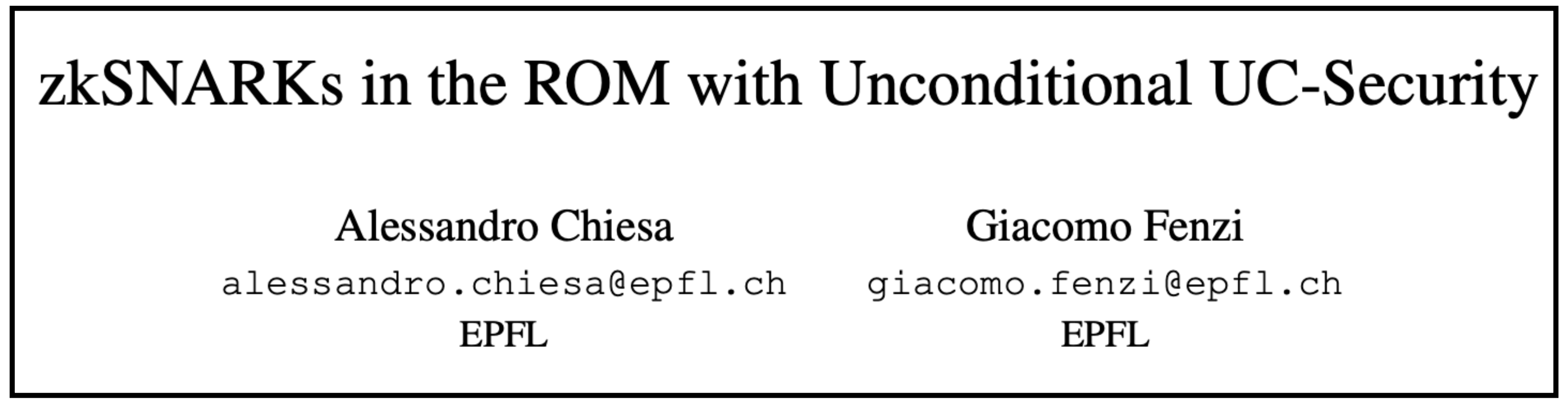

zkSNARKs in the ROM with Unconditional UC-Security

Alessandro Chiesa
alessandro.chiesa@epfl.ch
EPFL

Giacomo Fenzi
giacomo.fenzi@epfl.ch
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This work!

Challenge I

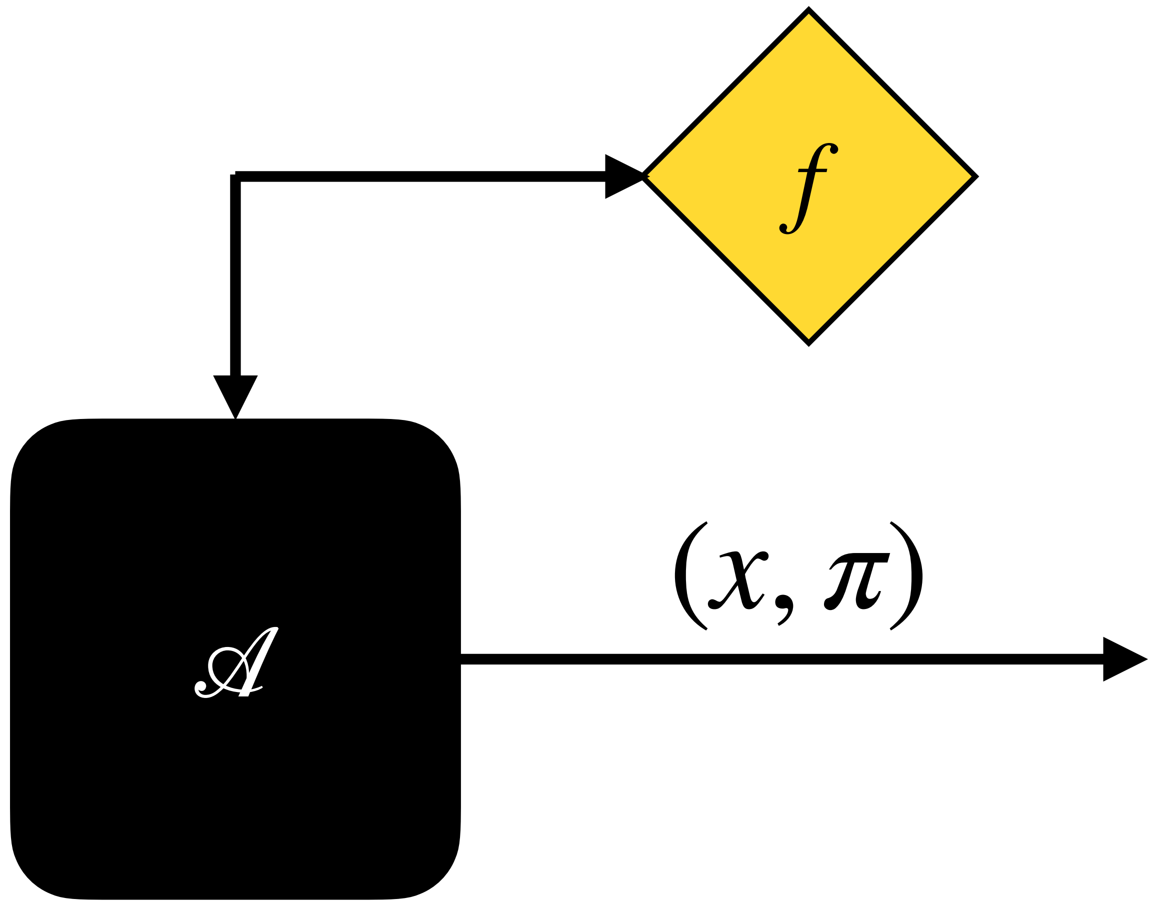
Challenge I

Rewinding

extractor

Challenge I

Rewinding extractor



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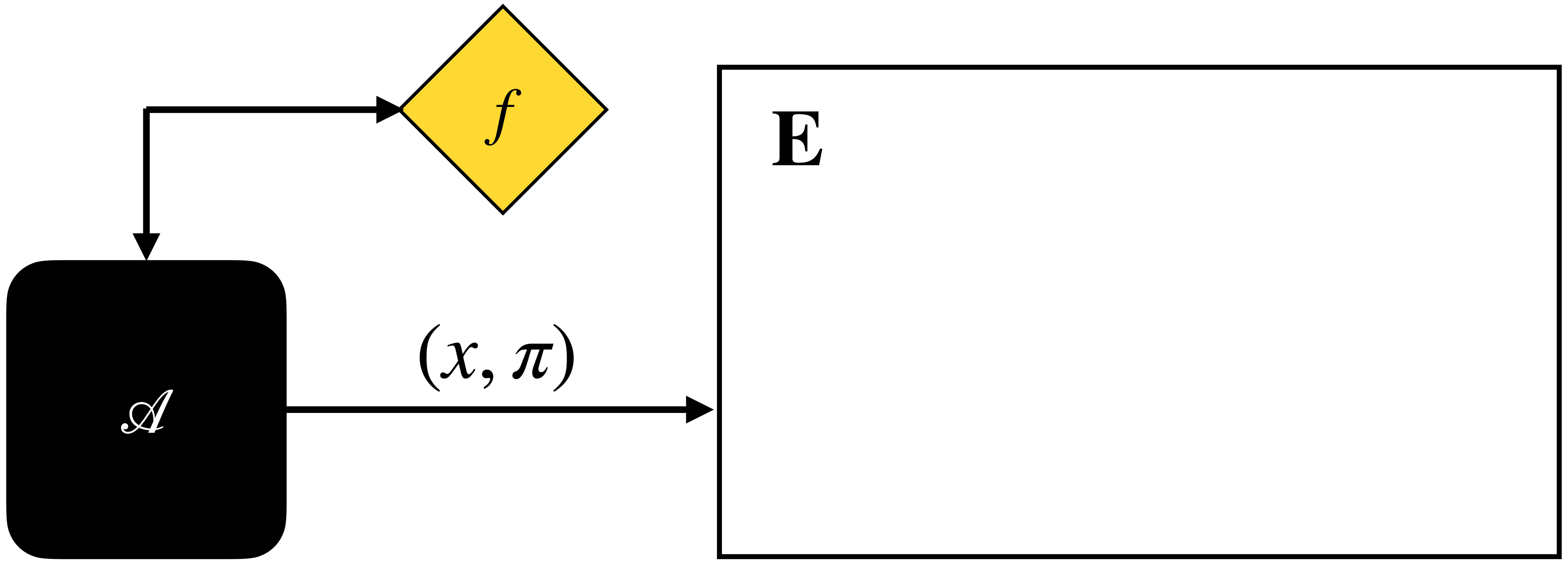
Rewinding extractor



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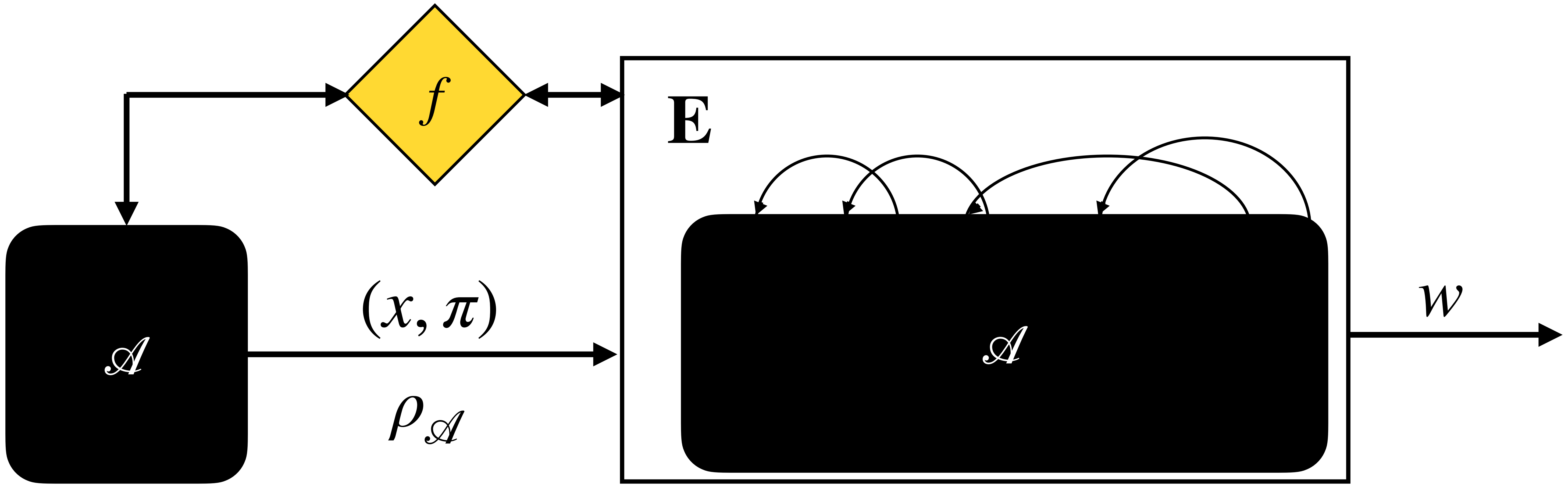

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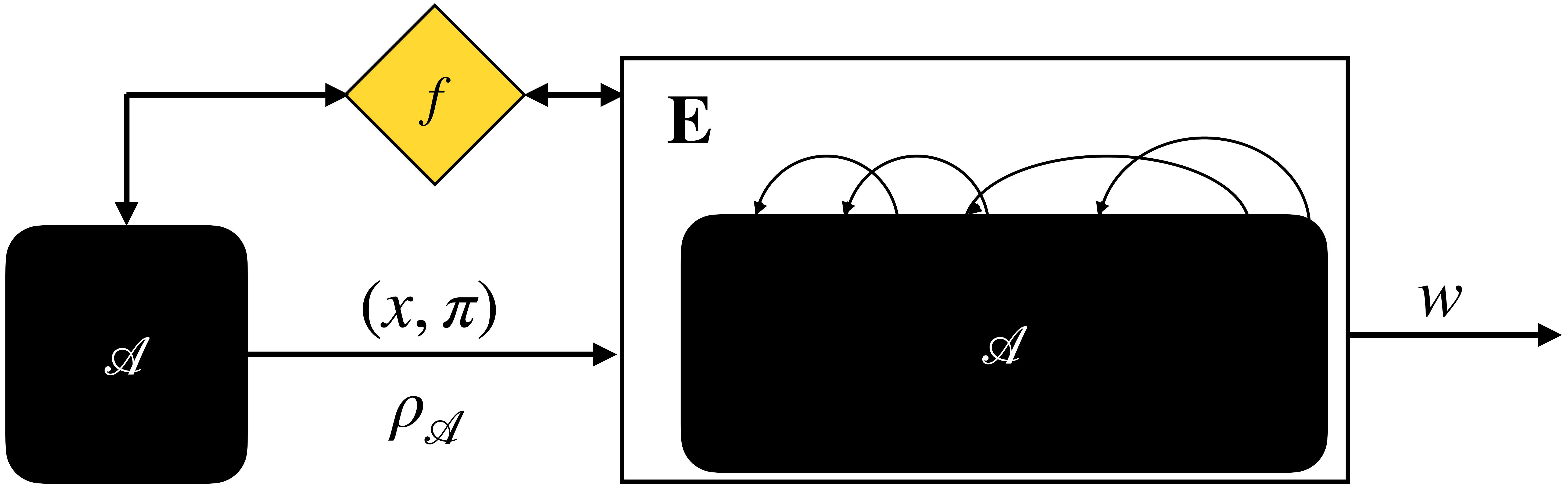

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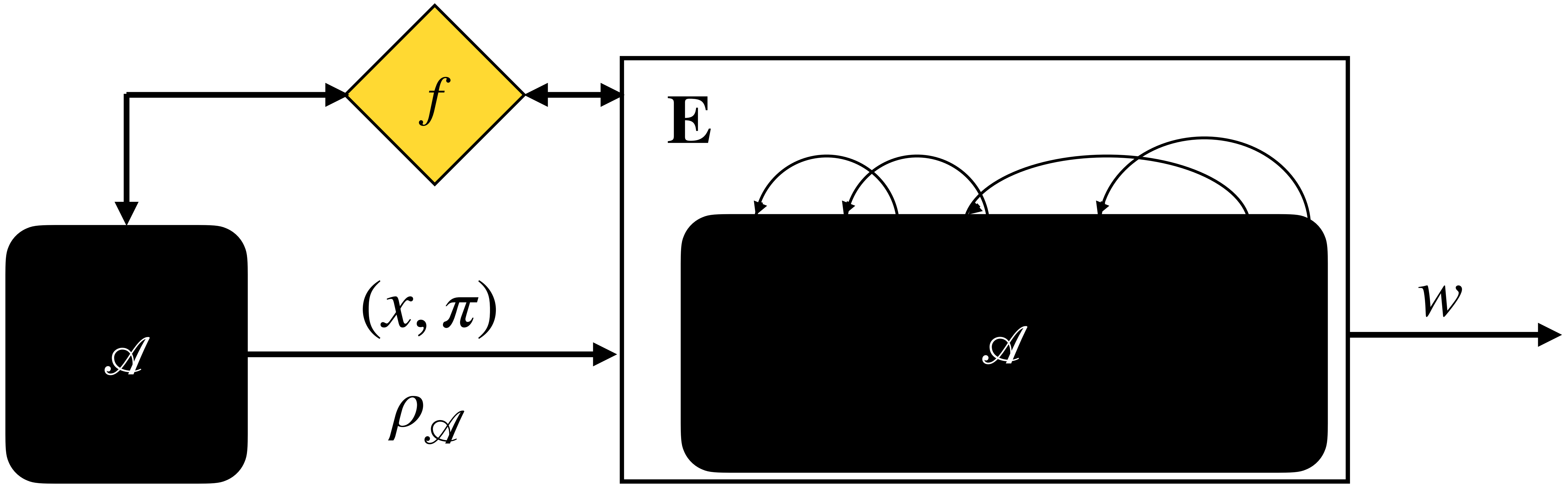

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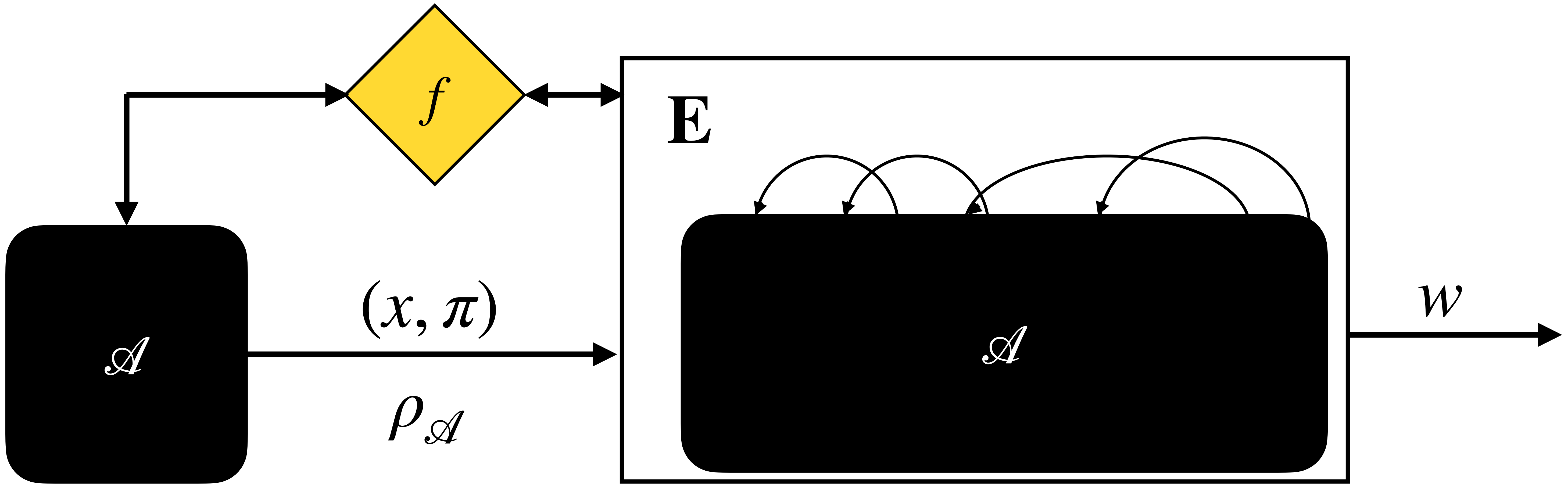

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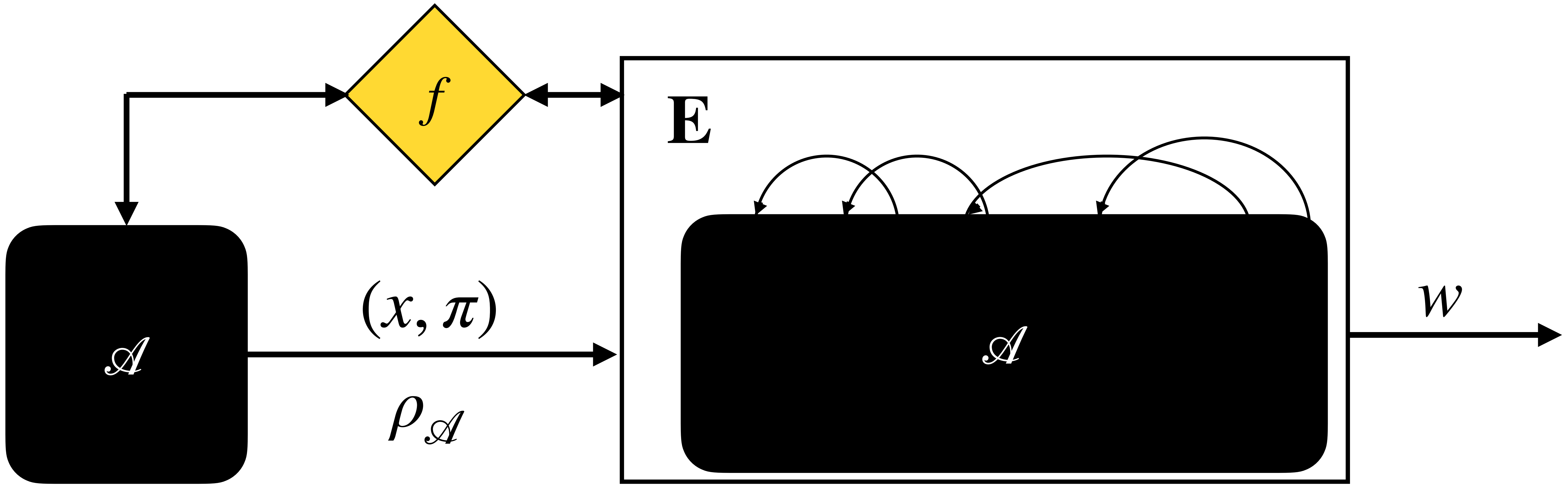

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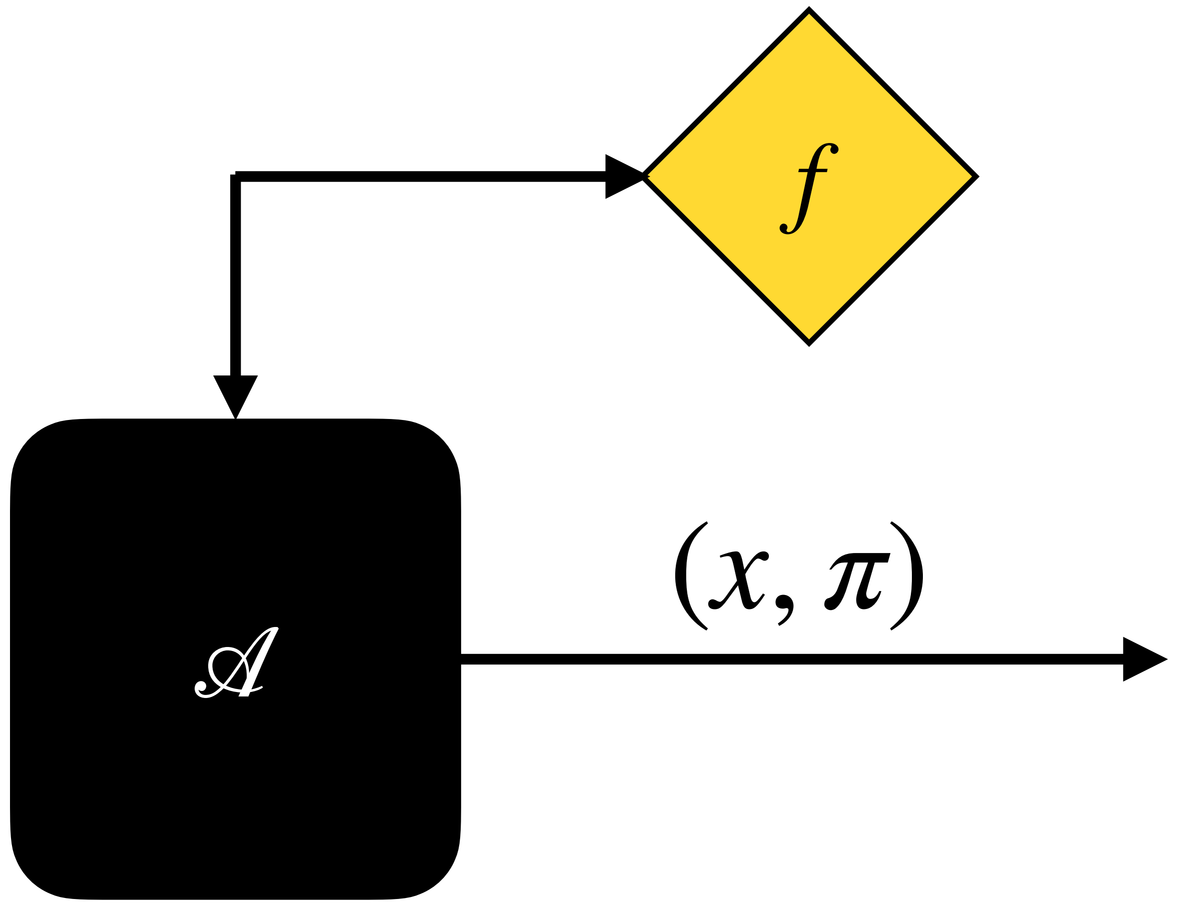

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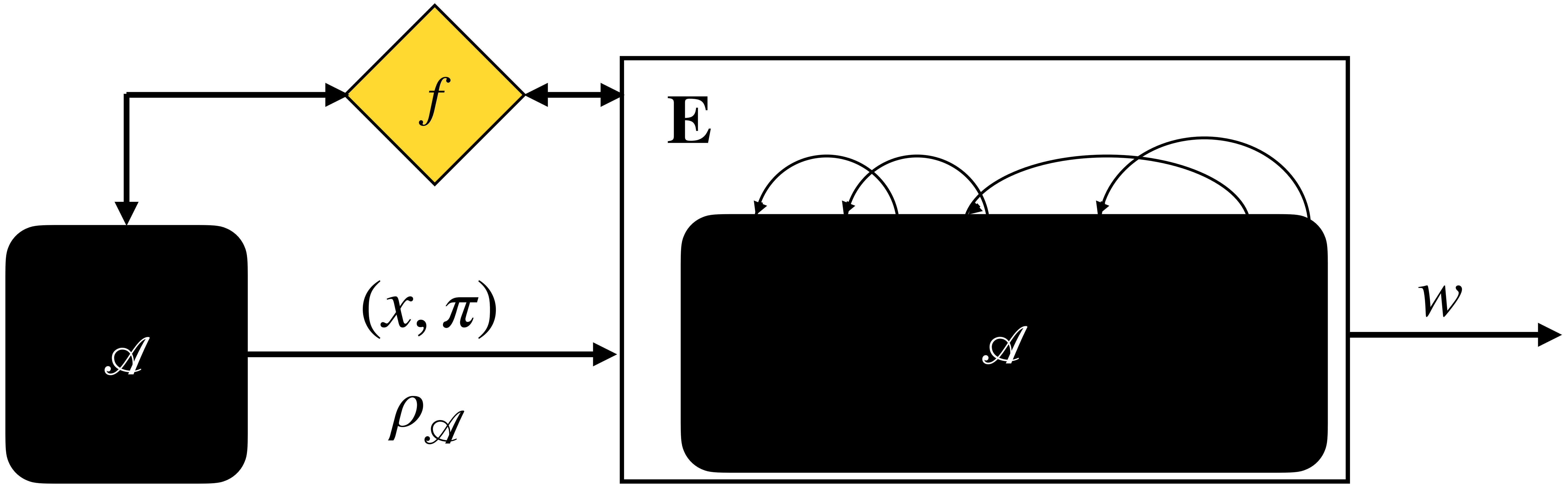

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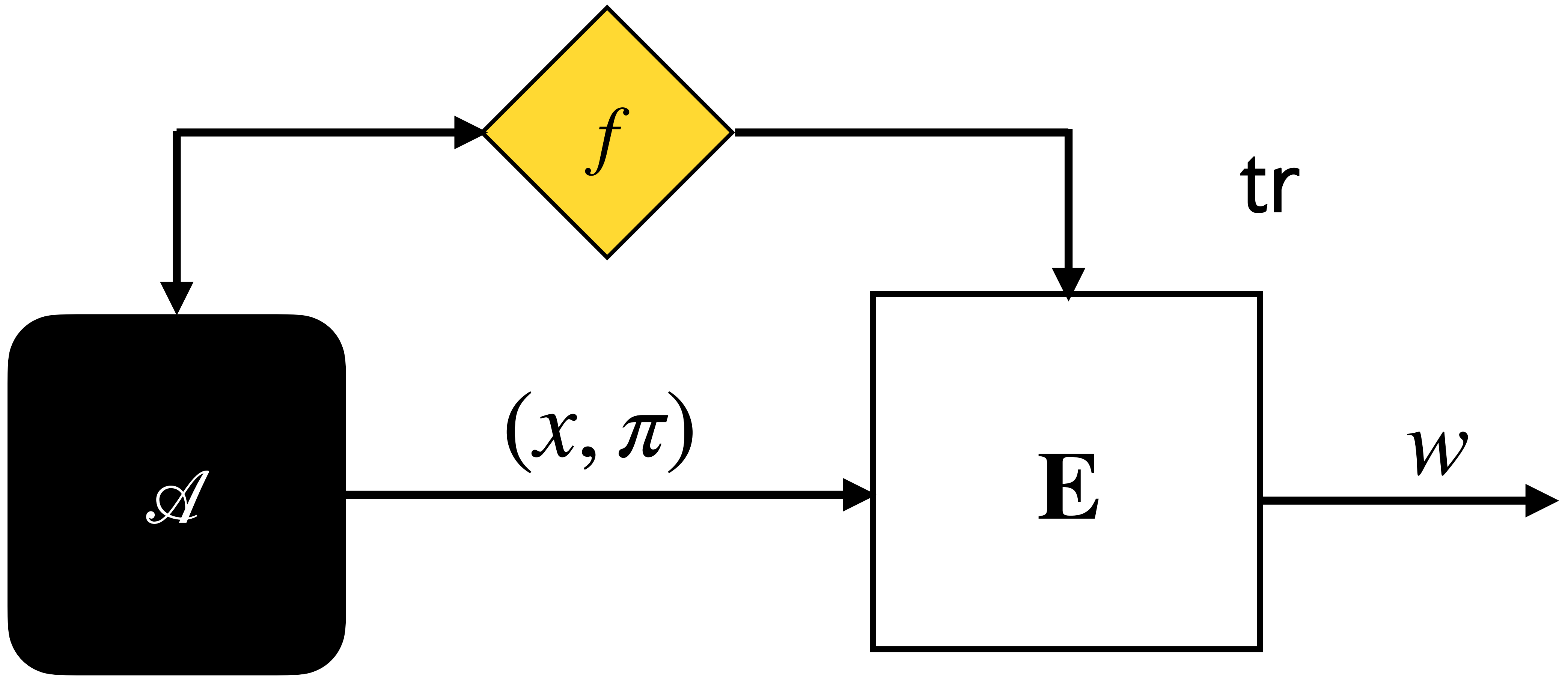

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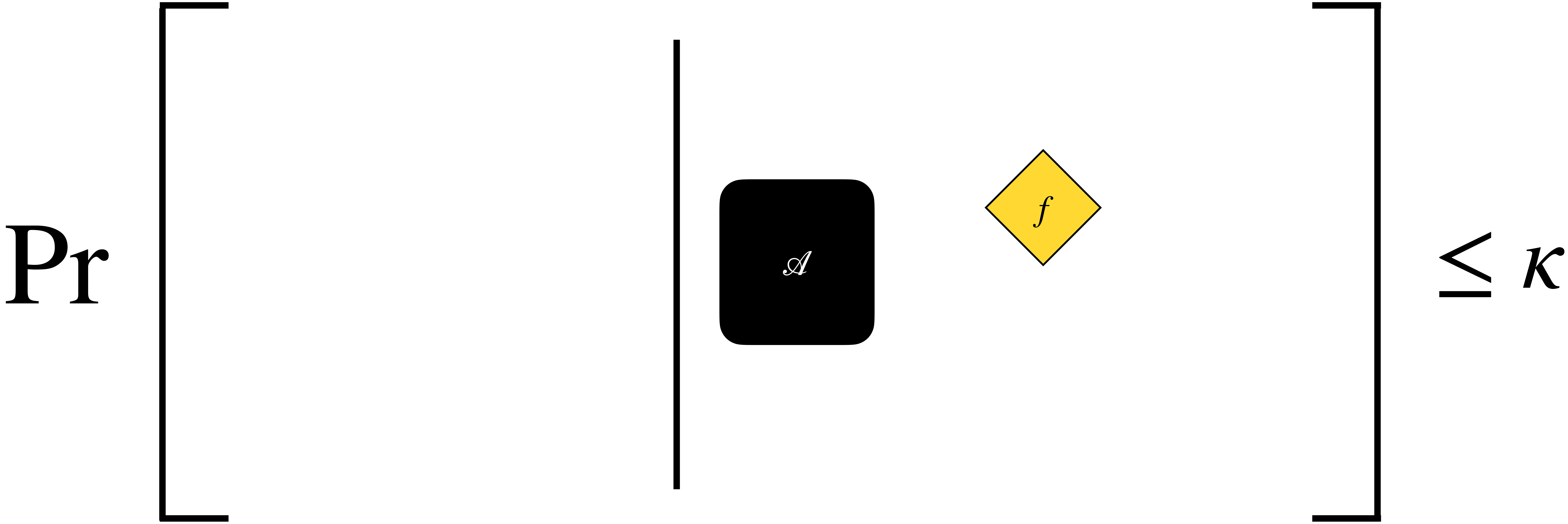

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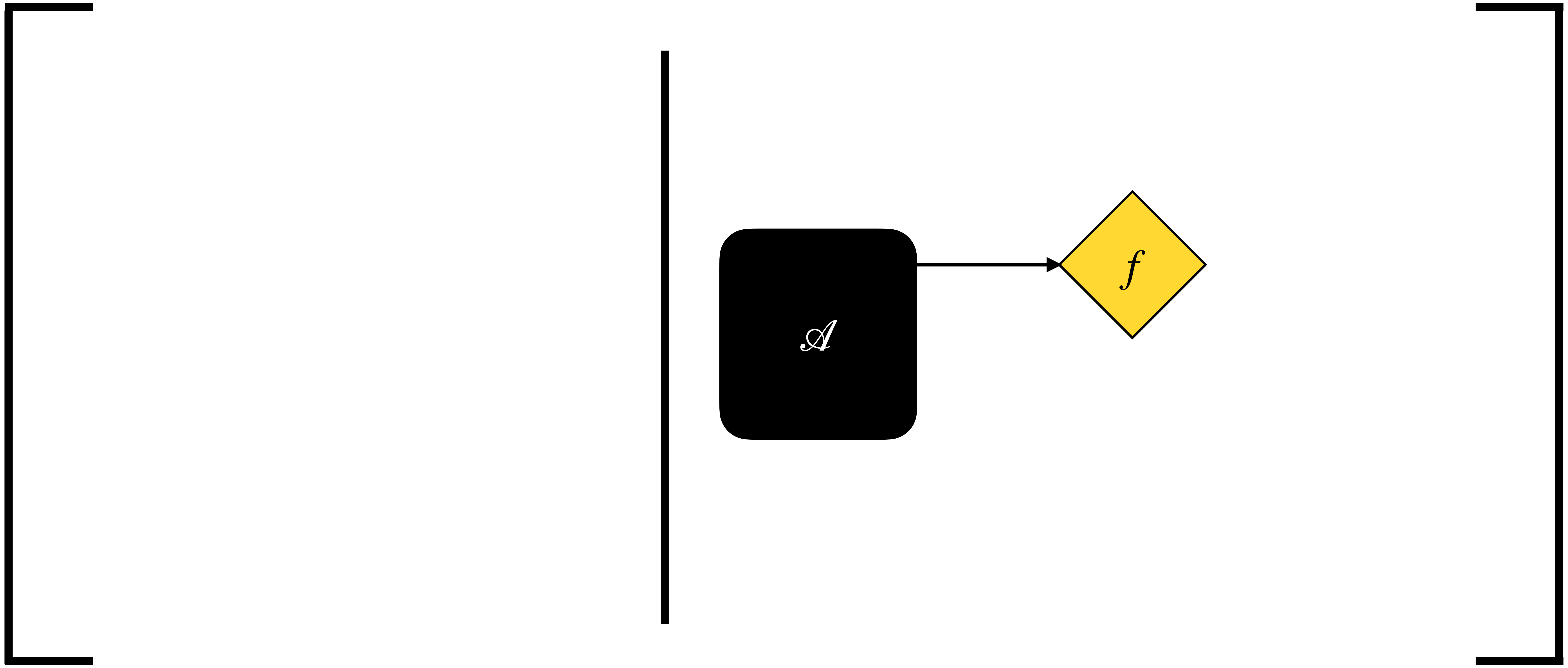

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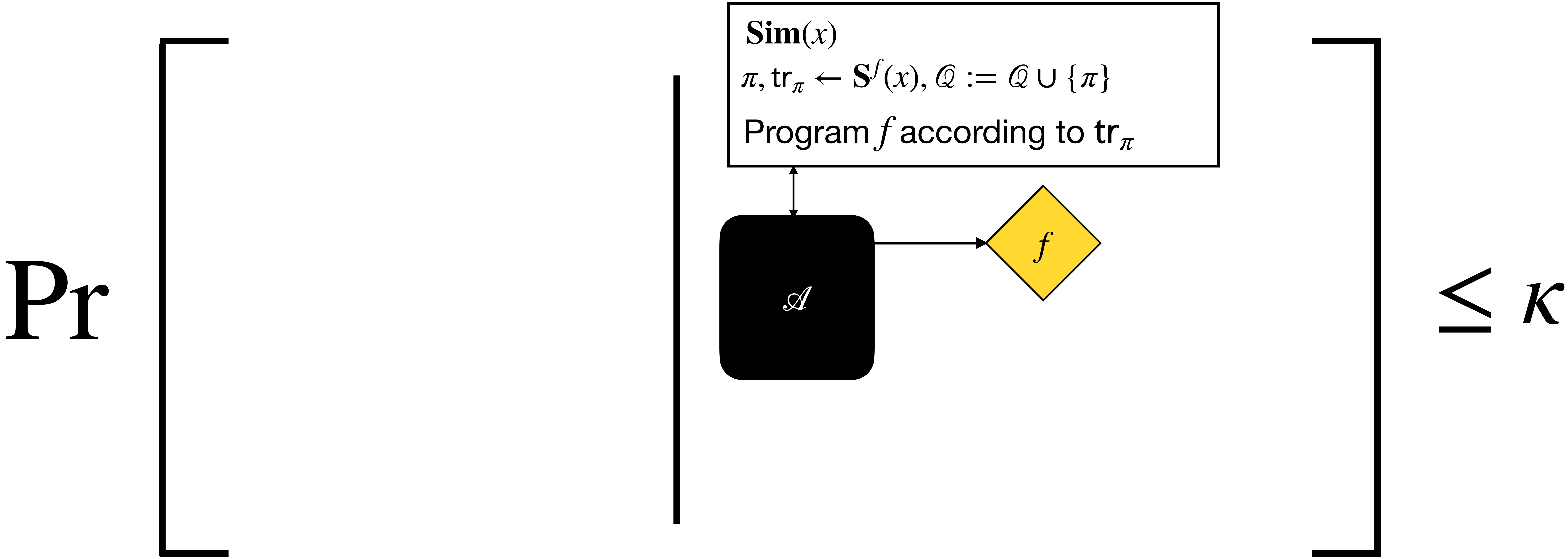

$\mathbf{Sim}(x)$

$\pi, \mathsf{tr}_\pi \leftarrow \mathbf{S}^f(x), \mathscr{Q} := \mathscr{Q} \cup \{\pi\}$

Program f according to tr_π

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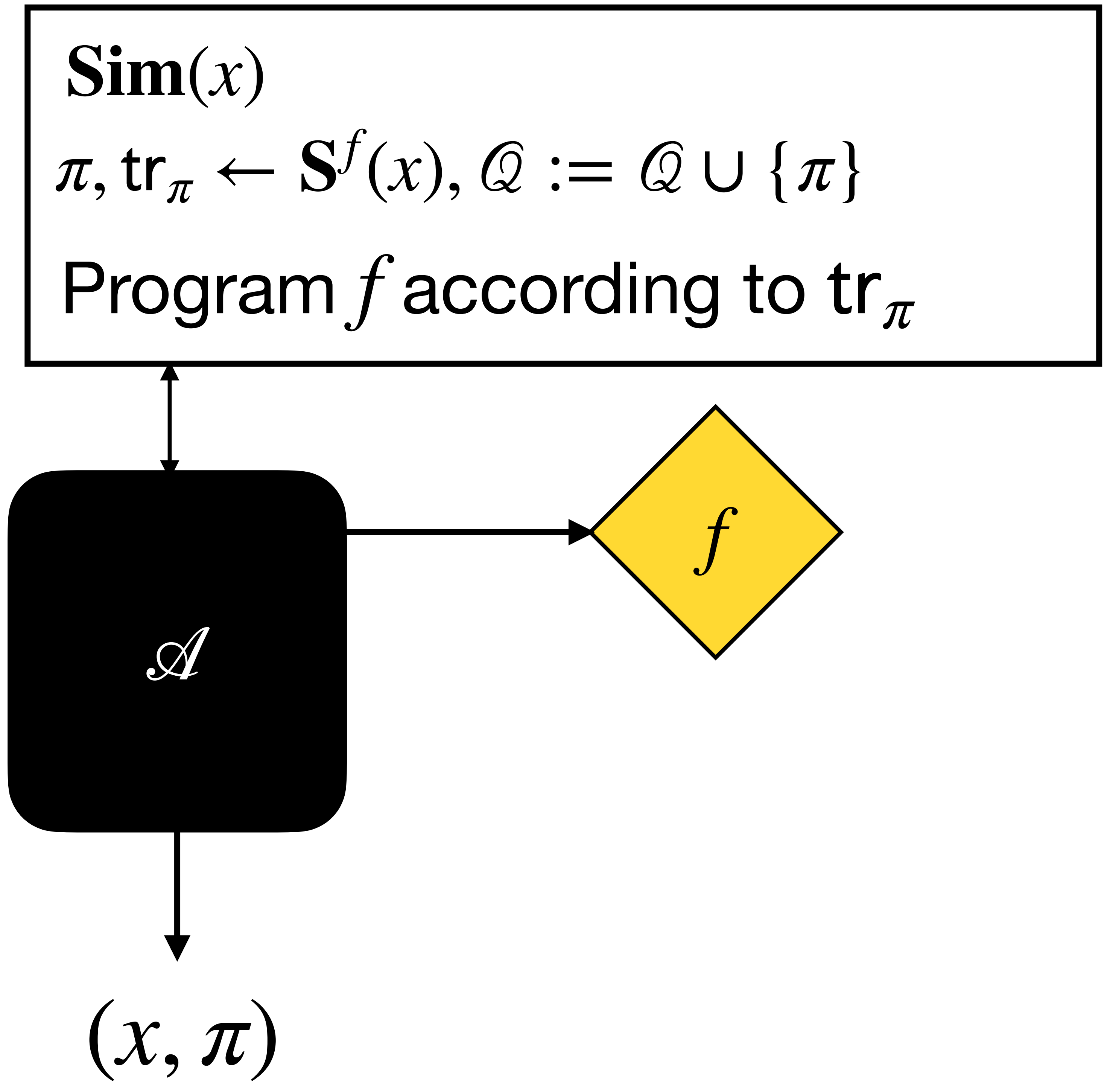

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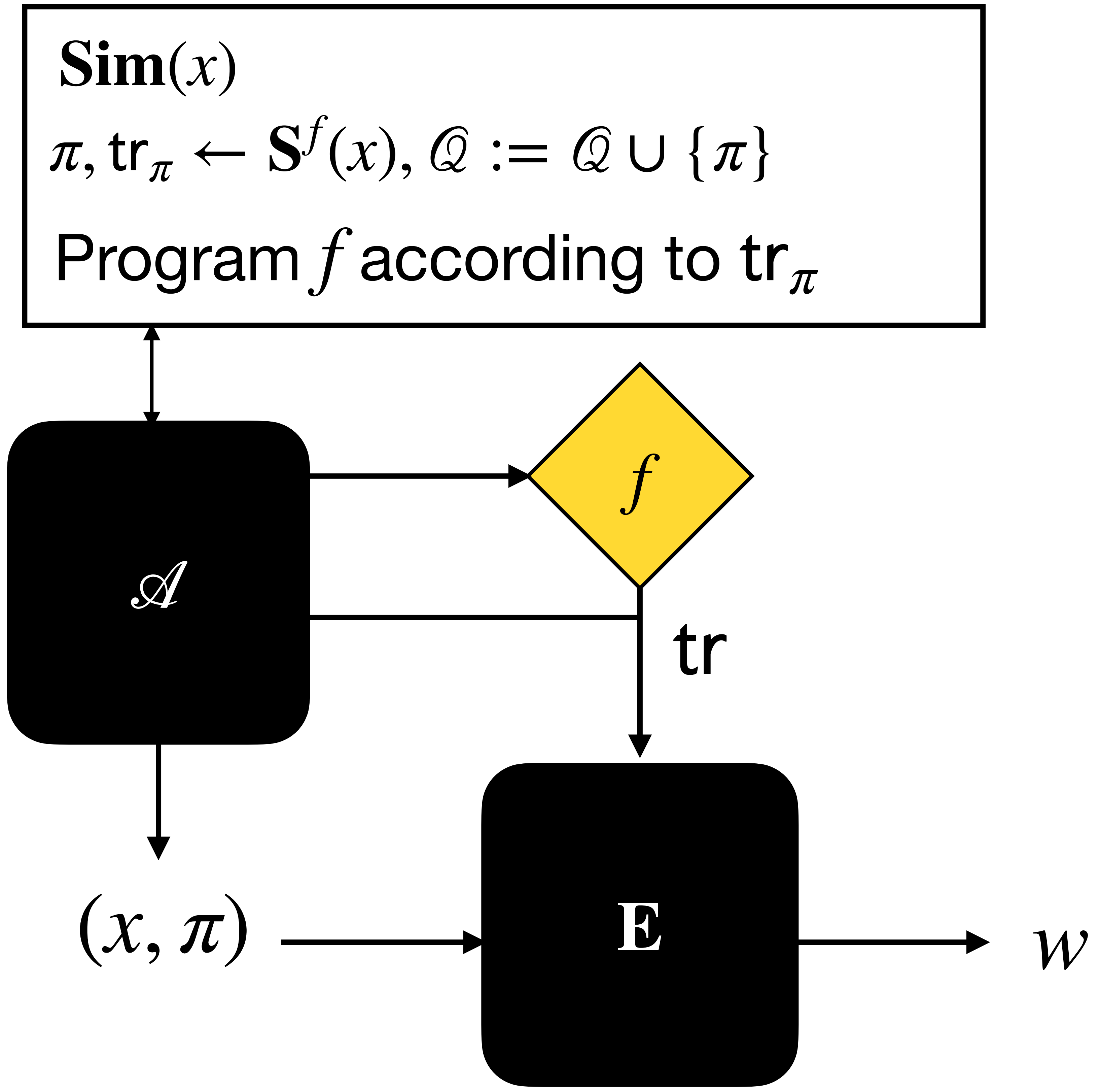

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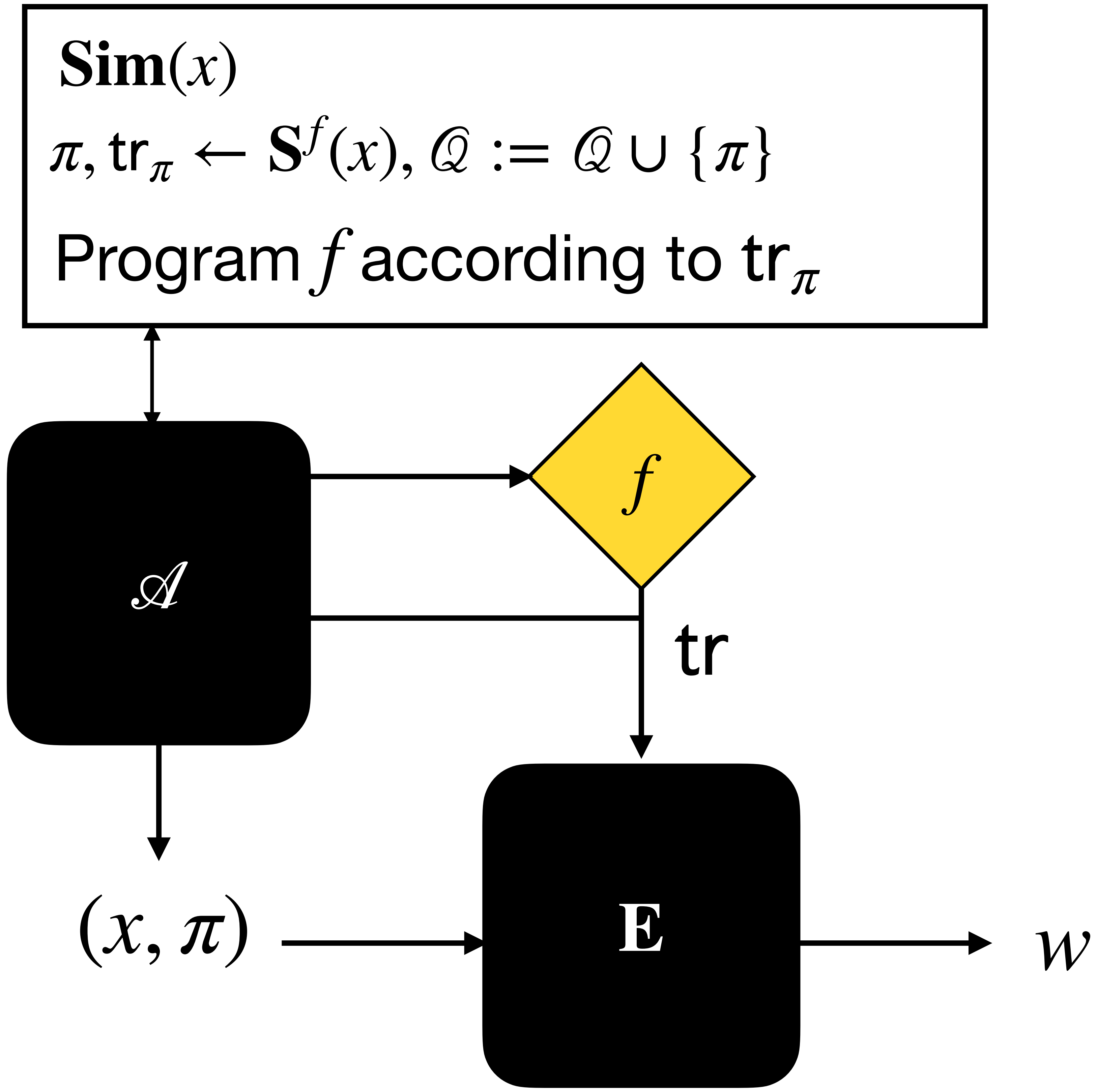
$$\Pr\left[\begin{array}{c} \mathbf{V}^f(x,\pi) = 1 \\ (x,w) \notin R \\ \pi \notin \mathscr{Q} \end{array}\ \middle|\right.$$



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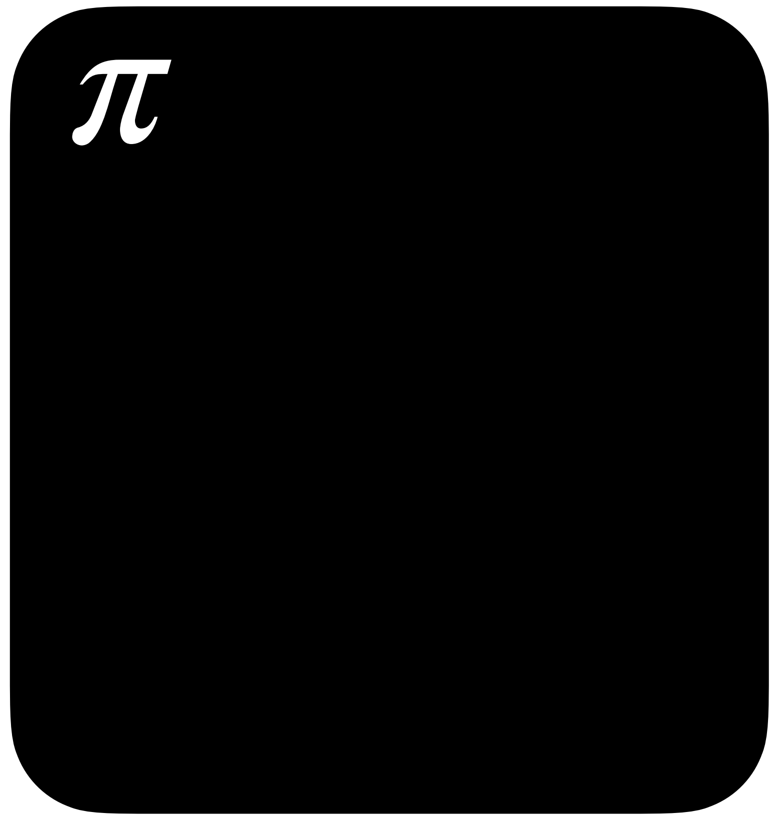

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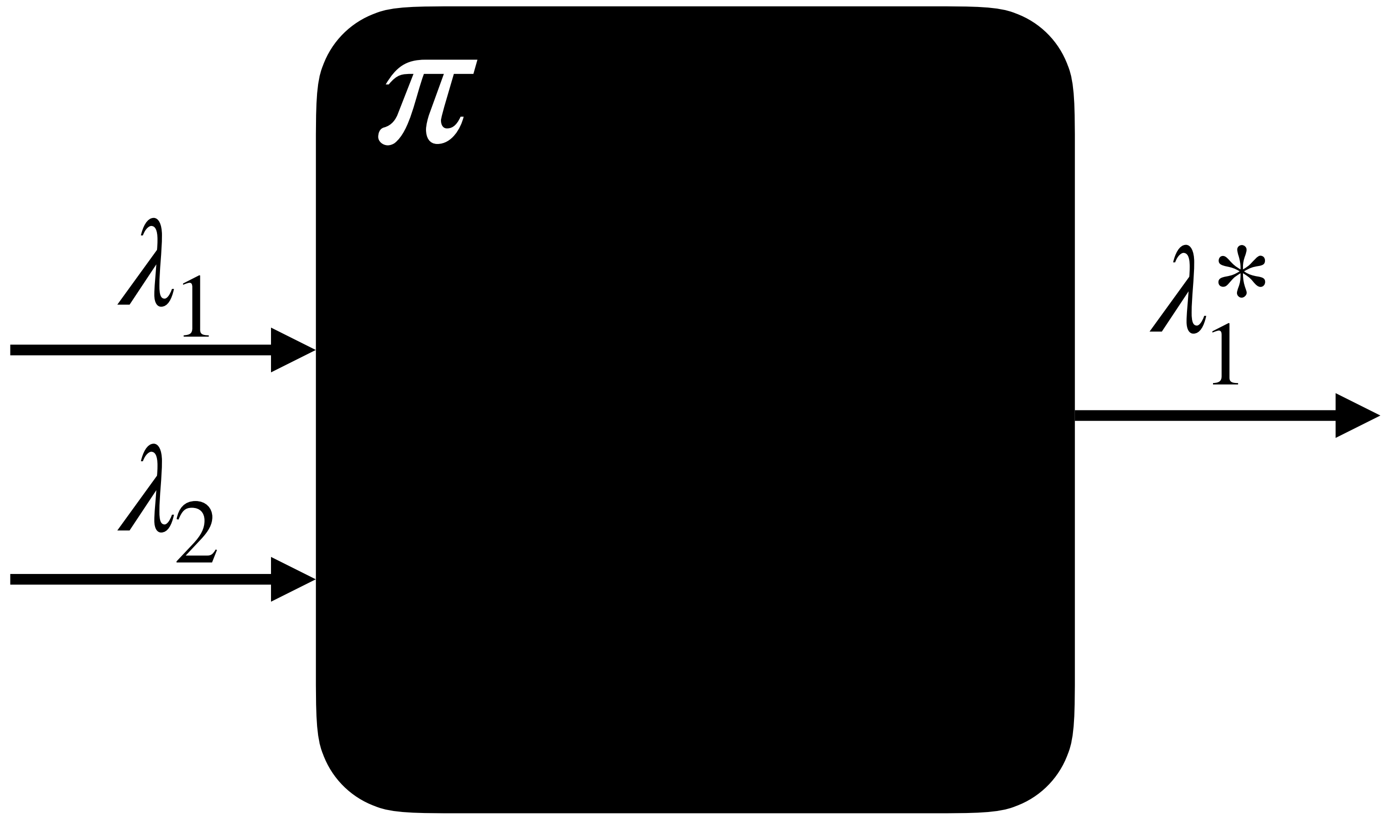

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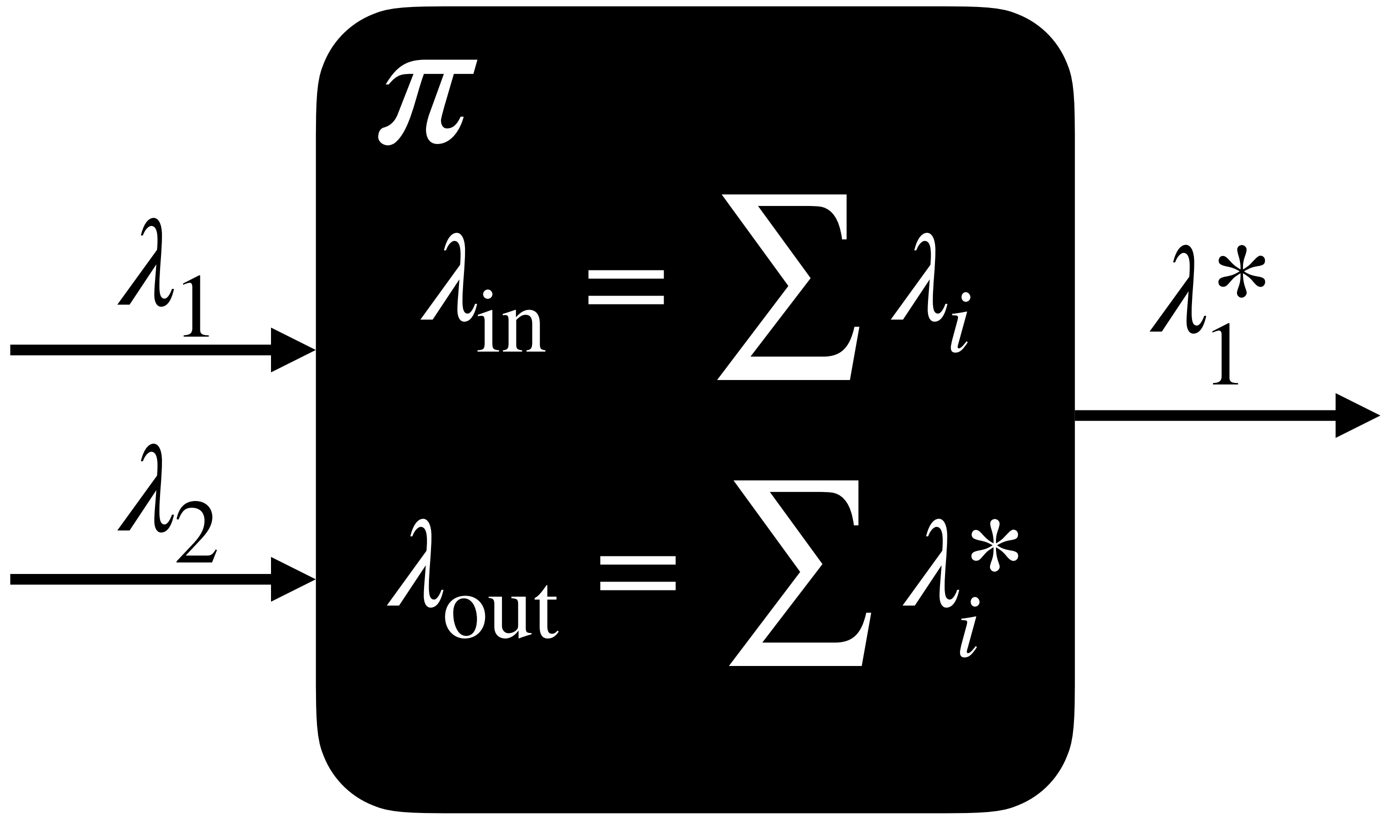

π
λ_1
λ_2
$\lambda_{\text{in}} = \sum \lambda_i$
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λ_1^*

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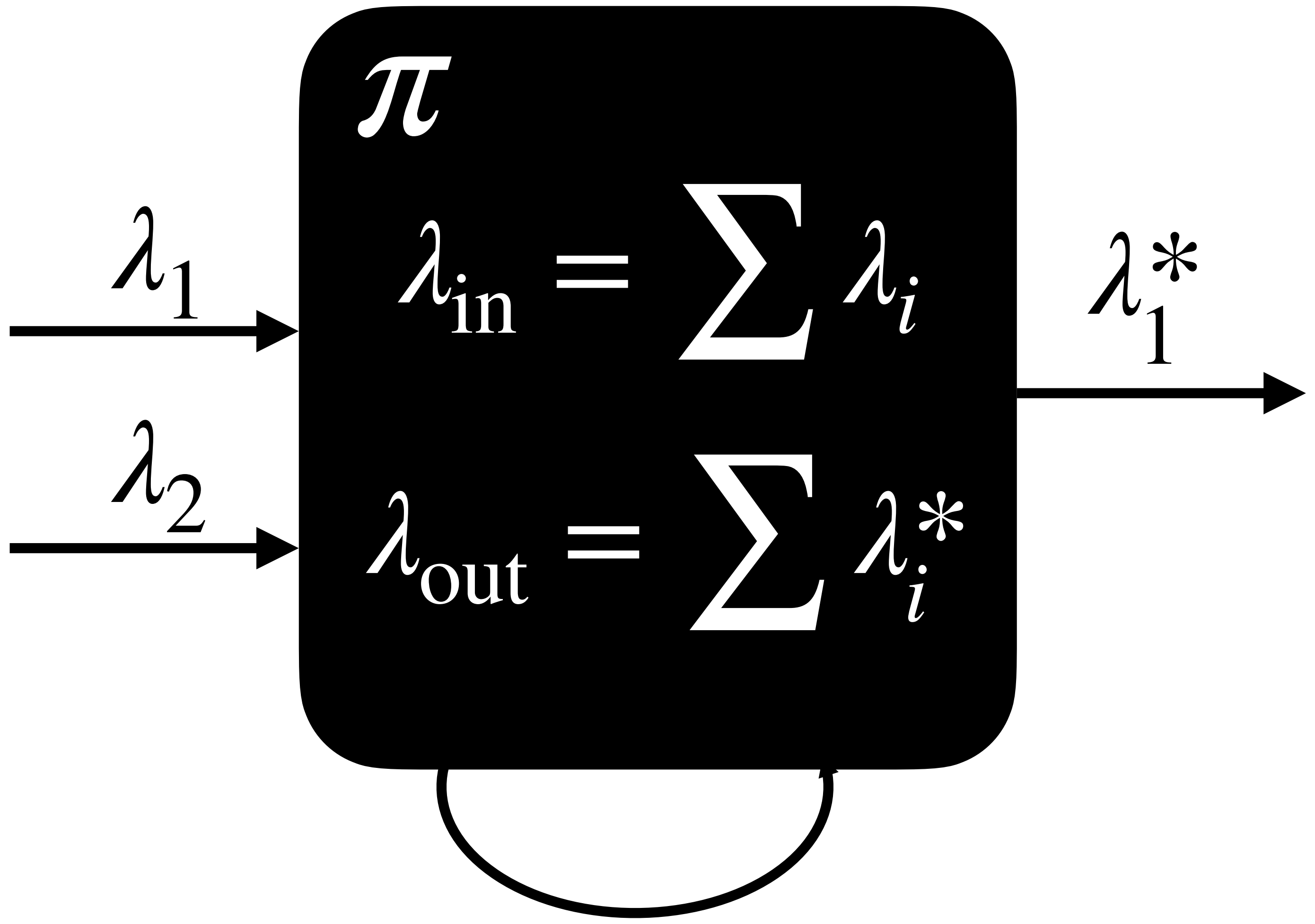
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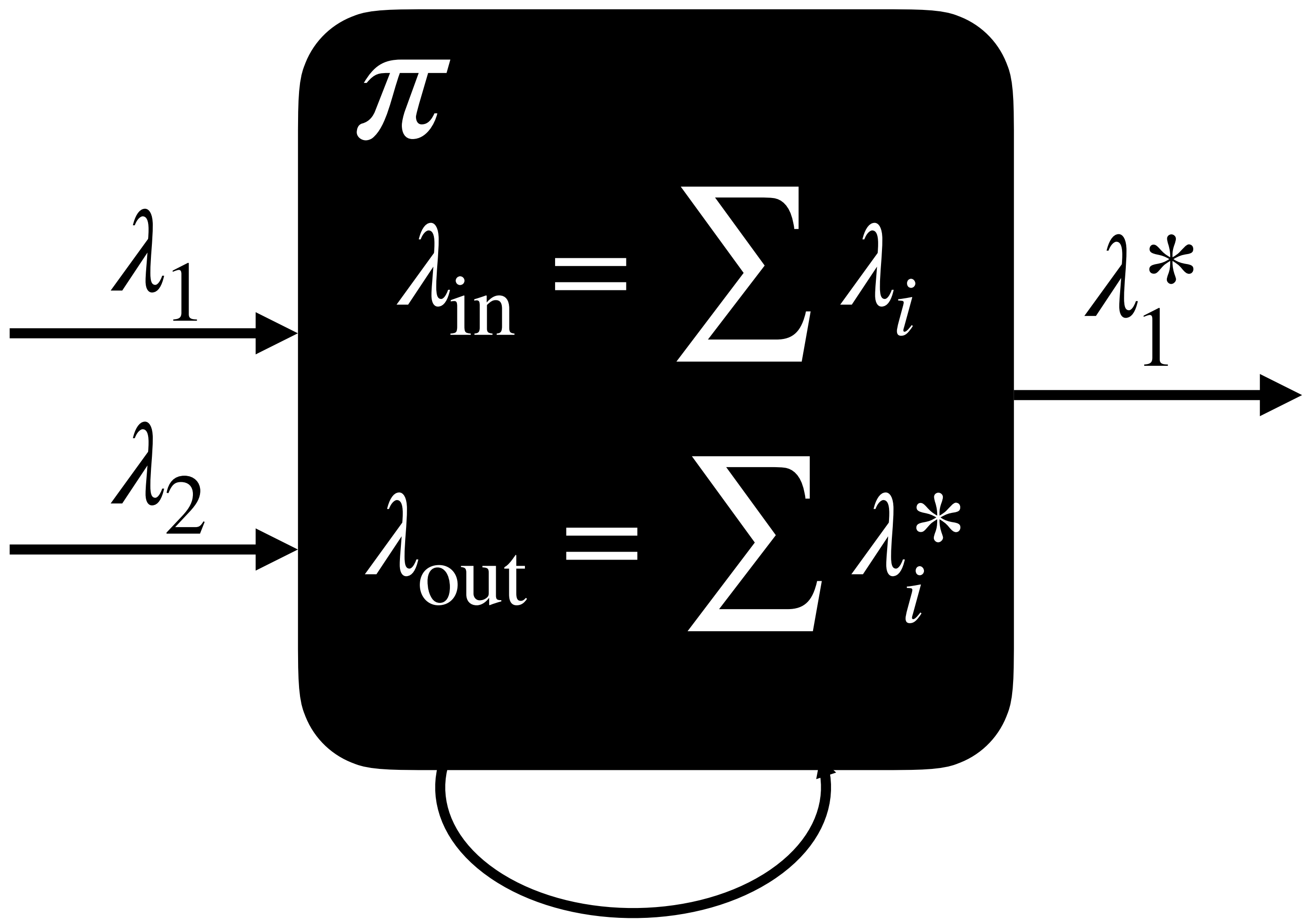
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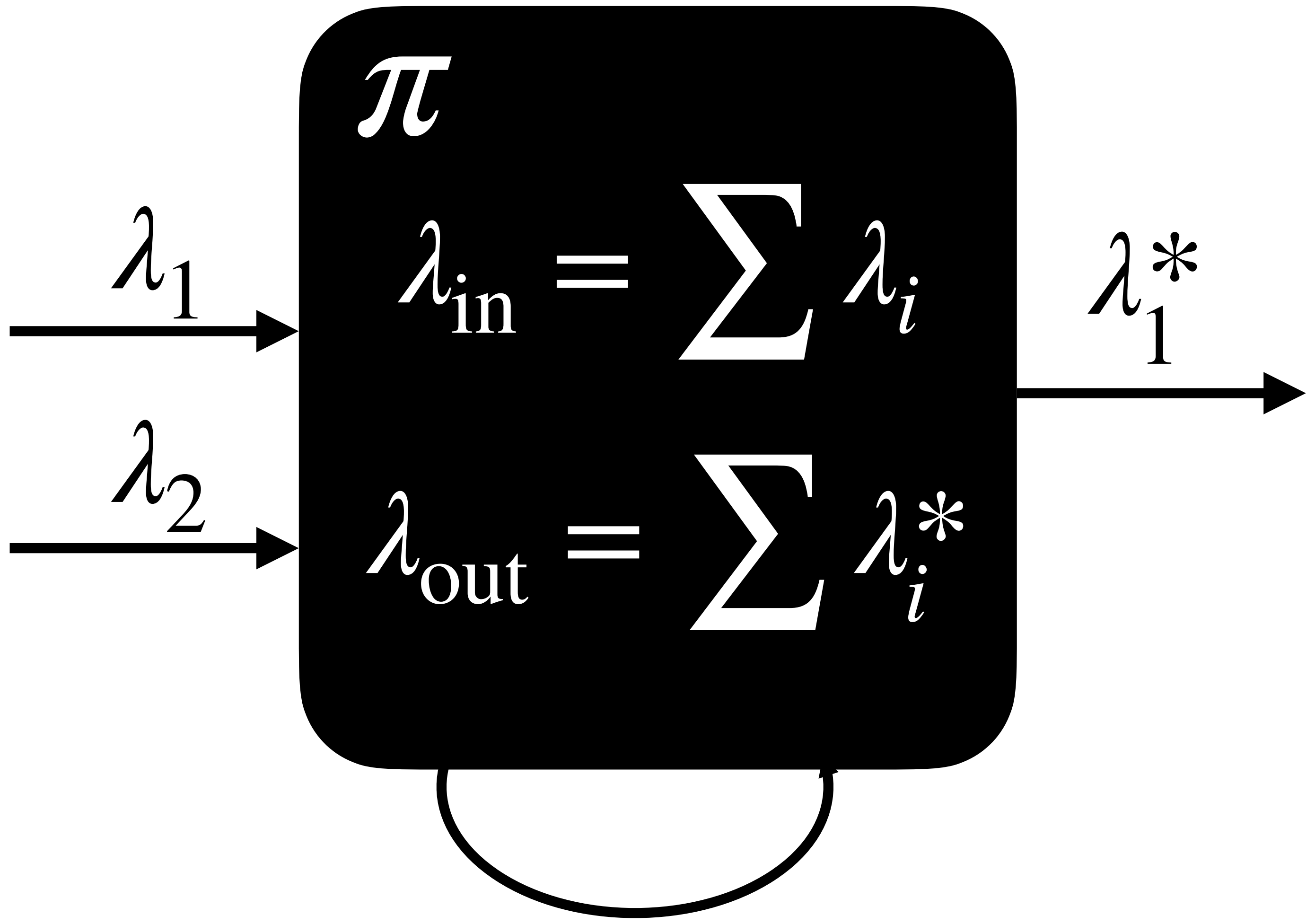


$$\lambda_{\text{in}} = \sum \lambda_i$$

$$\lambda_{\text{out}} = \sum \lambda_i^*$$

$$\text{time}(\pi) \leq p(\lambda_{\text{in}} - \lambda_{\text{out}})$$

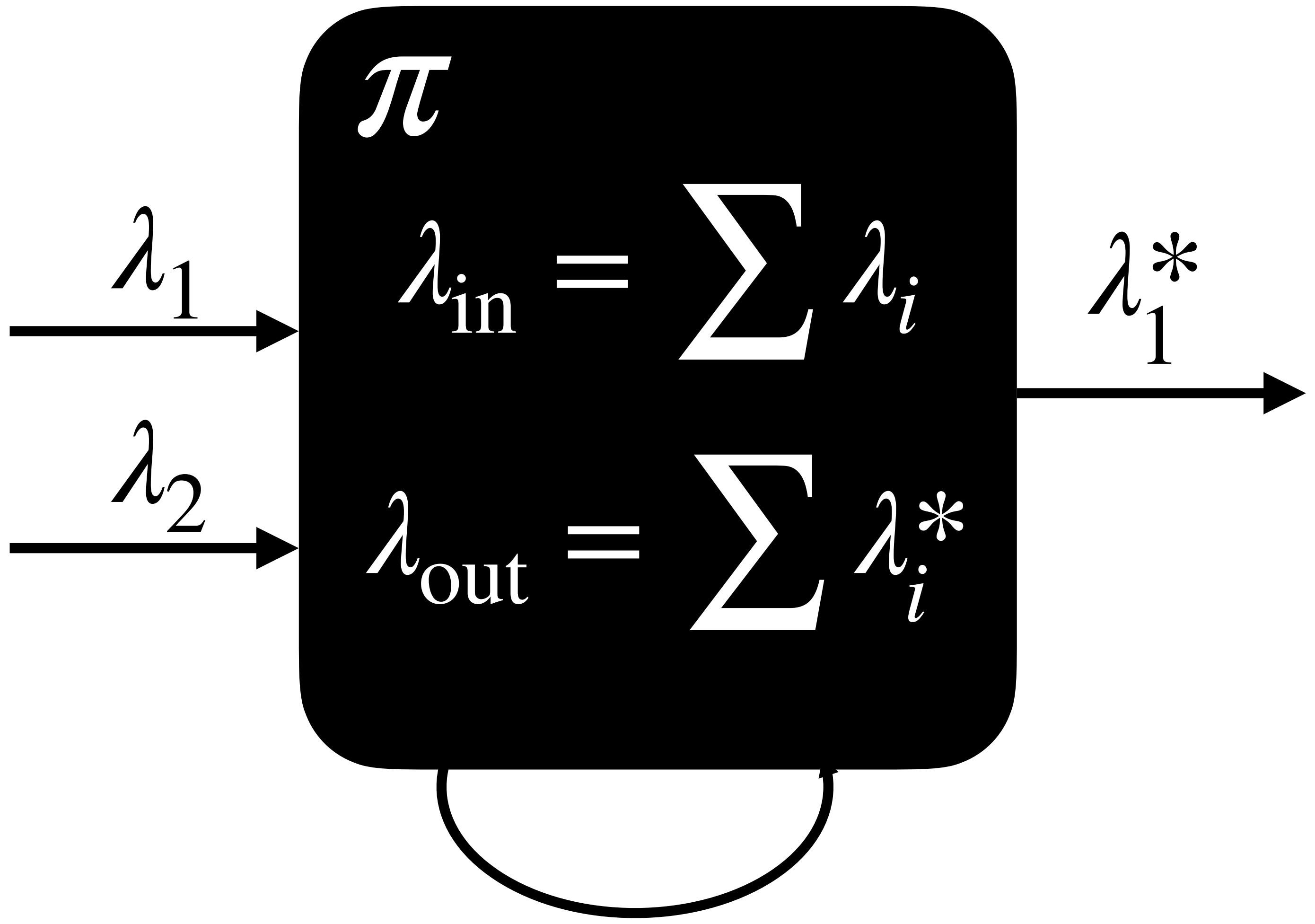
π

$$\mathscr{B} = \mathscr{B}_{\text{start}} + \sum \mathscr{B}_{\text{in}}$$

$$\mathscr{B} = (t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$$

UC with Budgets

Plain UC only models adversaries that are **computationally** bounded


π
λ_1
λ_2
$\lambda_{\text{in}} = \sum \lambda_i$
$\lambda_{\text{out}} = \sum \lambda_i^*$
λ_1^*

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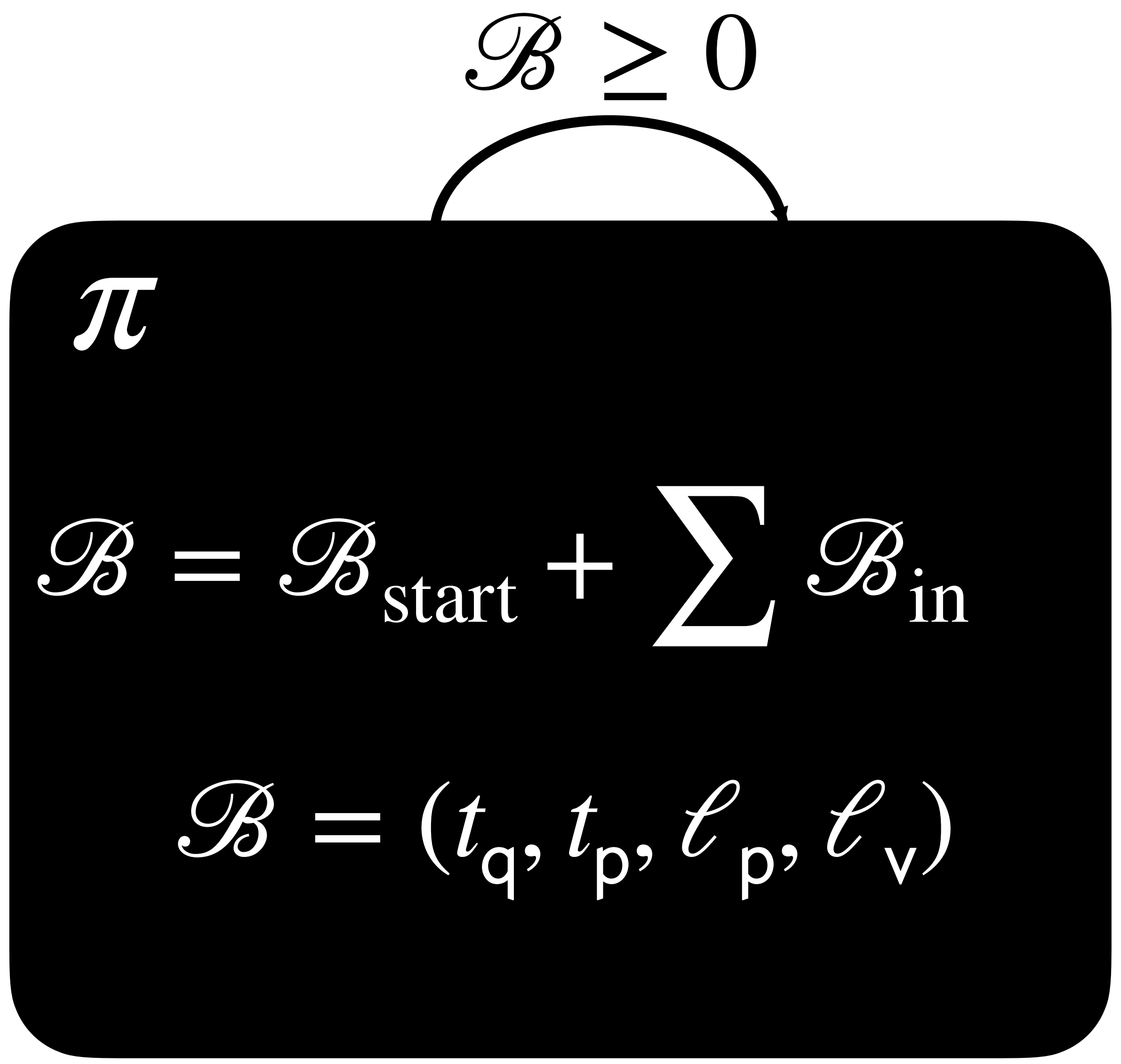
$\mathscr{B} \geq 0$
π
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$\mathscr{B} = (t_{\mathsf{q}}, t_{\mathsf{p}}, \ell_{\mathsf{p}}, \ell_{\mathsf{v}})$

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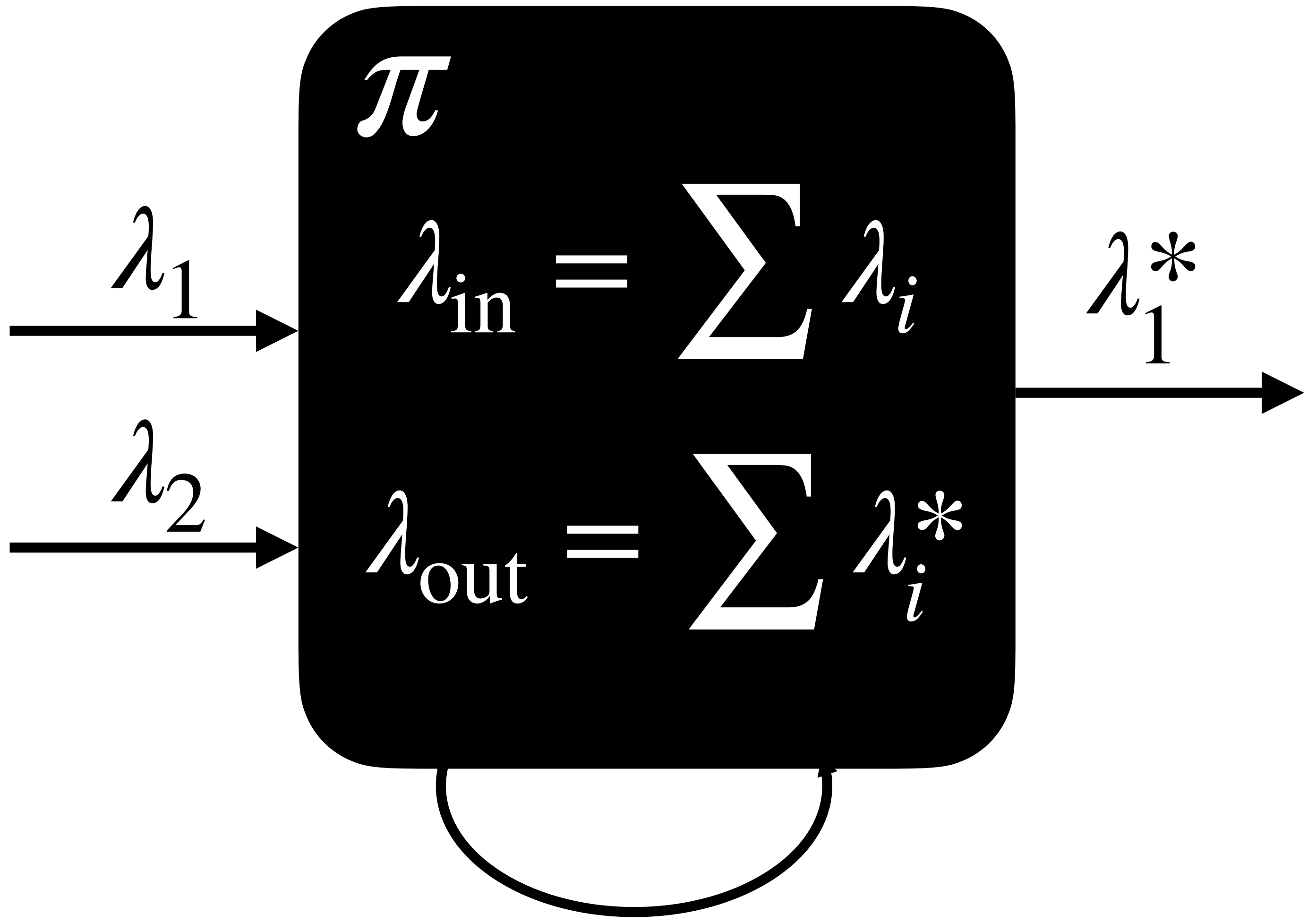

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λ_2

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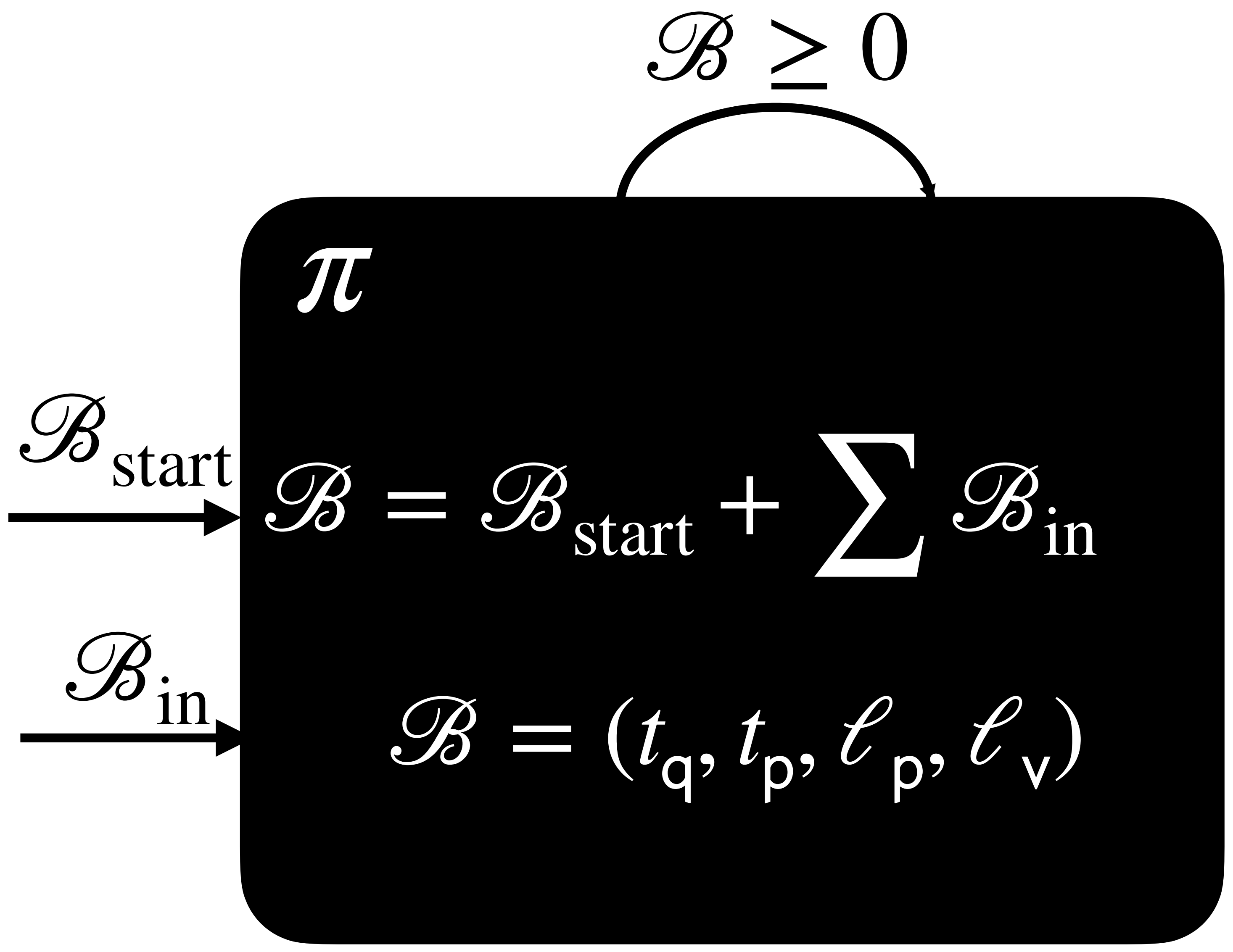
λ_1^*

time$(\pi) \leq p(\lambda_{\text{in}} - \lambda_{\text{out}})$



$\mathscr{B} \geq 0$

π

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$\mathscr{B}_{\text{in}}$

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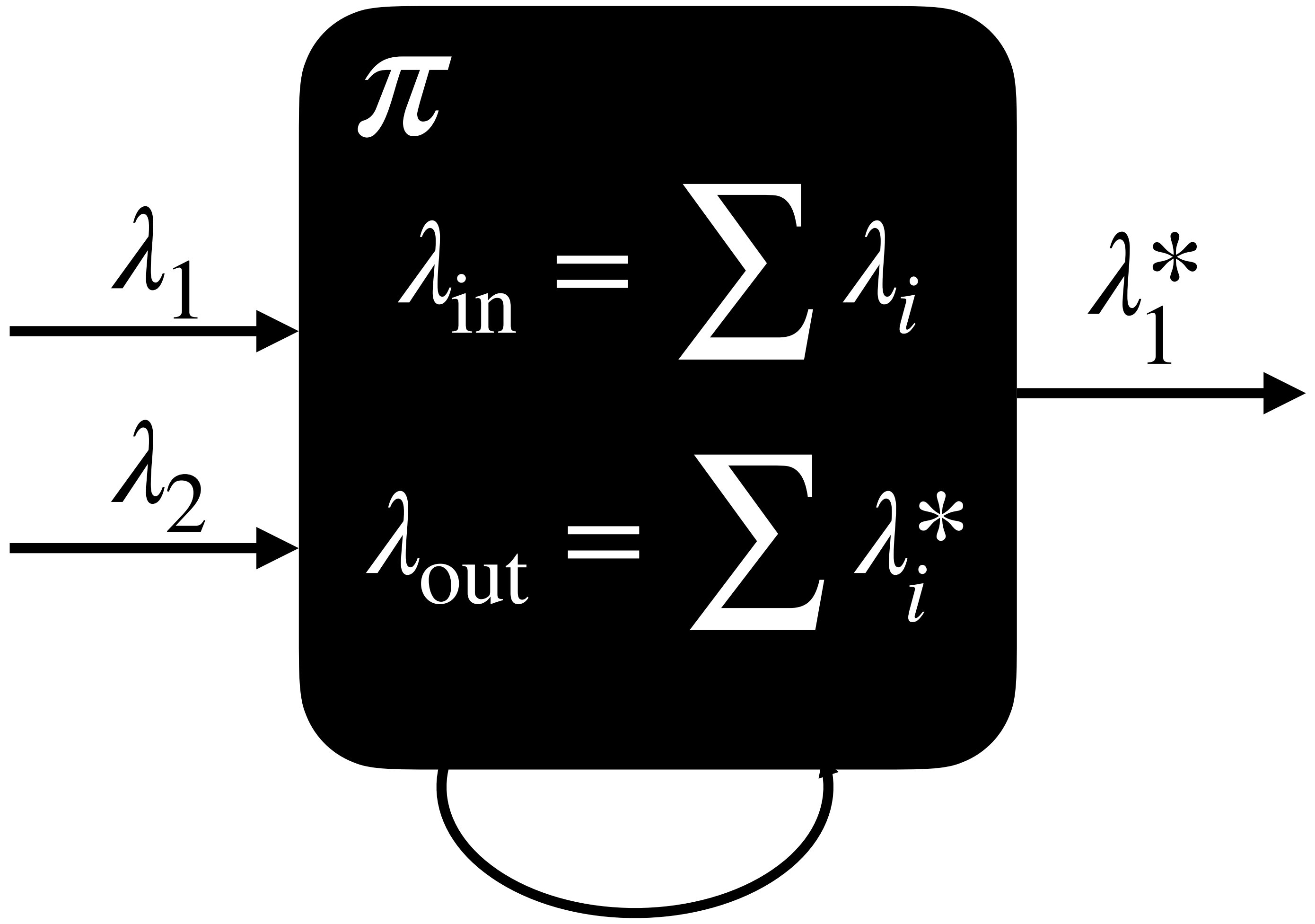
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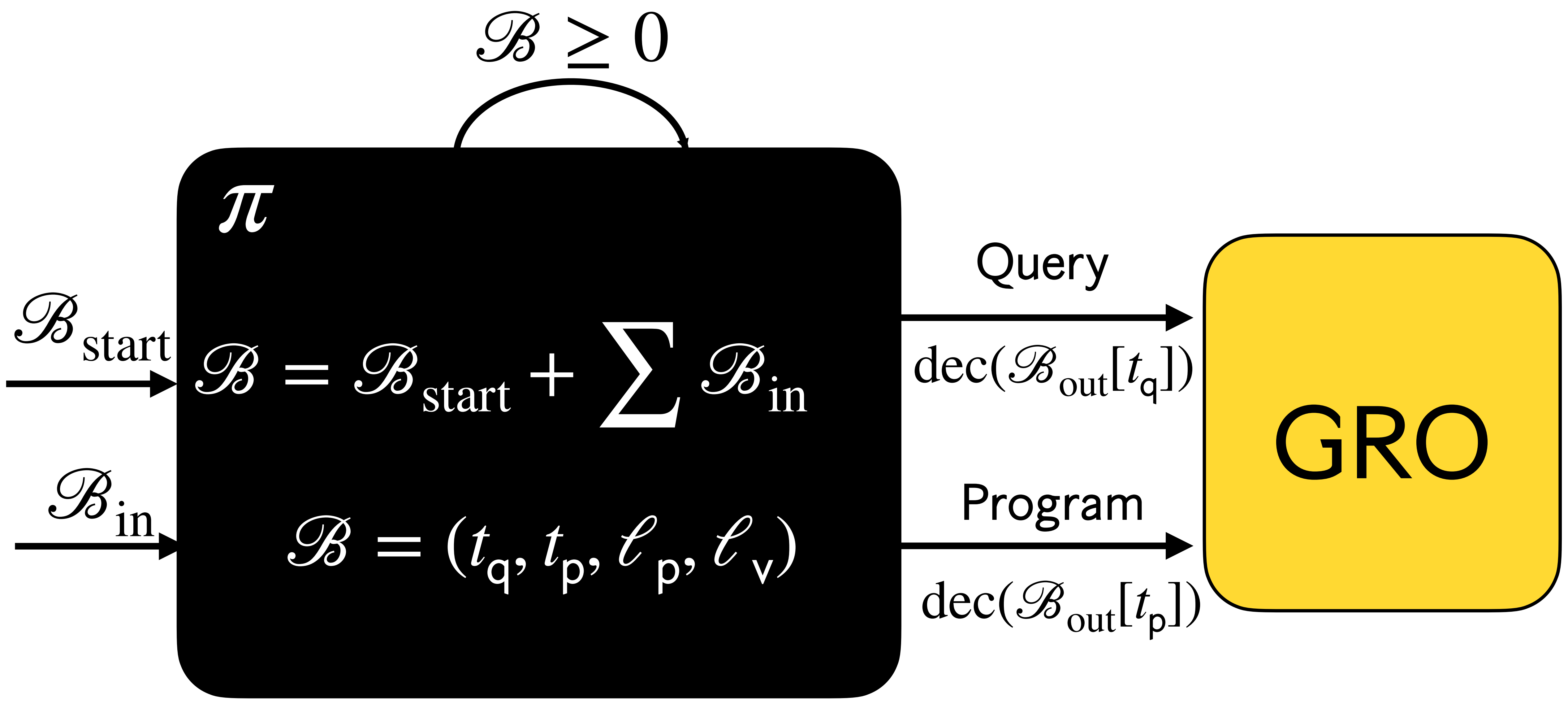
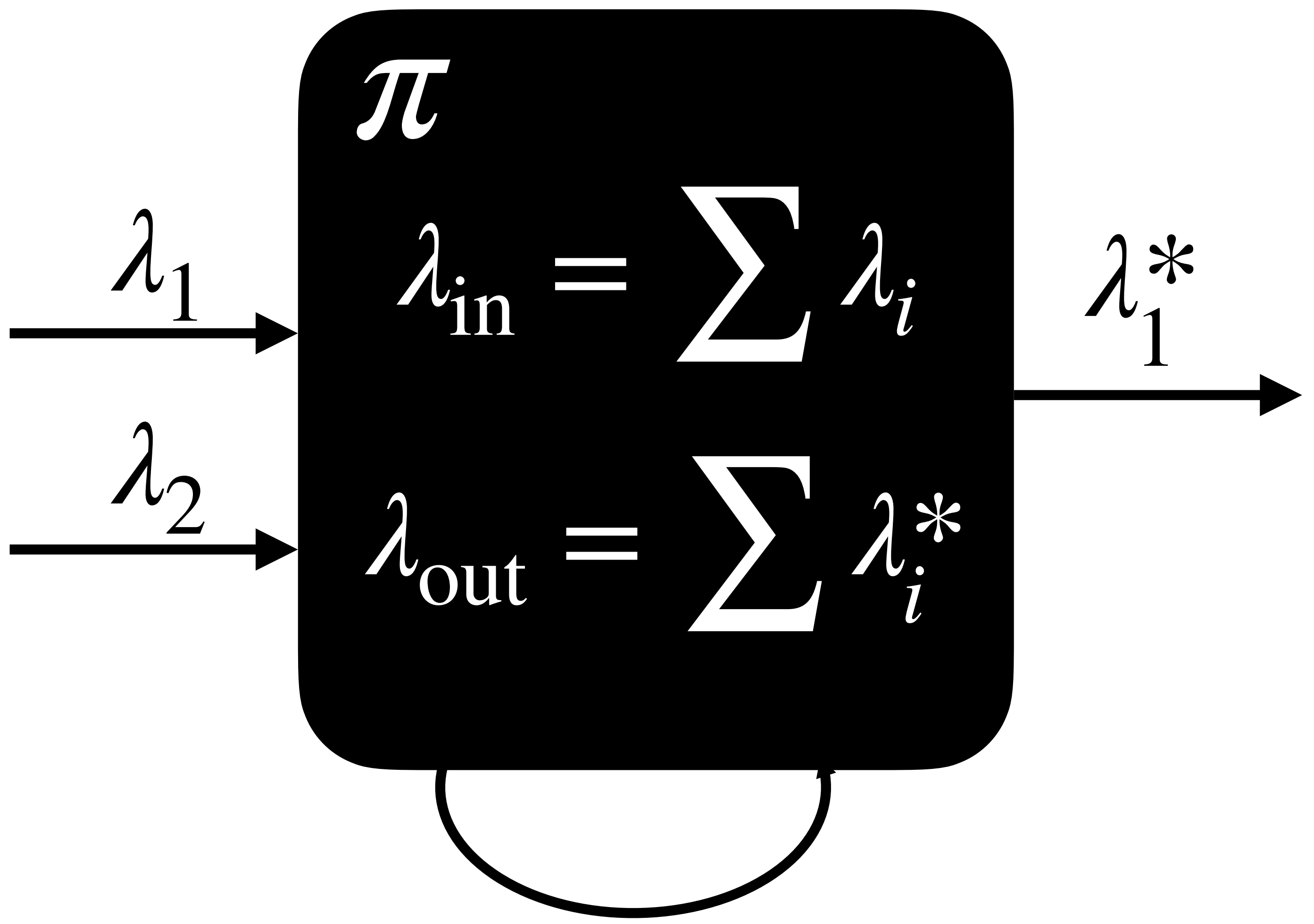

$\mathscr{B} \geq 0$
π
$\mathscr{B}_{\text{start}}$
$\mathscr{B}_{\text{in}}$
$\mathscr{B} = \mathscr{B}_{\text{start}} + \sum \mathscr{B}_{\text{in}}$
$\mathscr{B} = (t_{\text{q}}, t_{\text{p}}, \ell_{\text{p}}, \ell_{\text{v}})$
Query
$\text{dec}(\mathscr{B}_{\text{out}}[t_{\text{q}}])$
Program
$\text{dec}(\mathscr{B}_{\text{out}}[t_{\text{p}}])$
GRO

$\text{dec}(x) := x \leftarrow x - 1$

UC with Budgets

Plain UC only models adversaries that are **computationally** bounded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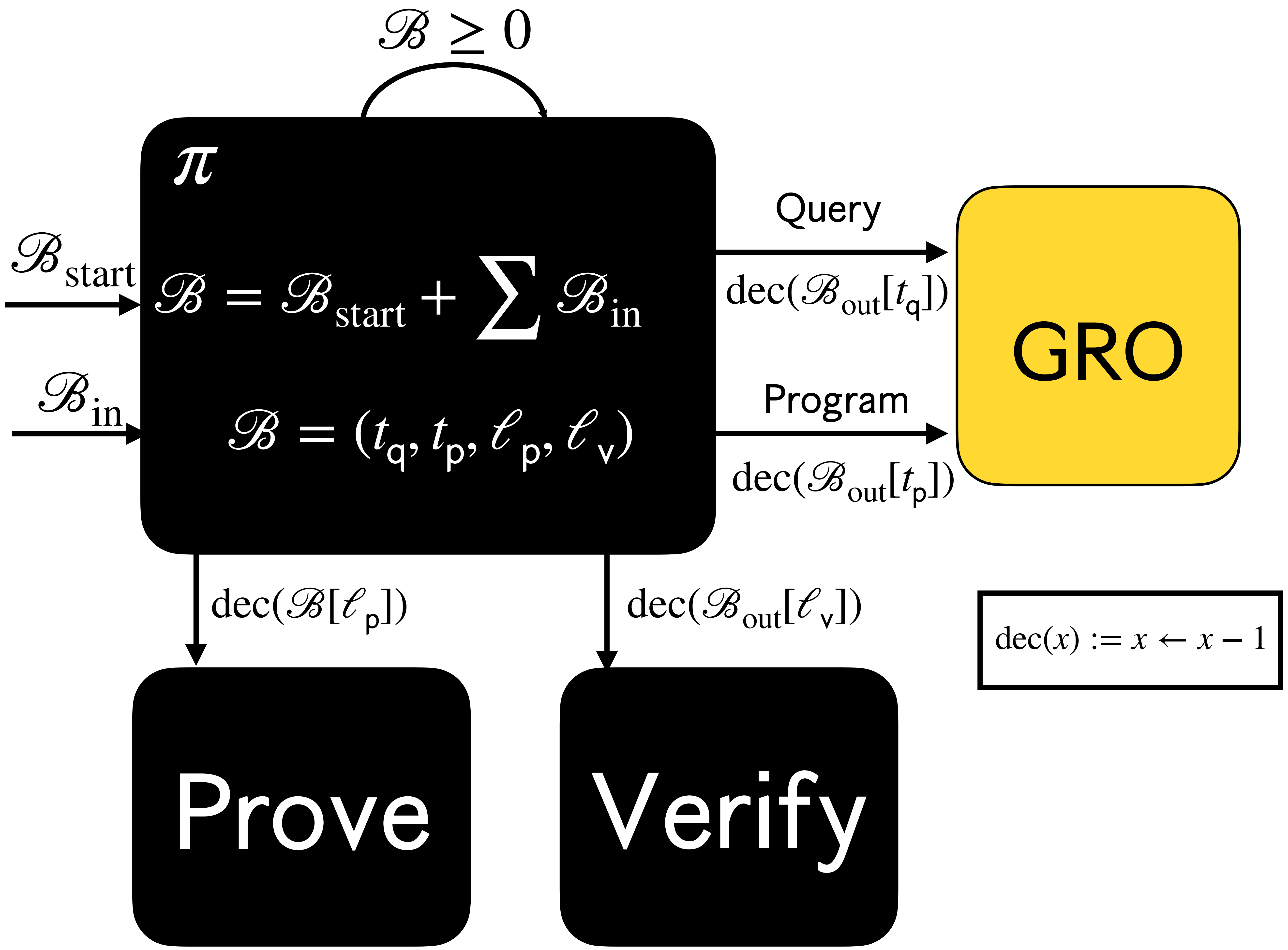
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$\mathscr{B}_{\text{in}}$
$\mathscr{B} = \mathscr{B}_{\text{start}} + \sum \mathscr{B}_{\text{in}}$
$\mathscr{B} = (t_{\text{q}}, t_{\text{p}}, \ell_{\text{p}}, \ell_{\text{v}})$
Query
$\text{dec}(\mathscr{B}_{\text{out}}[t_{\text{q}}])$
Program
$\text{dec}(\mathscr{B}_{\text{out}}[t_{\text{p}}])$
GRO
$\text{dec}(\mathscr{B}[\ell_{\text{p}}])$
$\text{dec}(\mathscr{B}_{\text{out}}[\ell_{\text{v}}])$
Prove
Verify
$\text{dec}(x) := x \leftarrow x - 1$