zkSNARKs in the ROM with Unconditional UC-Security

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

Giacomo Fenzi @ EPFL

eprint.iacr.org/2024/724

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.

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E.g.: proof based rollups
to improve scalability

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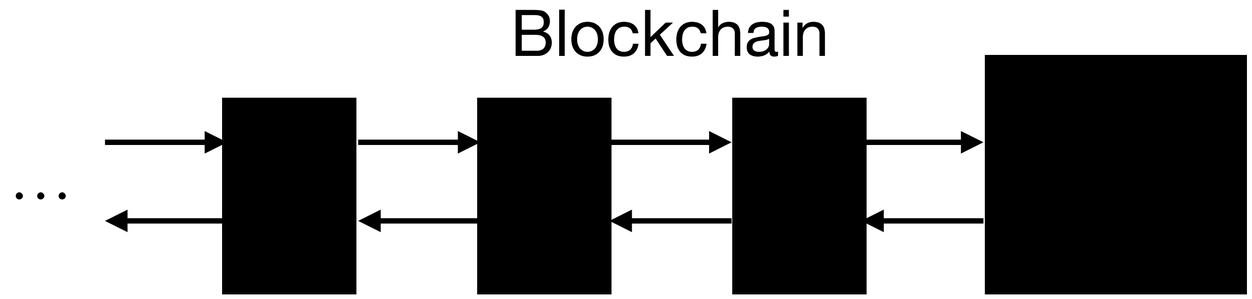

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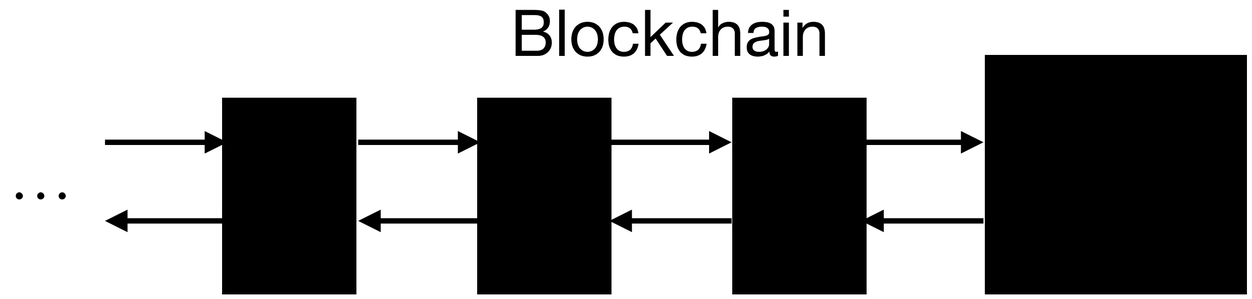
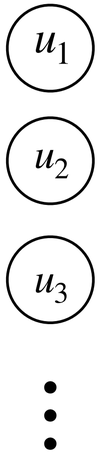


Rollup Users



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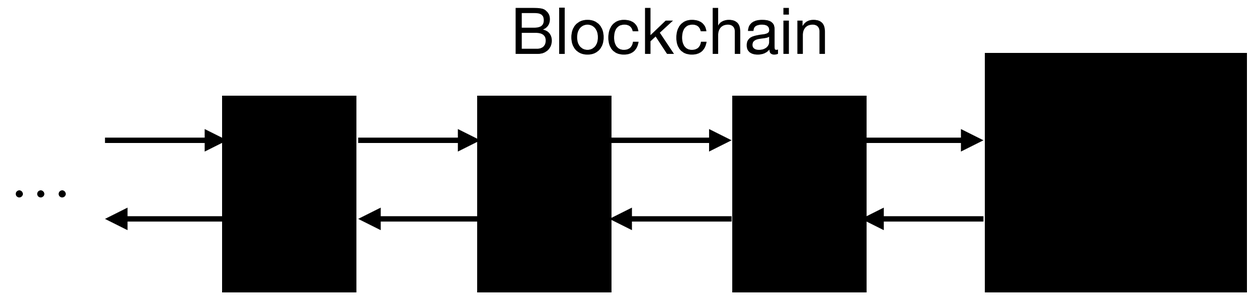

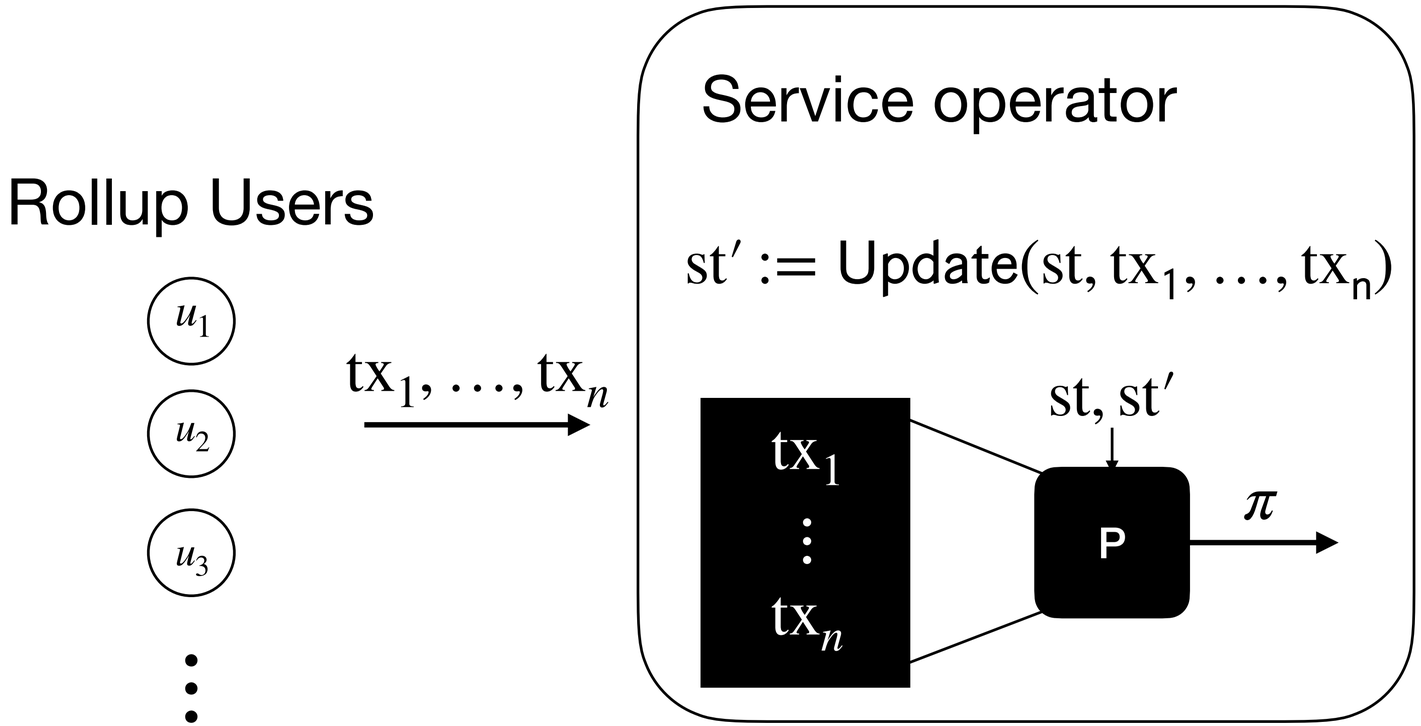

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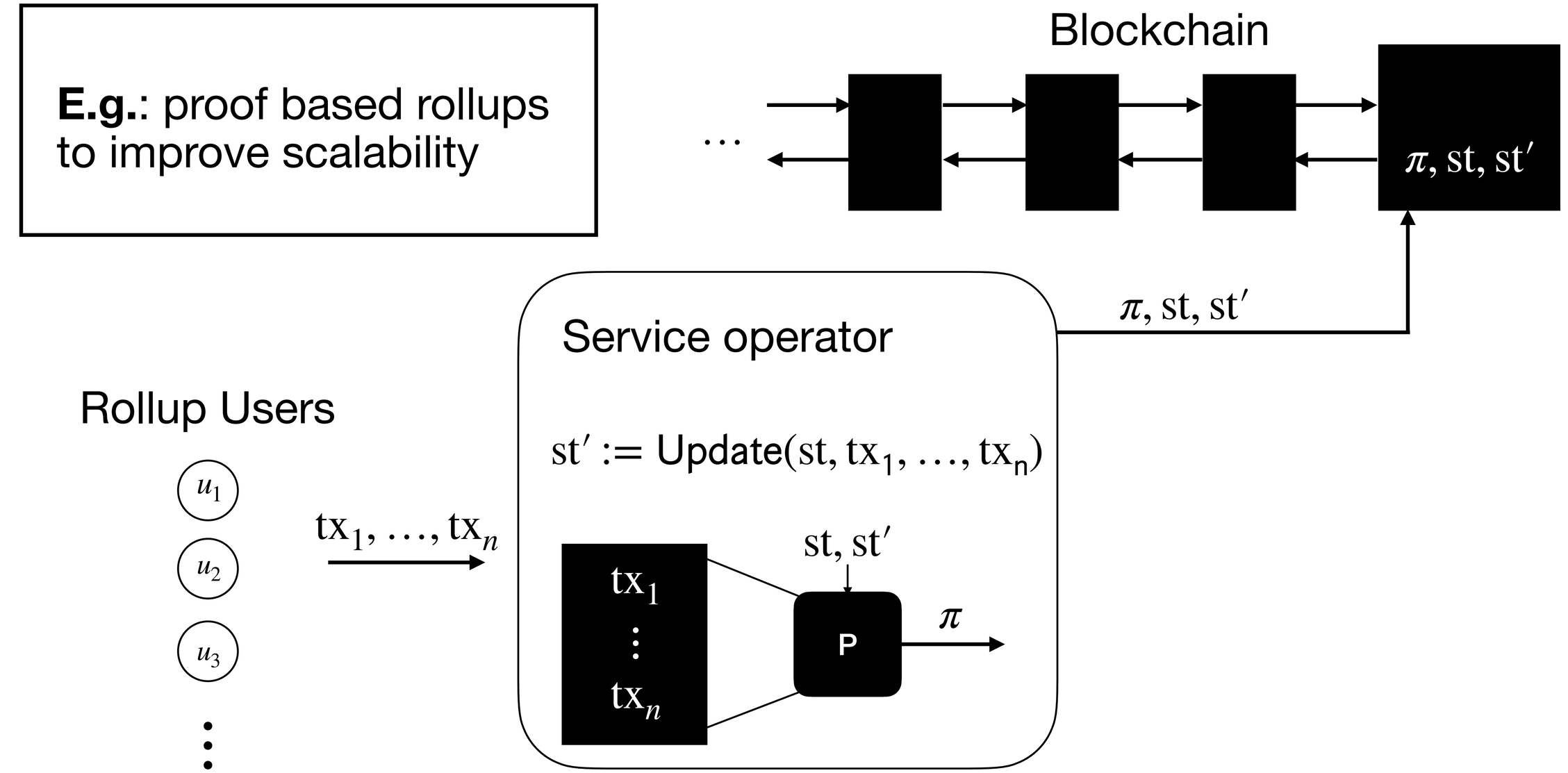

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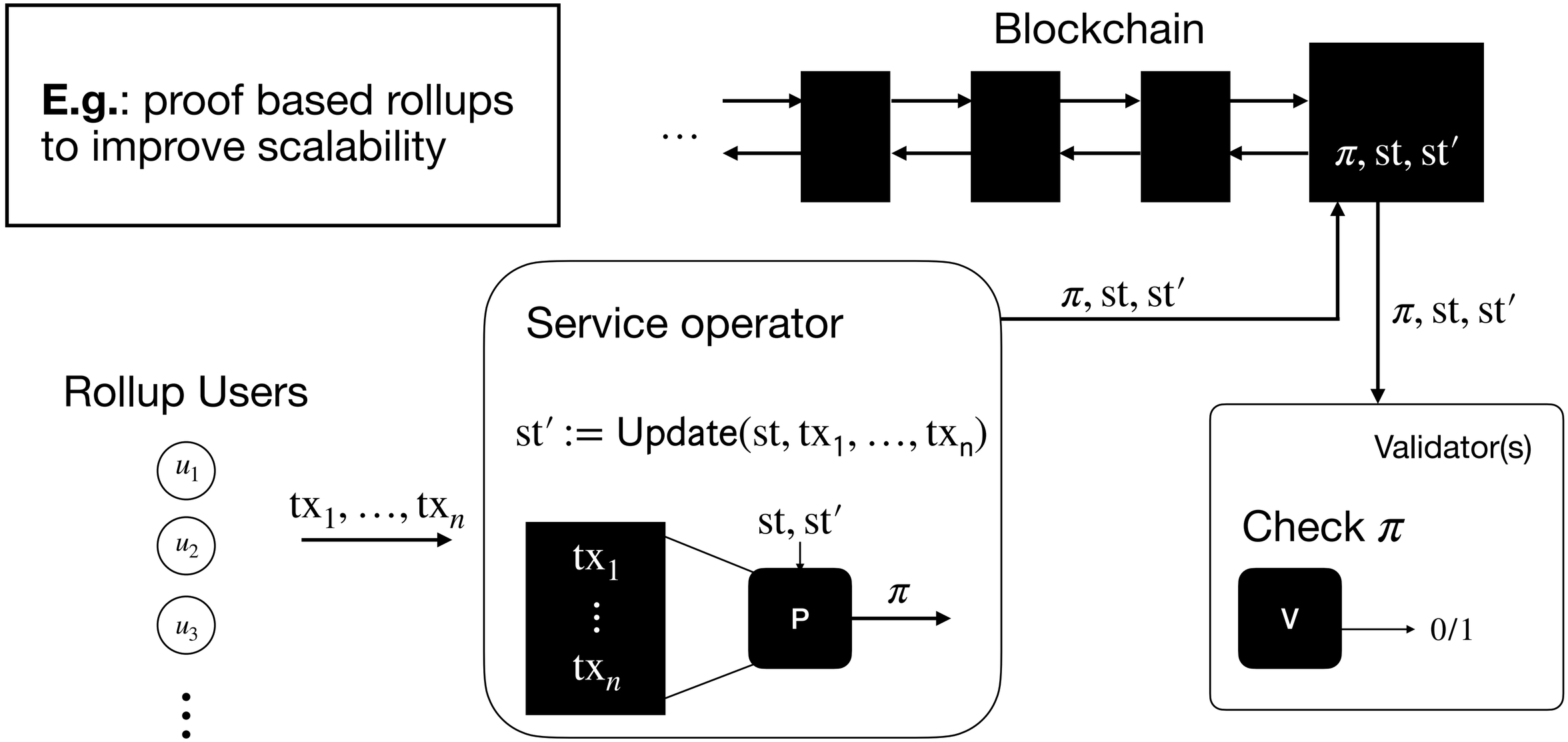

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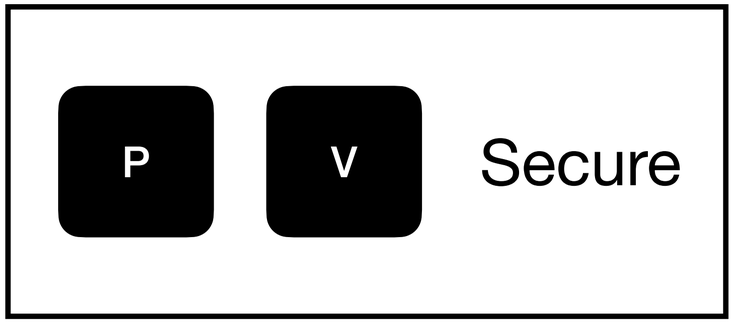

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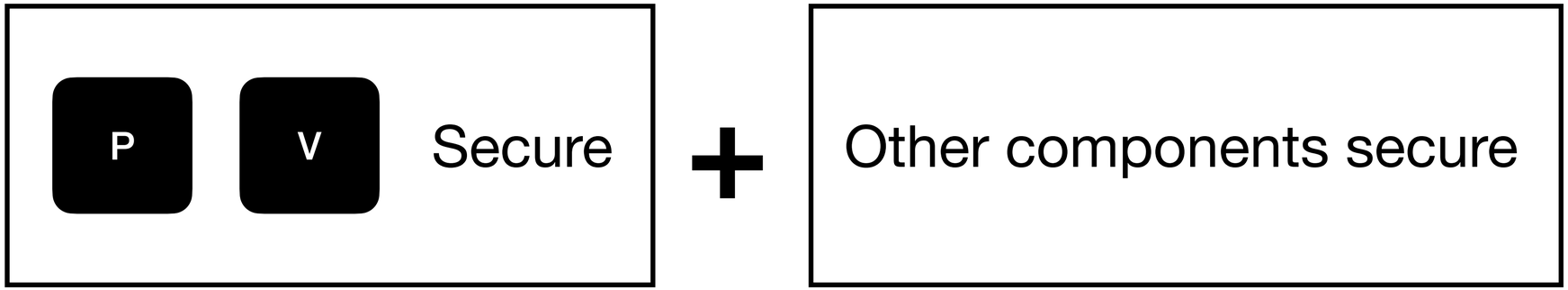

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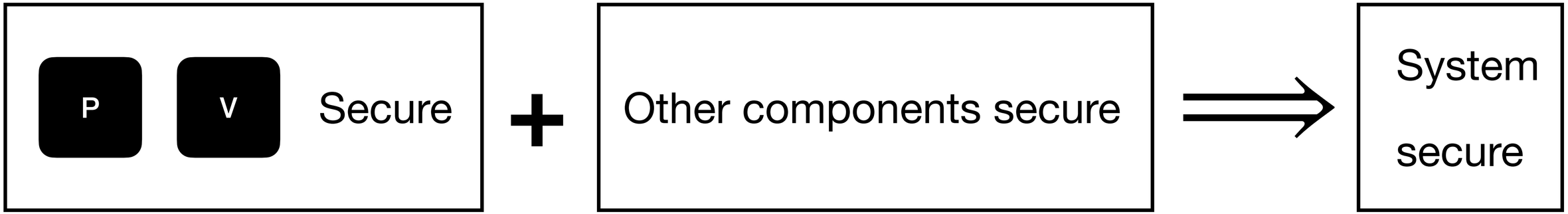

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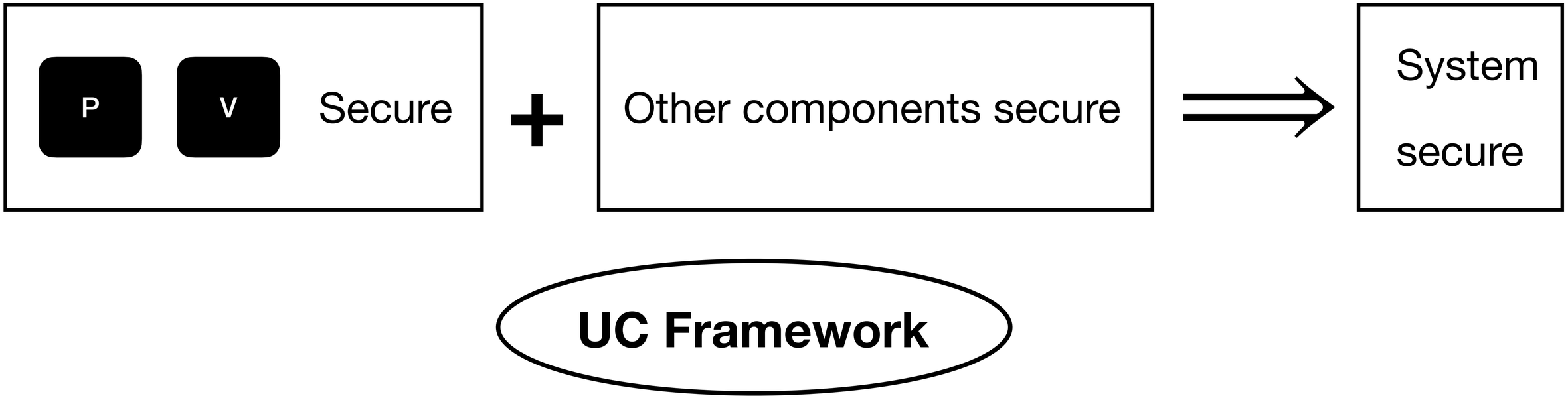

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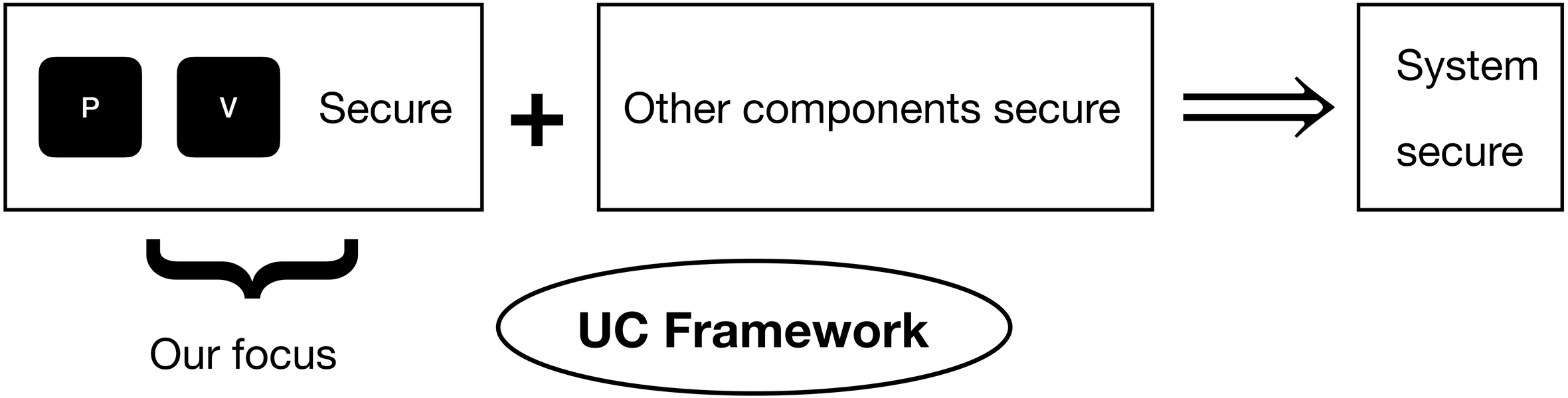

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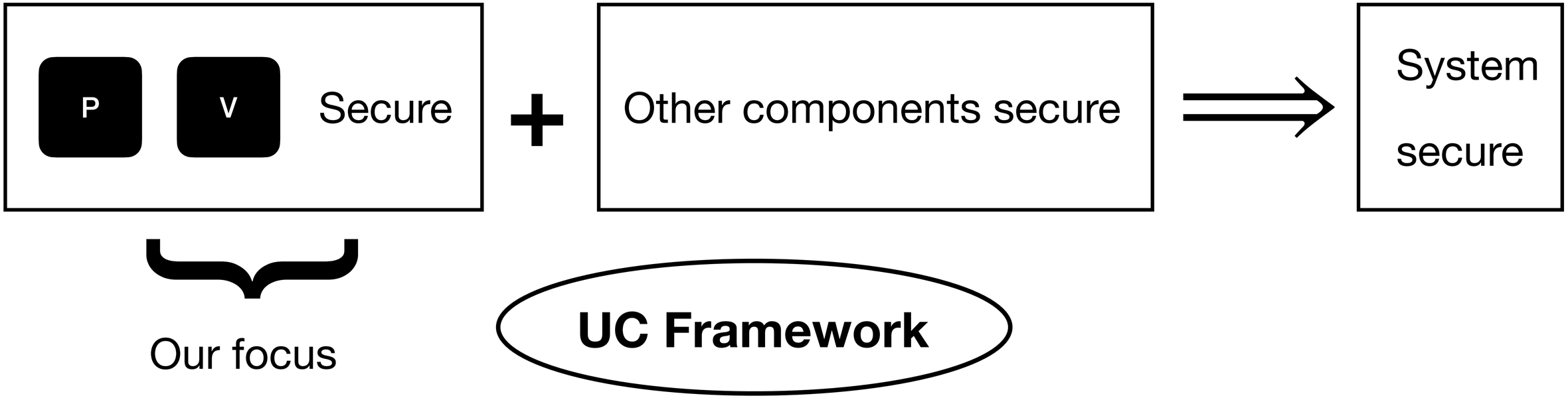

Which zkSNARKs are UC-secure?

Related works

Related works

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

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

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

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Compile Σ-protocol into NIZK

+ Techniques inspired this work

- Not succinct

- Expensive compilation (non-FS)

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Succinct UC-secure zkSNARKs

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\- Focuses on asymptotic security

This work

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

Concrete security bounds: useful for practitioners

Background

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

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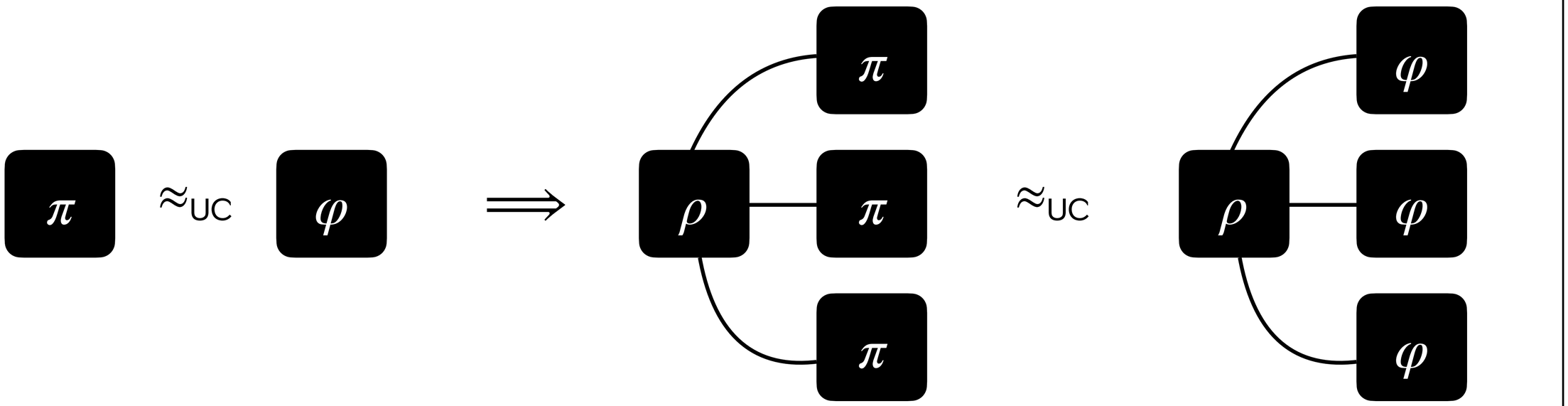

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Goal: Cannot distinguish protocol from idealized version.

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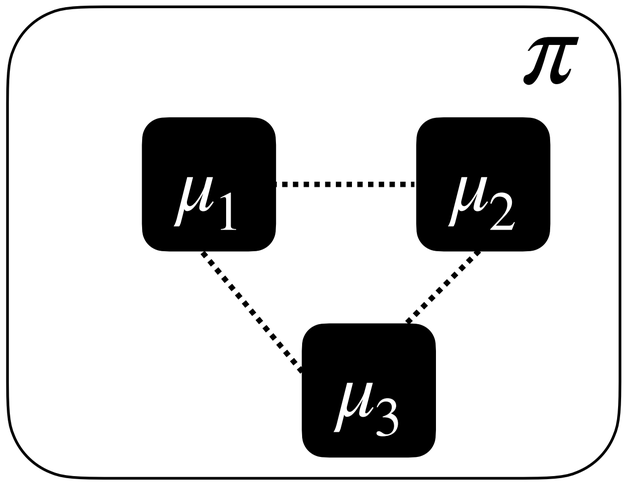

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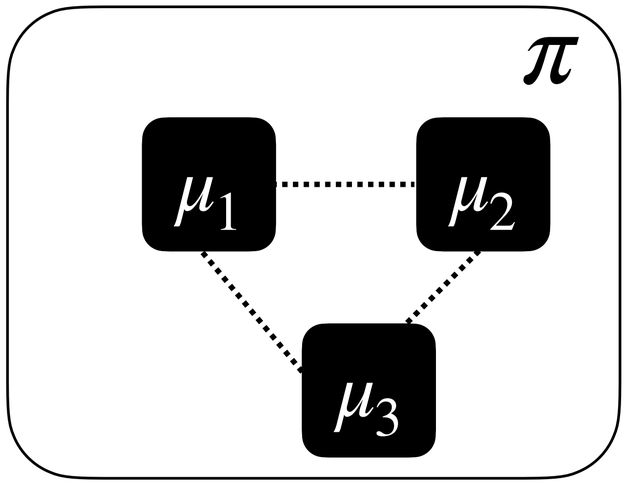

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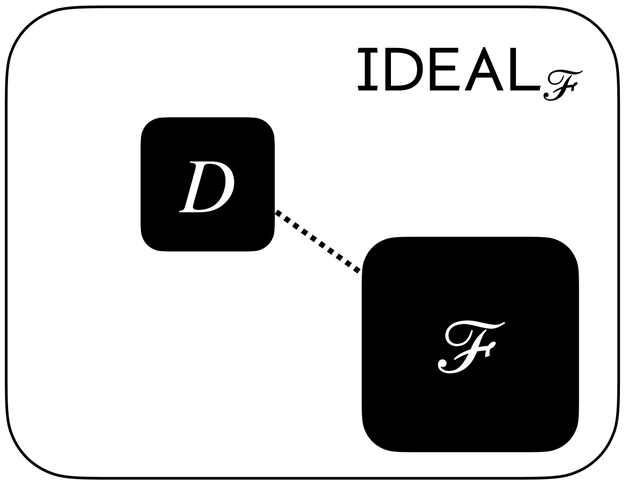

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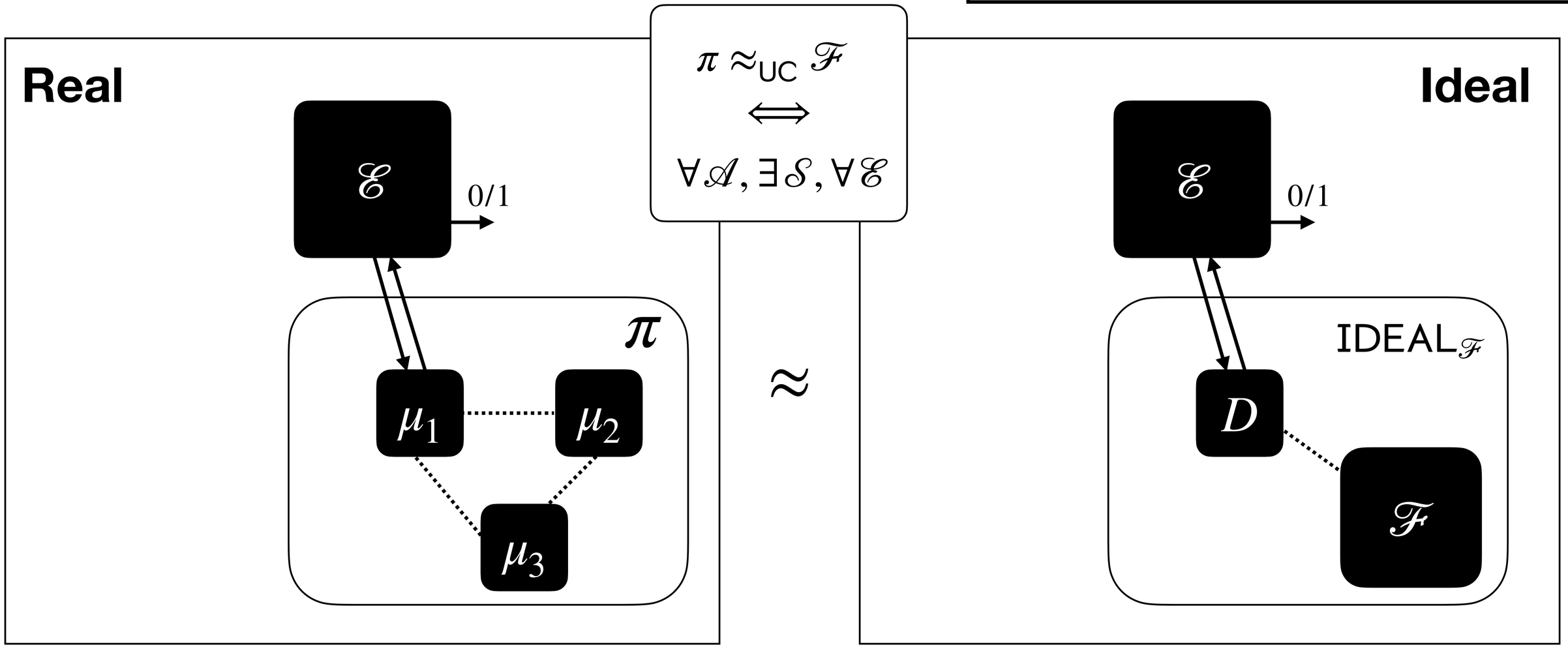

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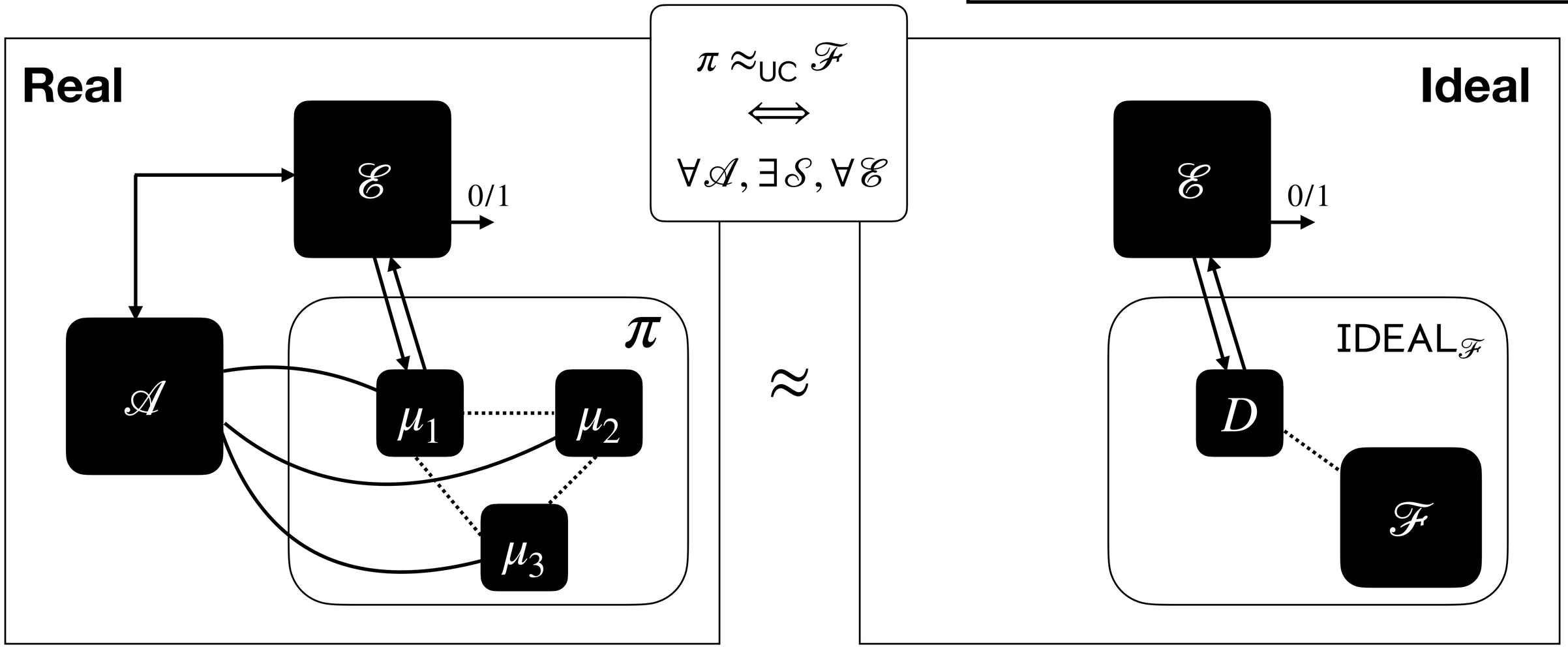

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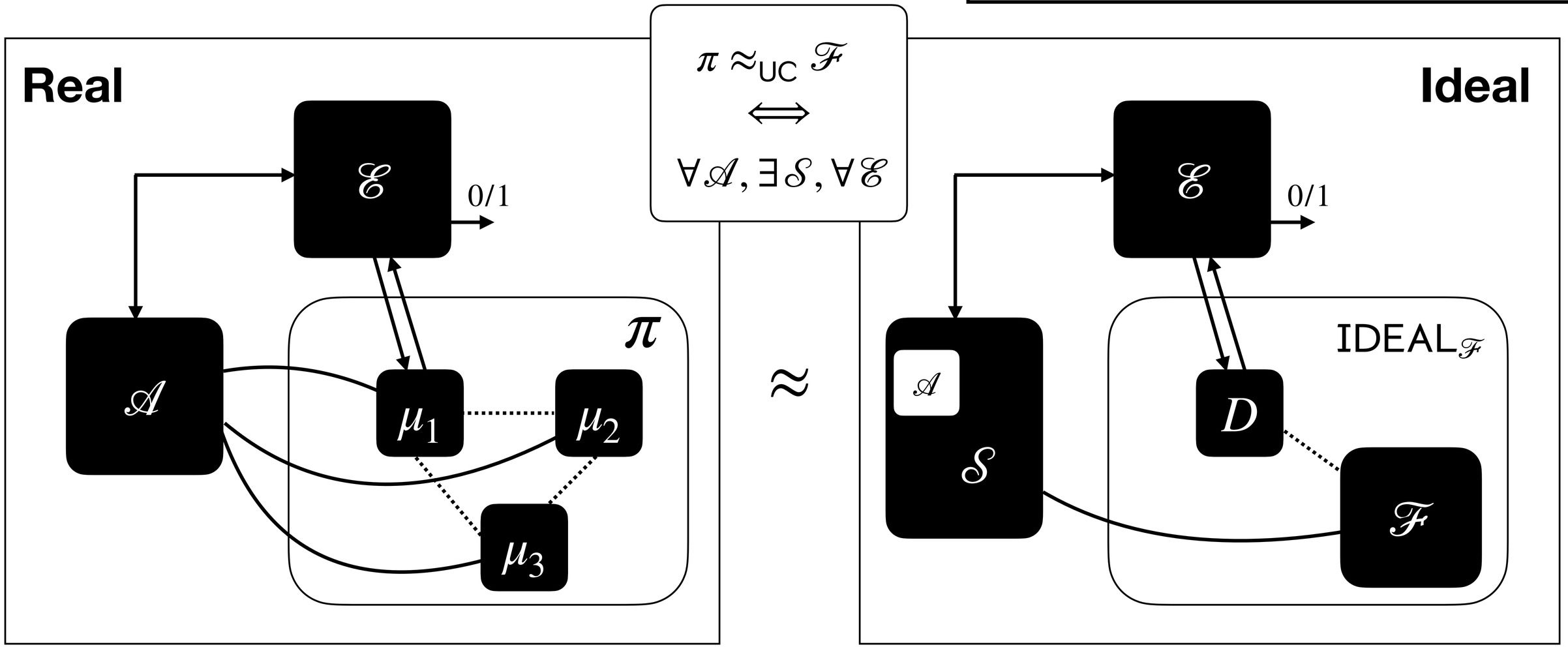

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[CDGLN18]

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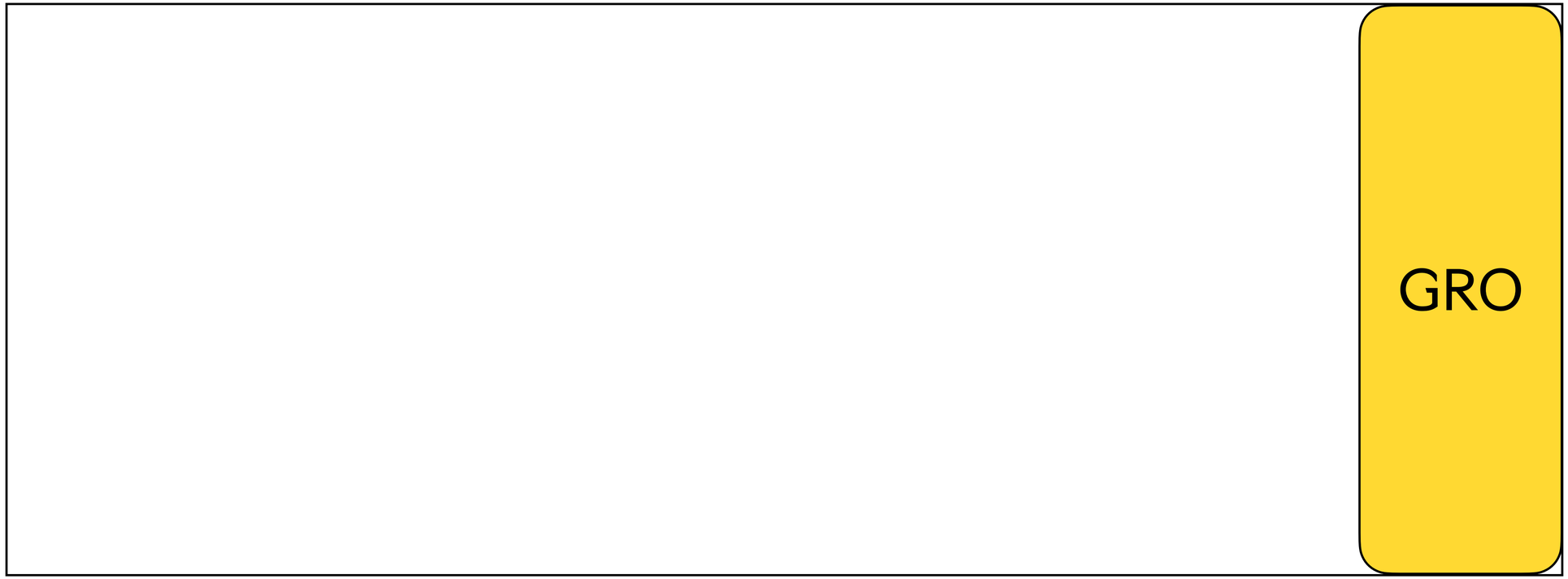

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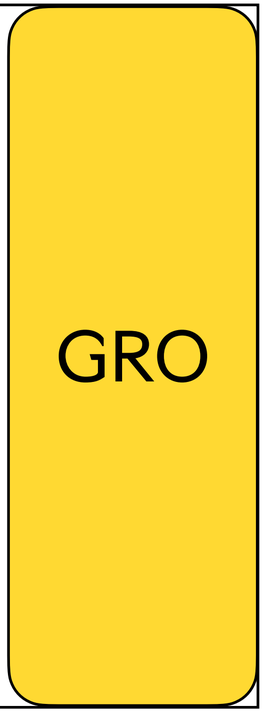

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- Observe(s): get all queries with prefix s from adversary or from parties with sid $\neq s$
- Program(x, y): Program the GRO (maintaining consistency)
- IsProgrammed(x): allows parties in session sid to check if a $x = \text{sid} \circ x'$ has been programmed

GRO

Crucial: Simulator can program points without being detected!

Argument functionality [LR22]

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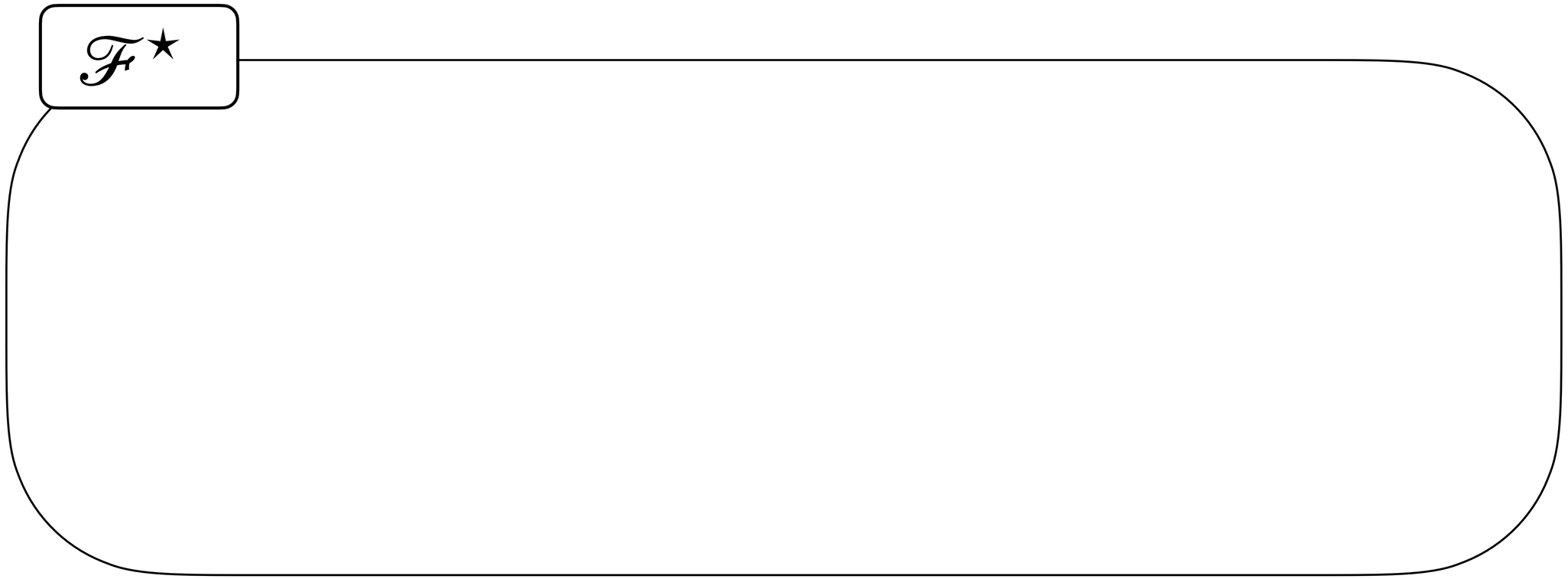

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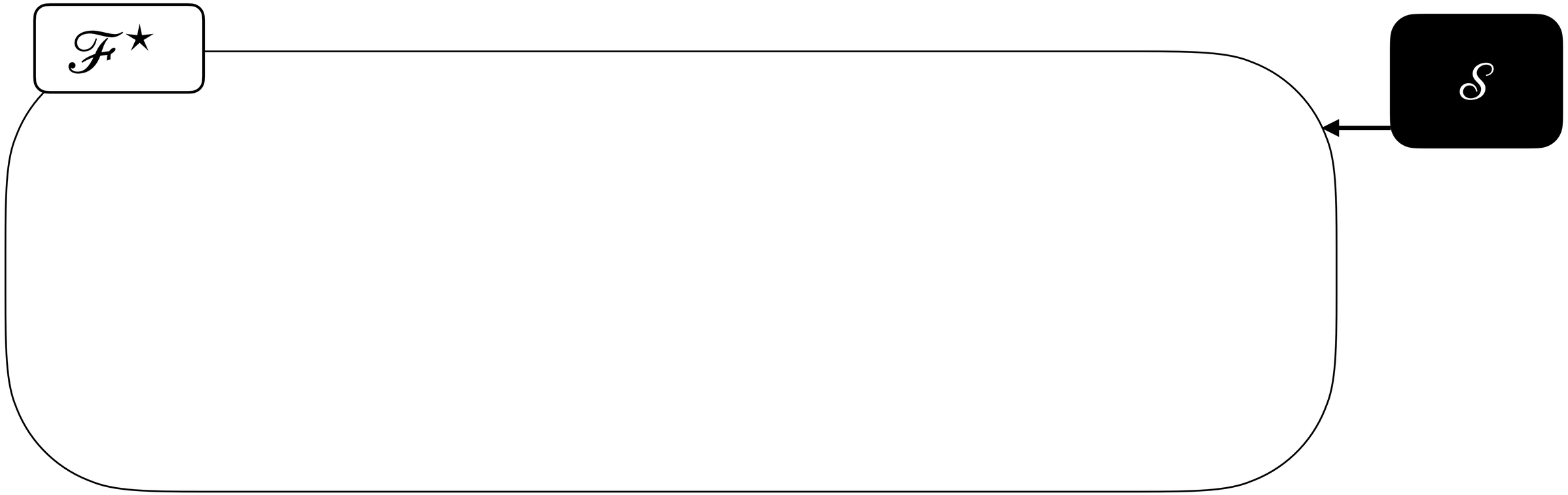

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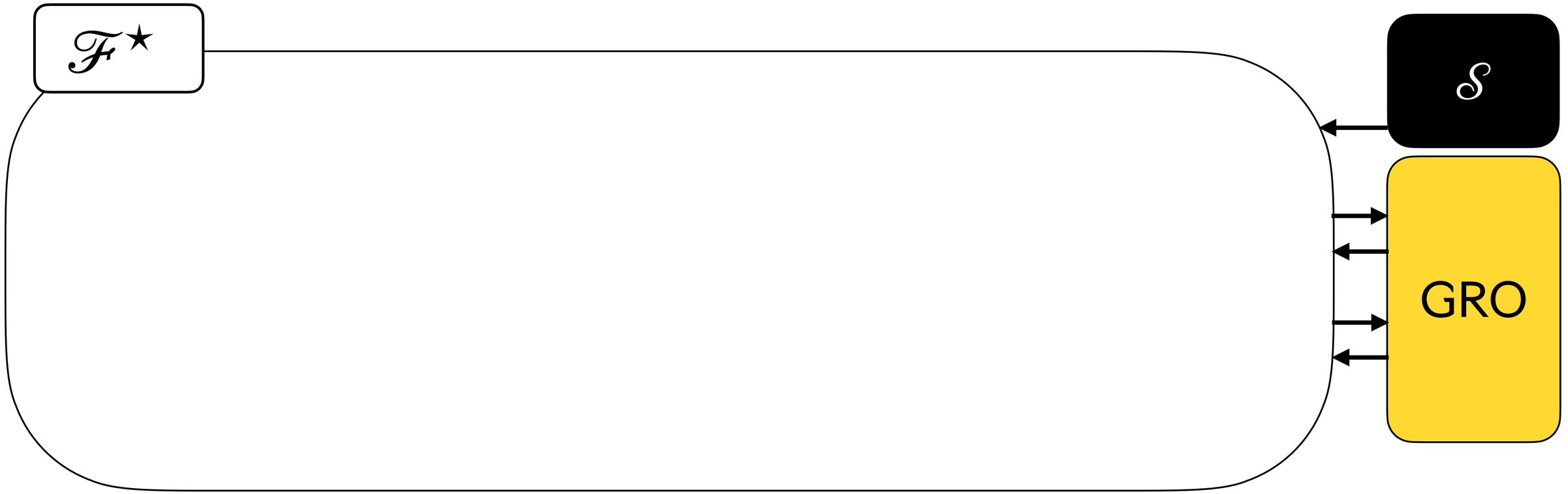

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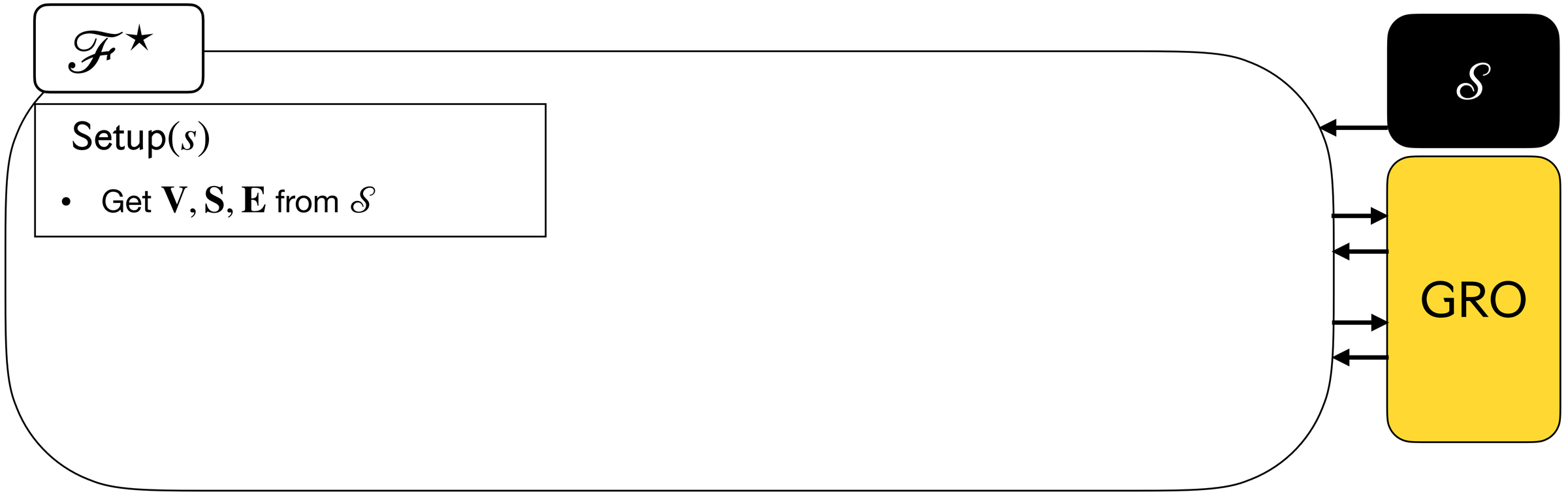

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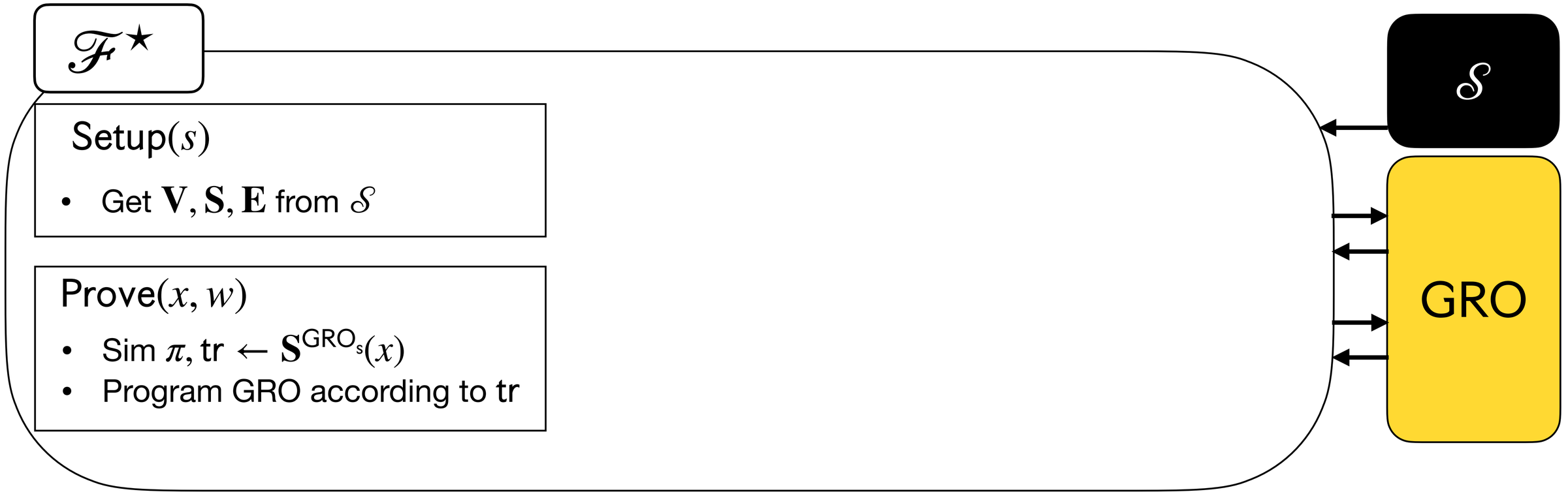

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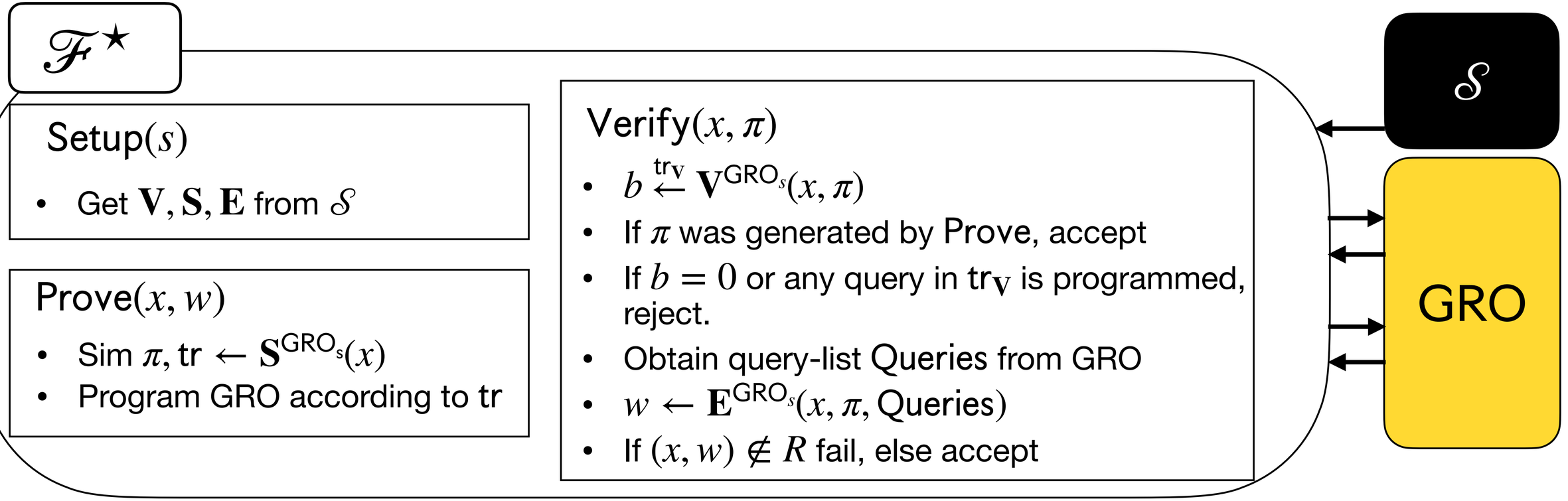

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Converts an argument $\mathsf{ARG} = (\mathbf{P}, \mathbf{V})$ in the ROM into a protocol in the GROM

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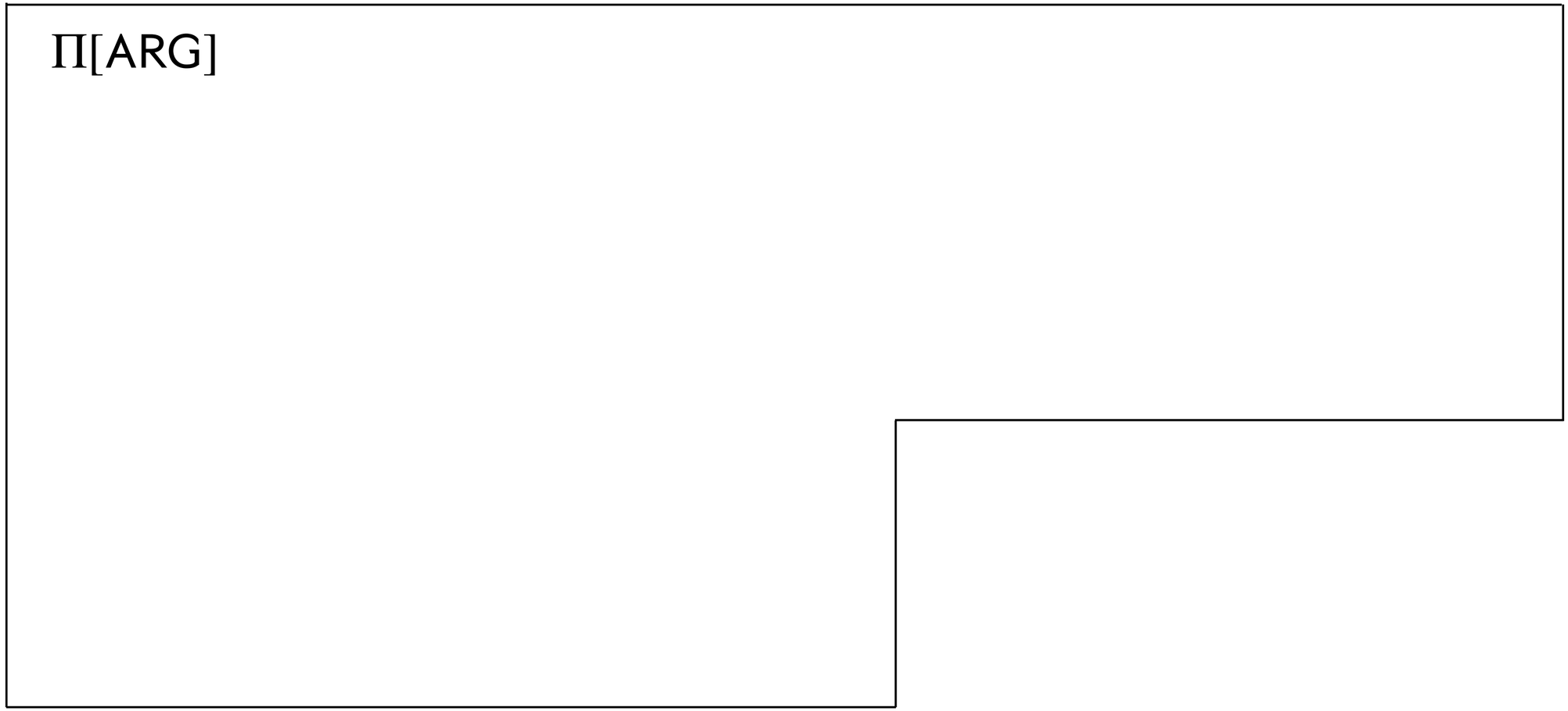

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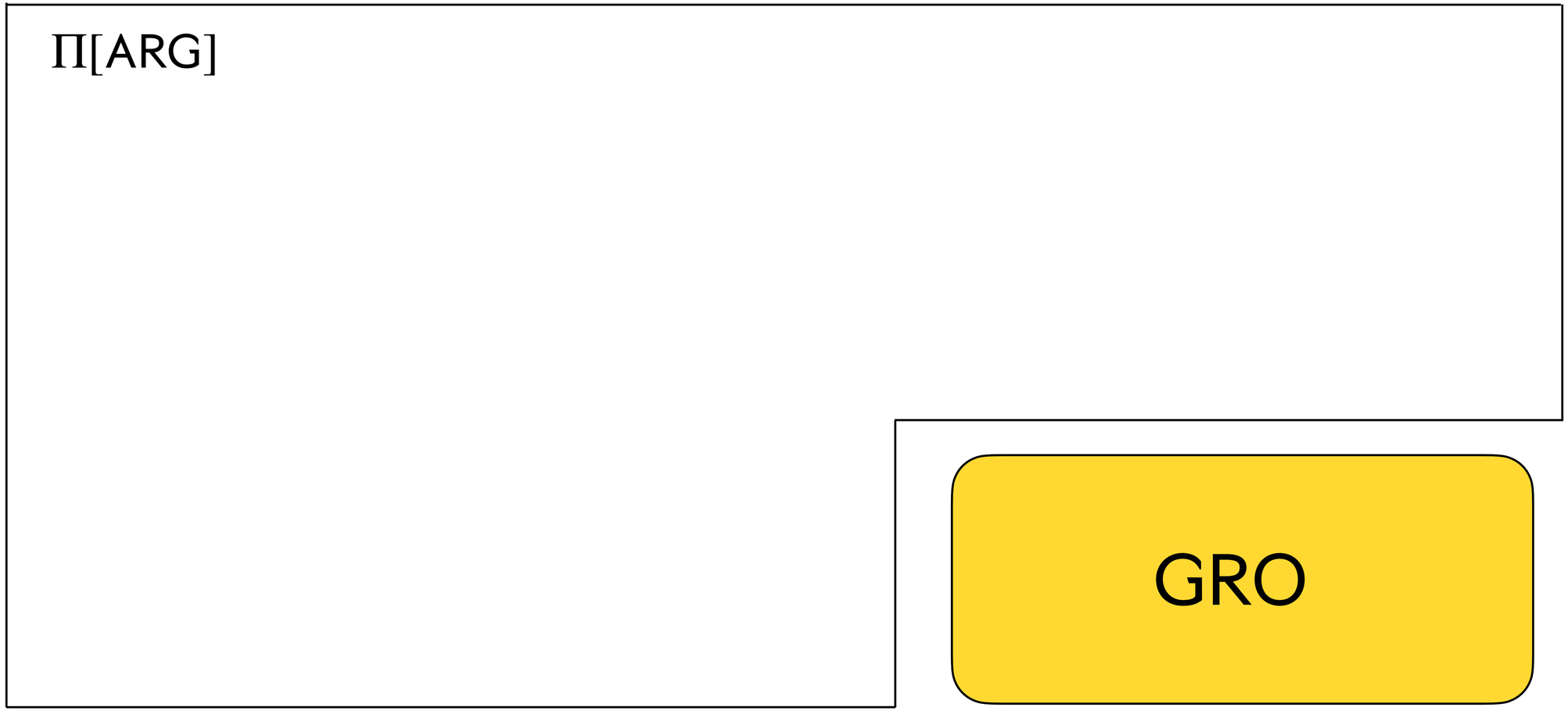

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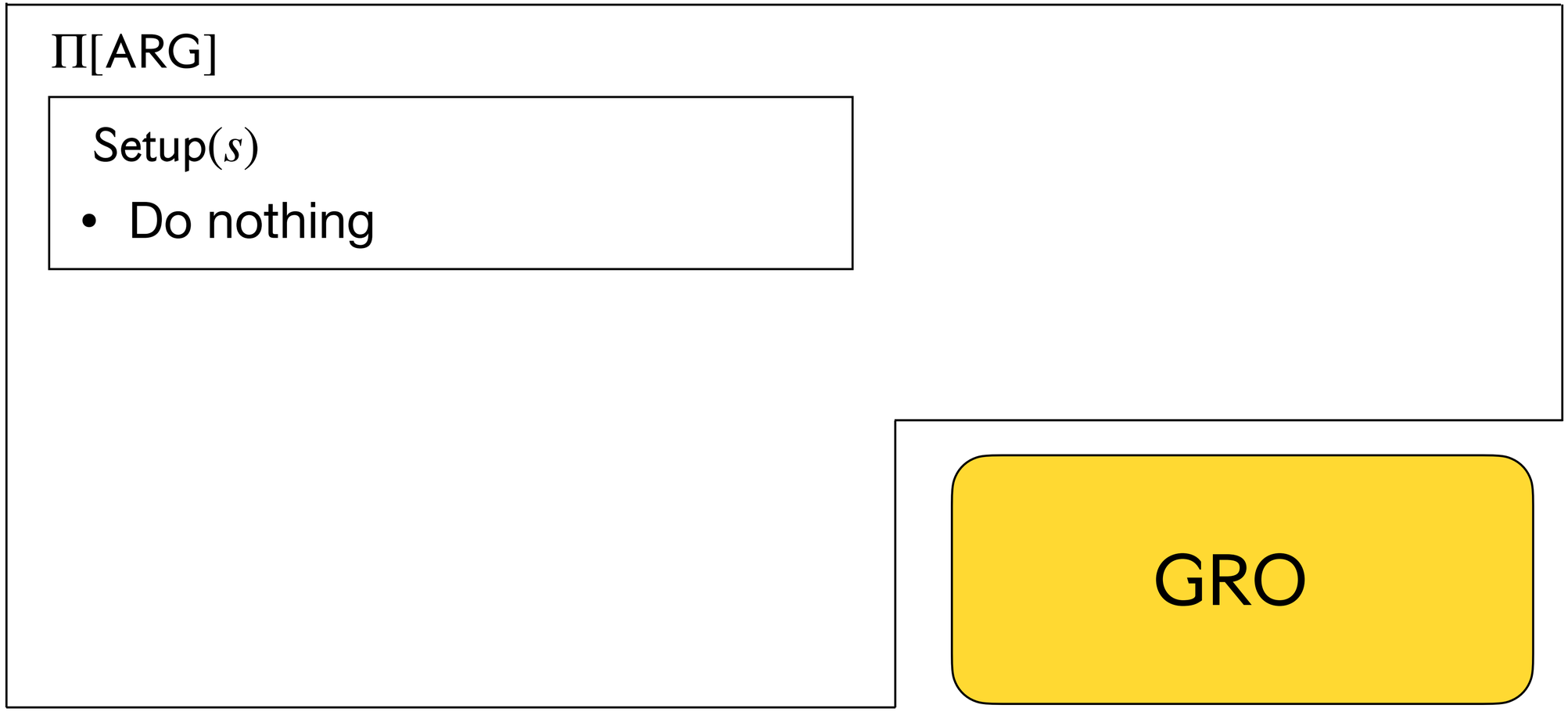

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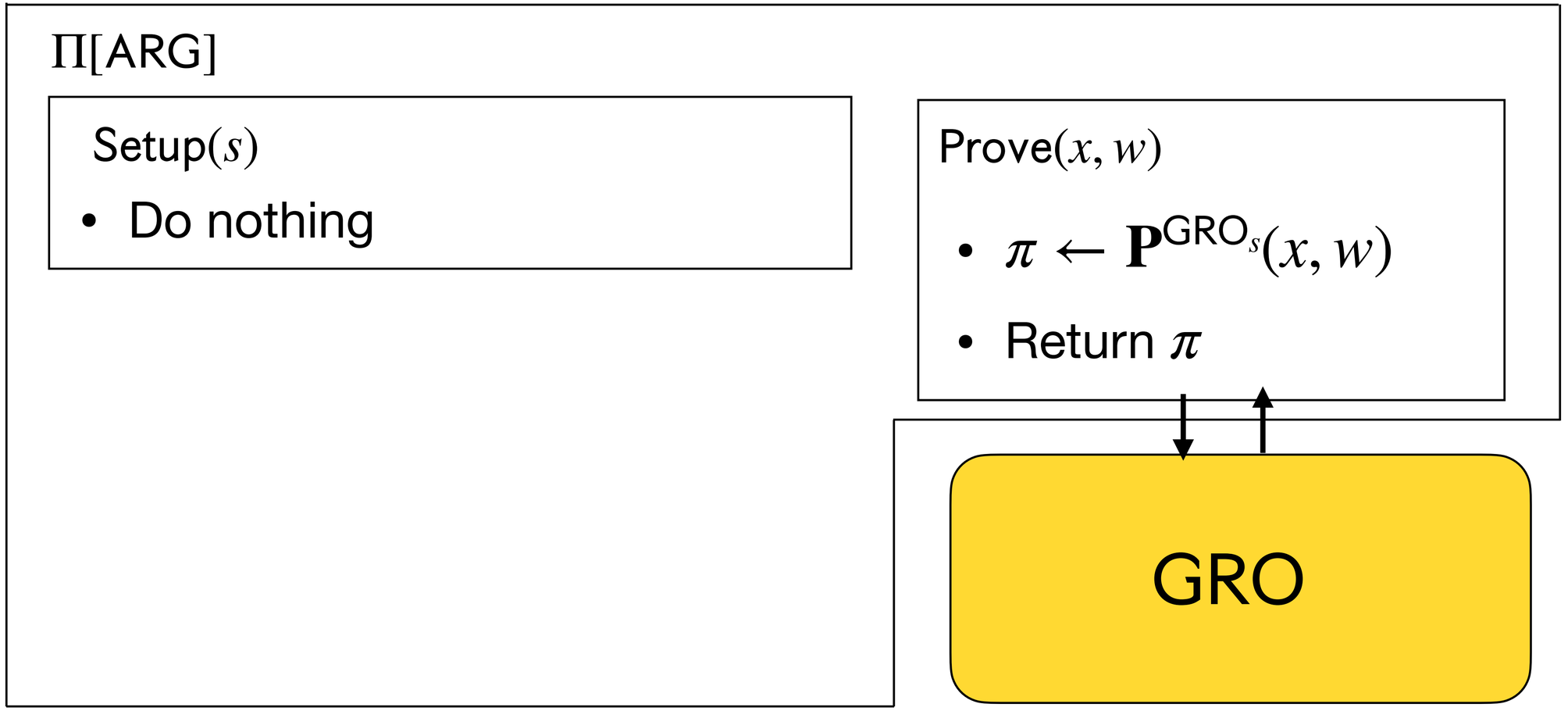

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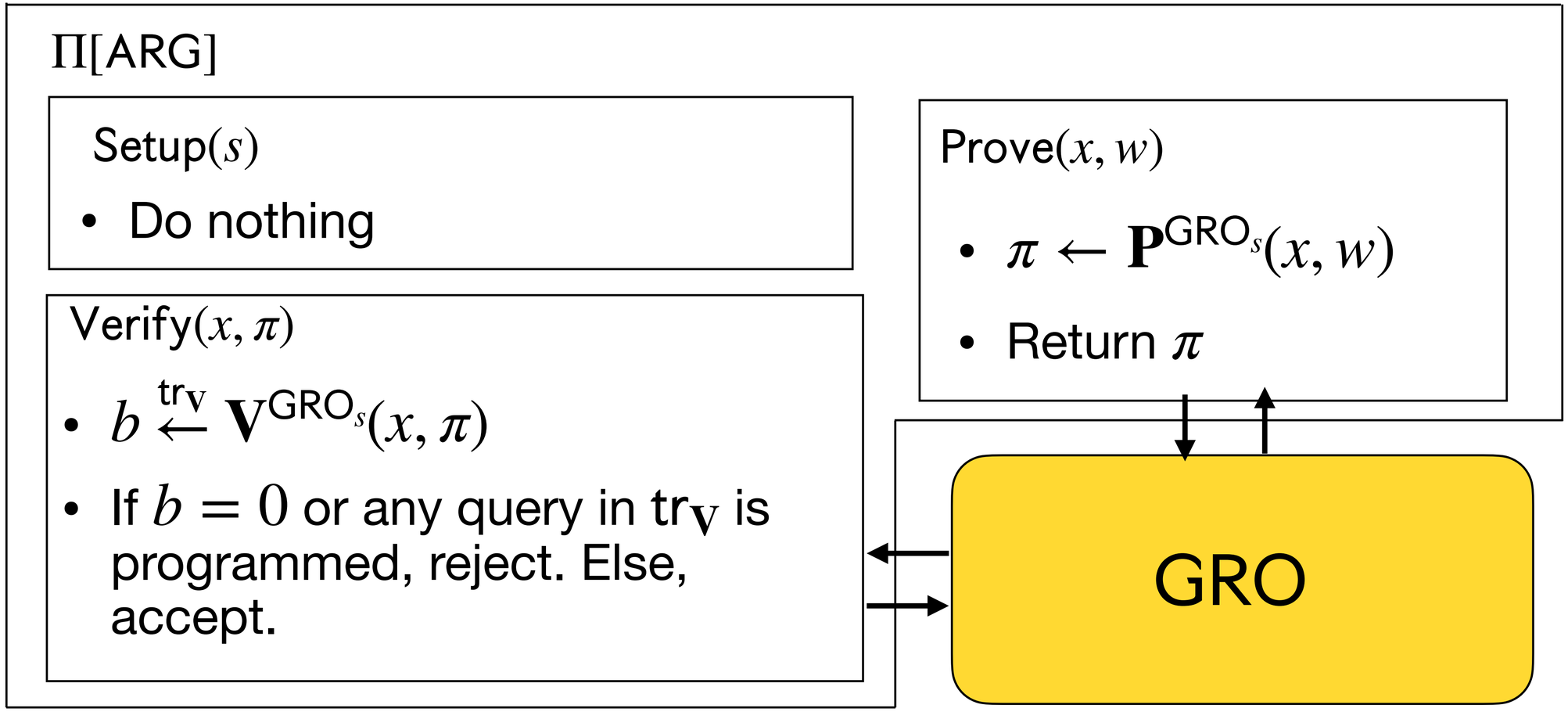

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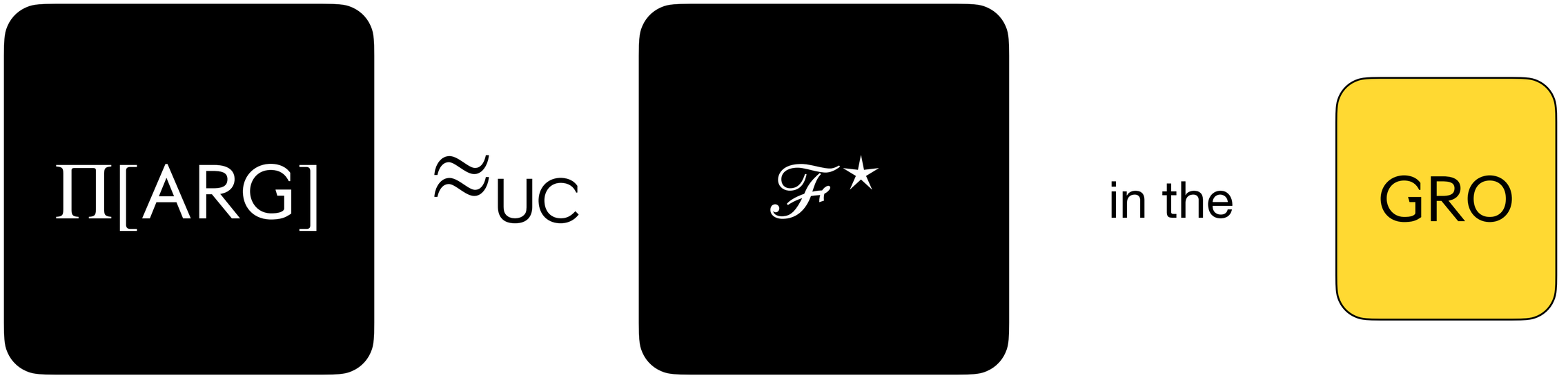

Our results

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, Π[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.

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.*

Techniques

Modelling shared functionalities

[BCHTZ22]

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

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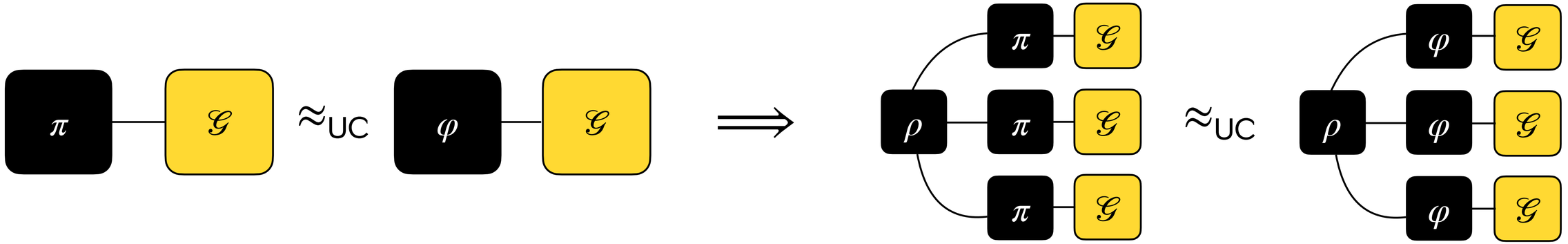

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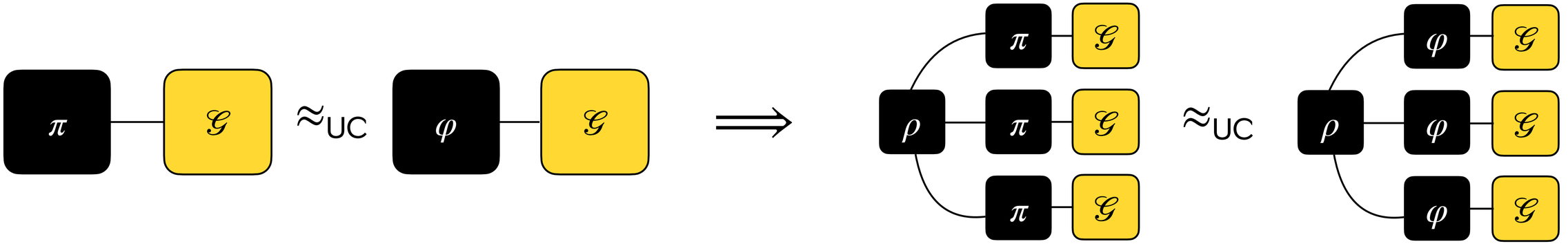

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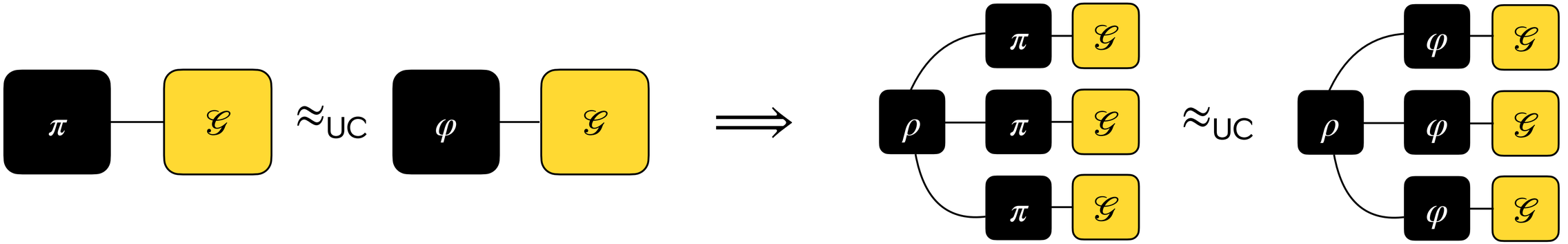

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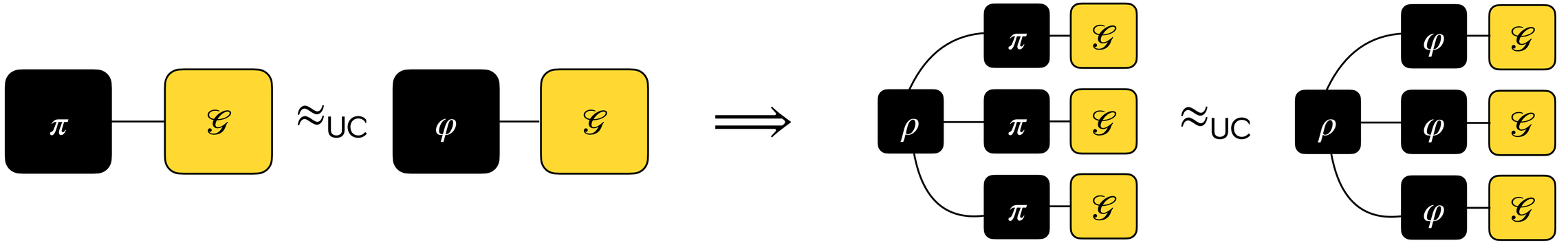

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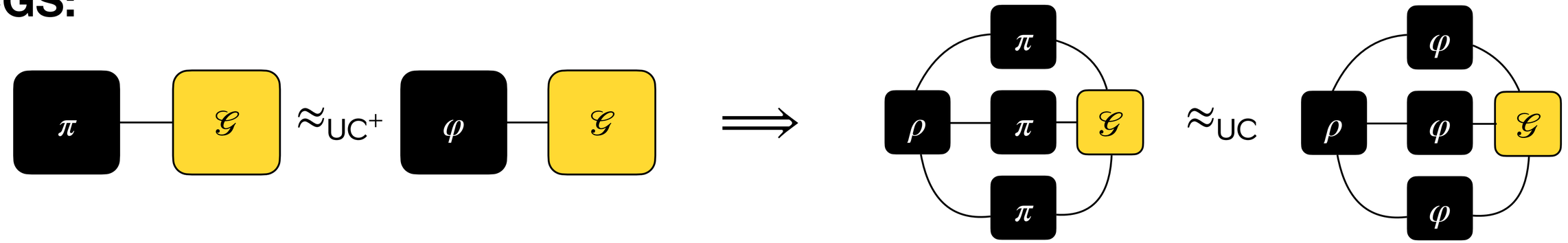

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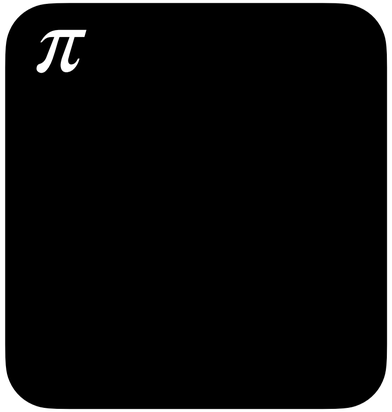

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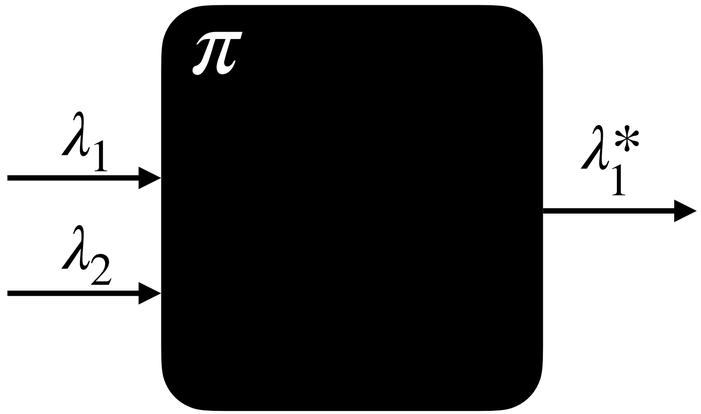

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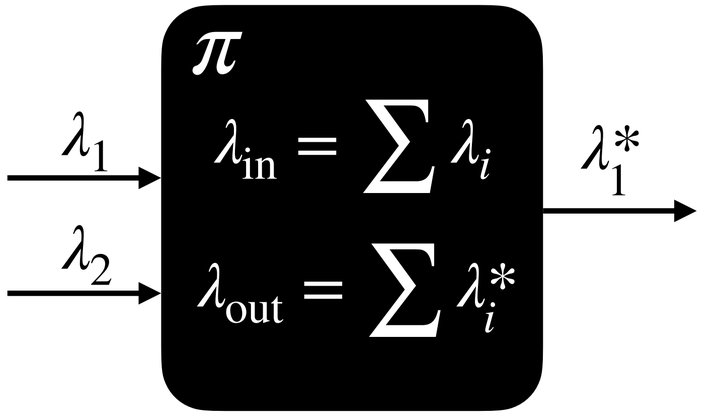

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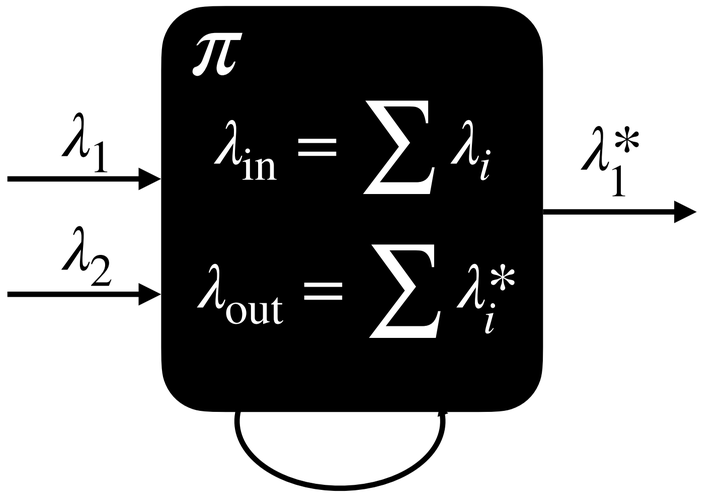

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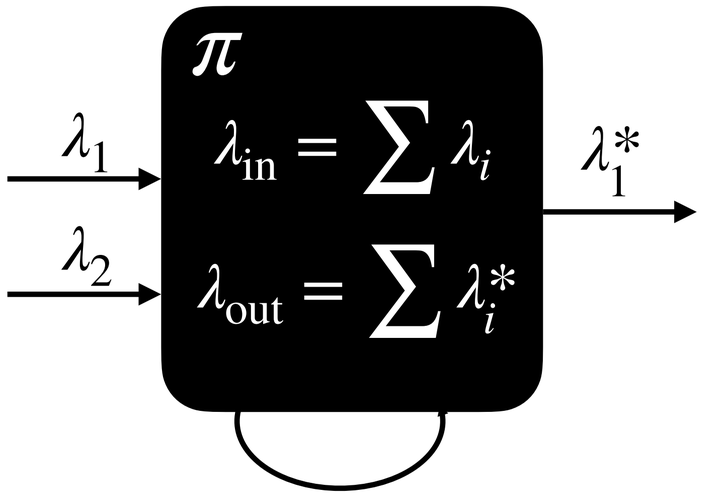

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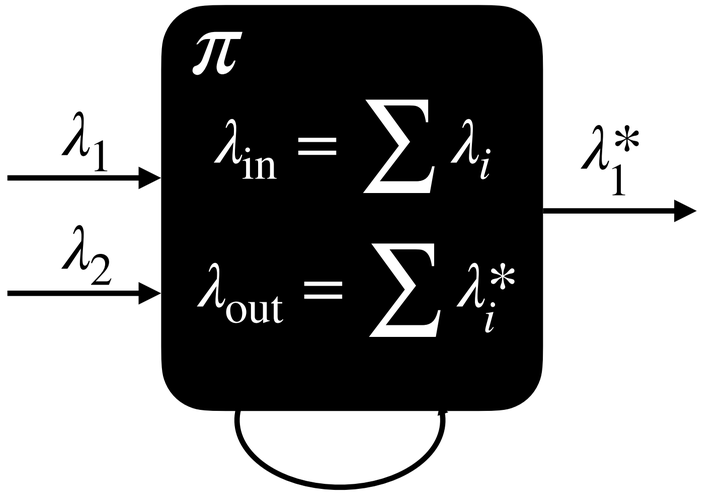

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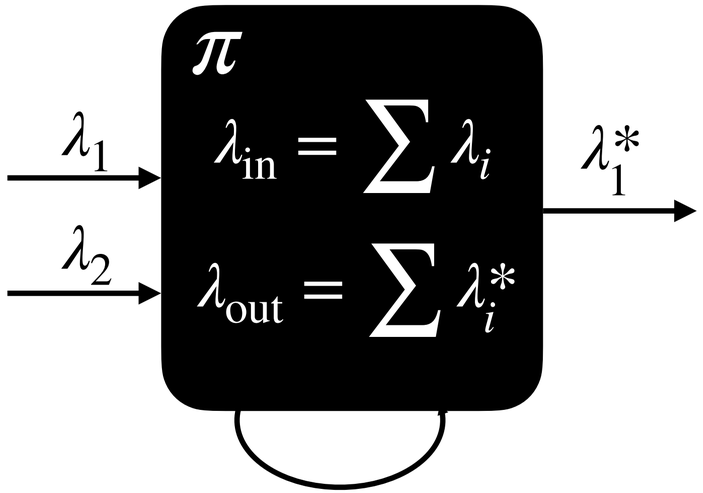

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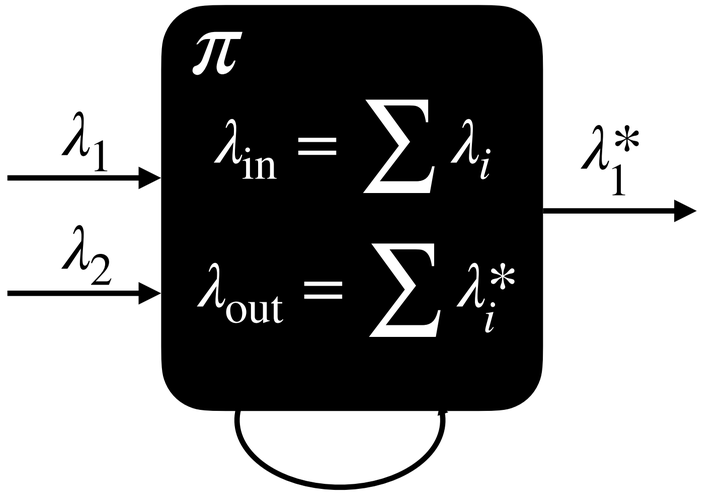

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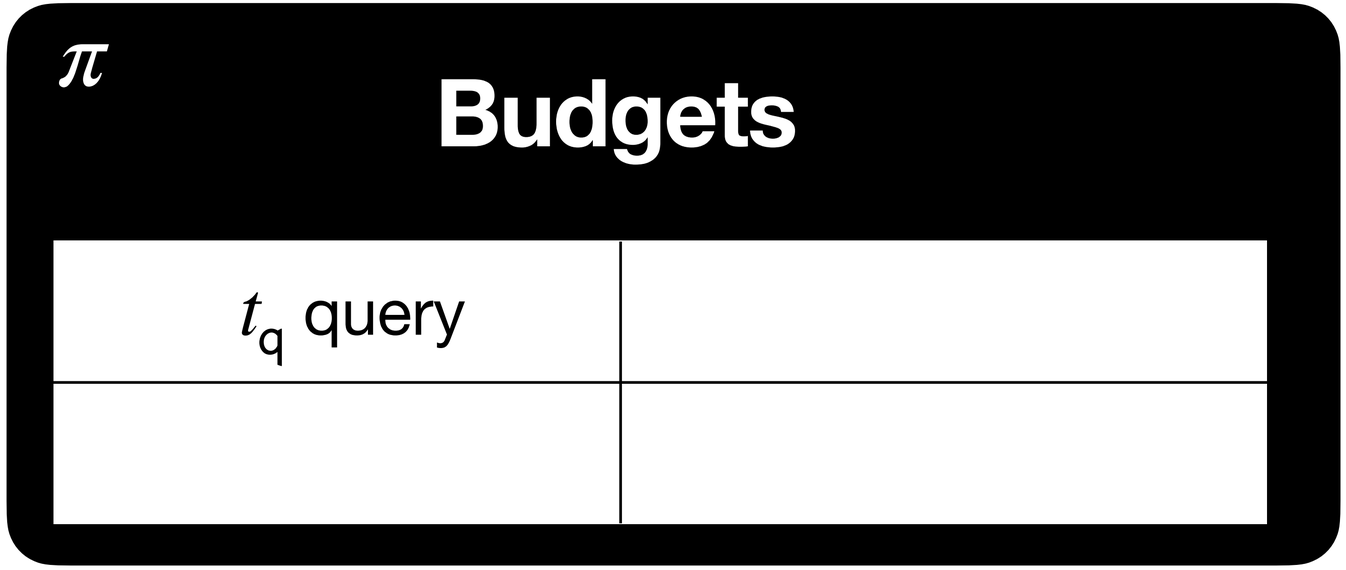

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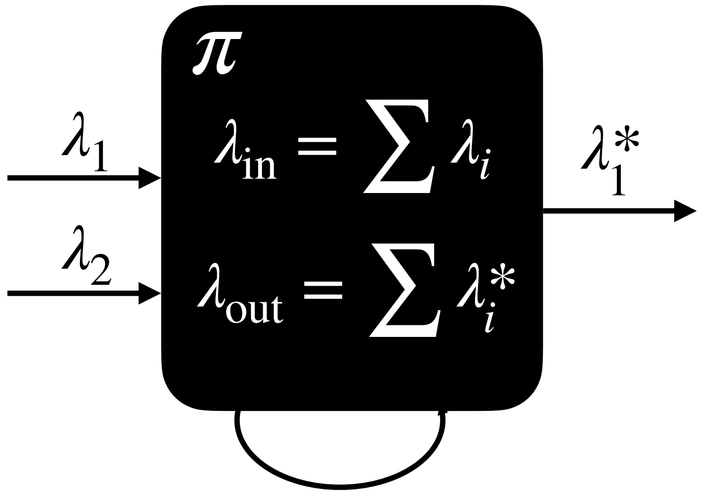

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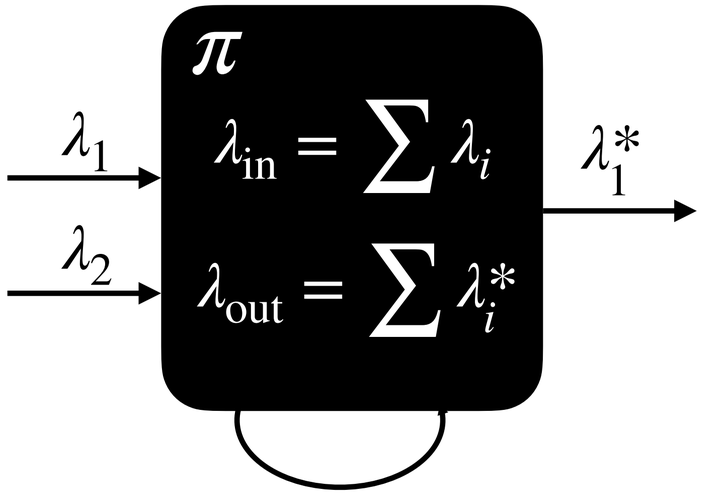

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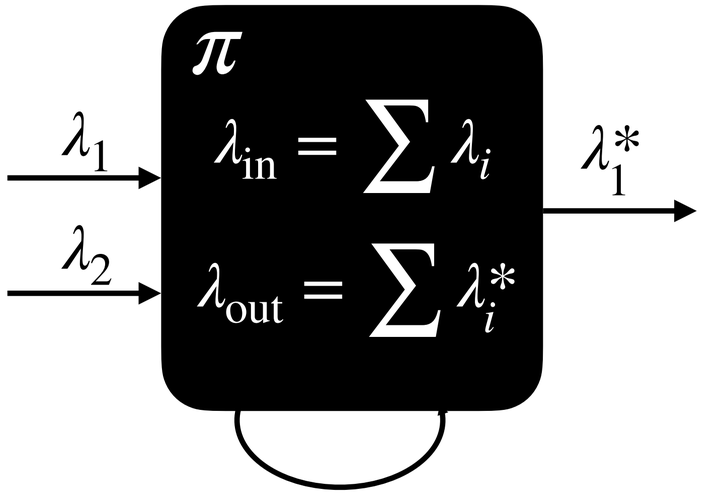

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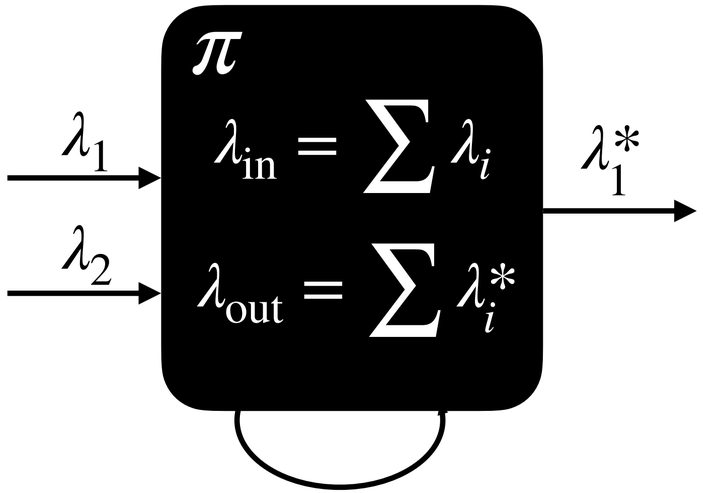

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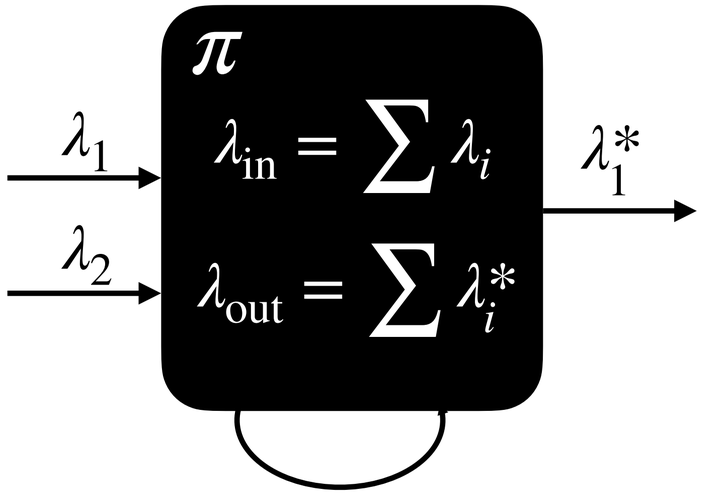

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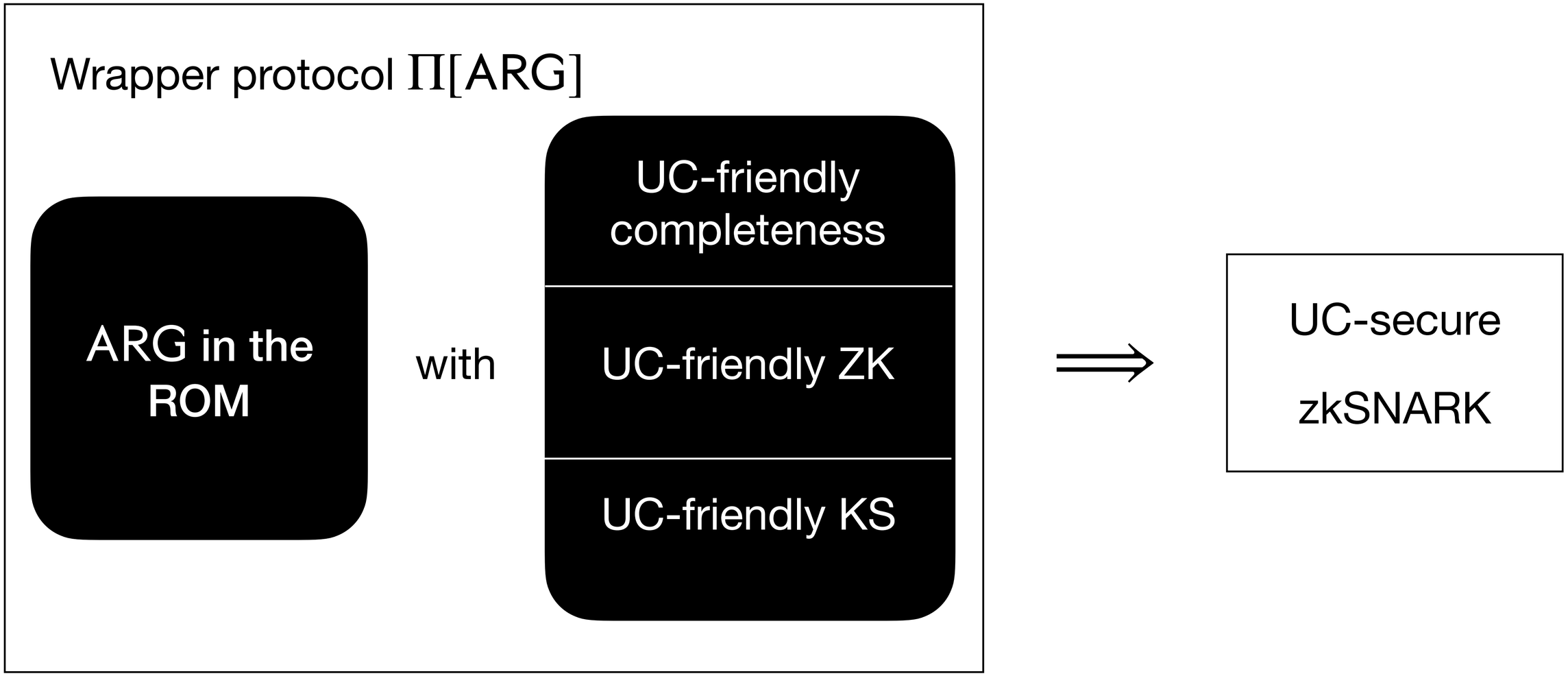
Budget can then be spent on:

GRO

Prove

Verify

Our main lemma



UC-friendly $\Longrightarrow$ UC-secure

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Real $\equiv G_0$

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$G_4 \equiv$ Ideal

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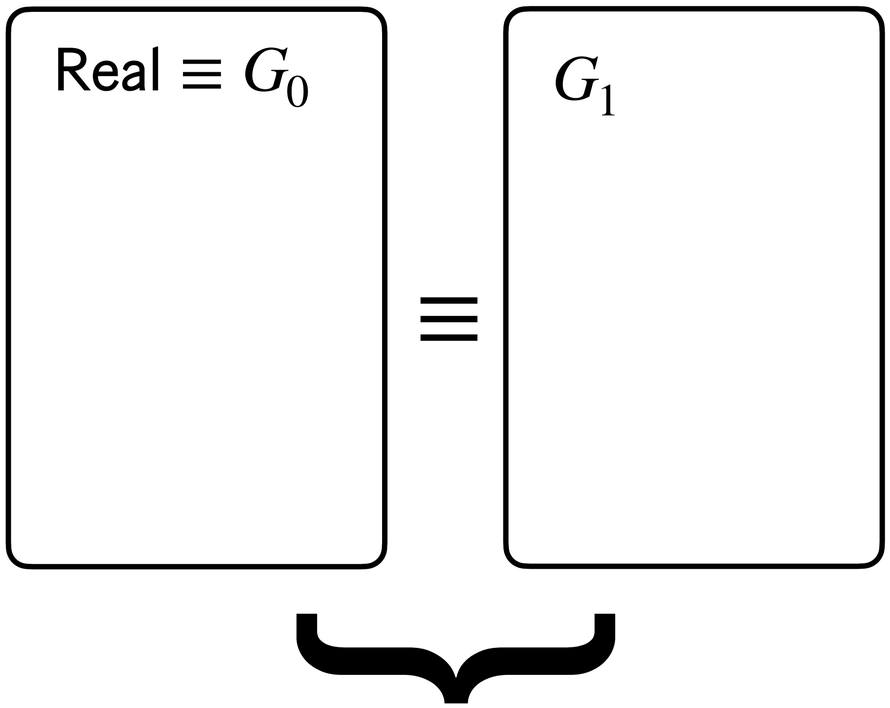
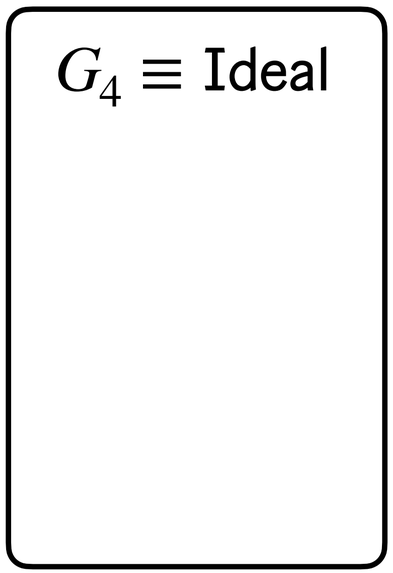


Simulator can program undetectably



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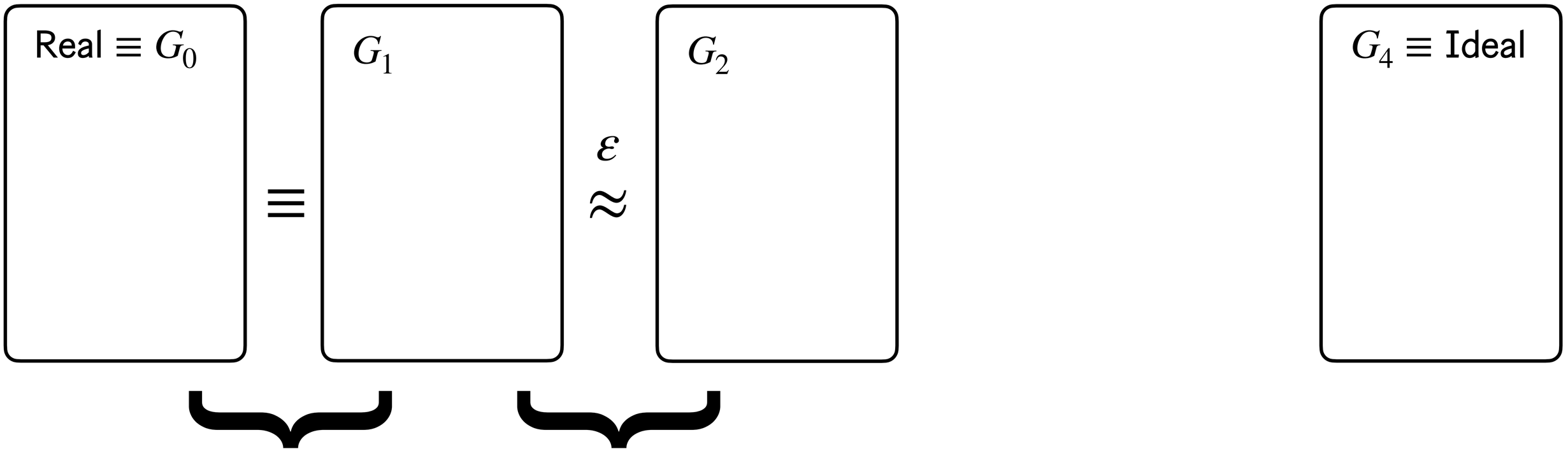

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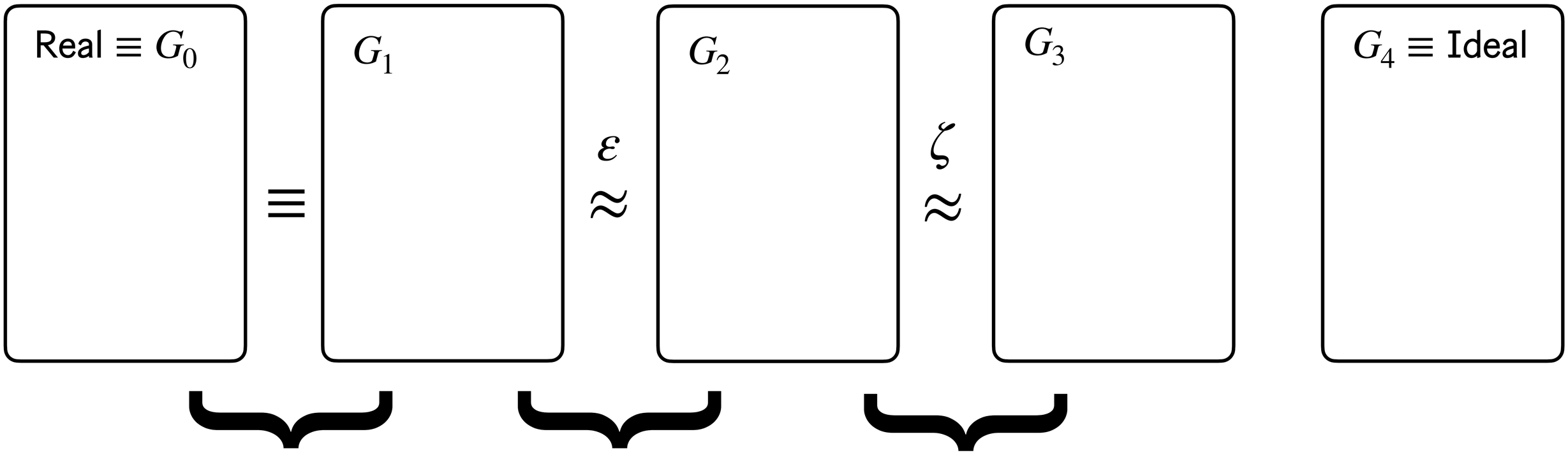

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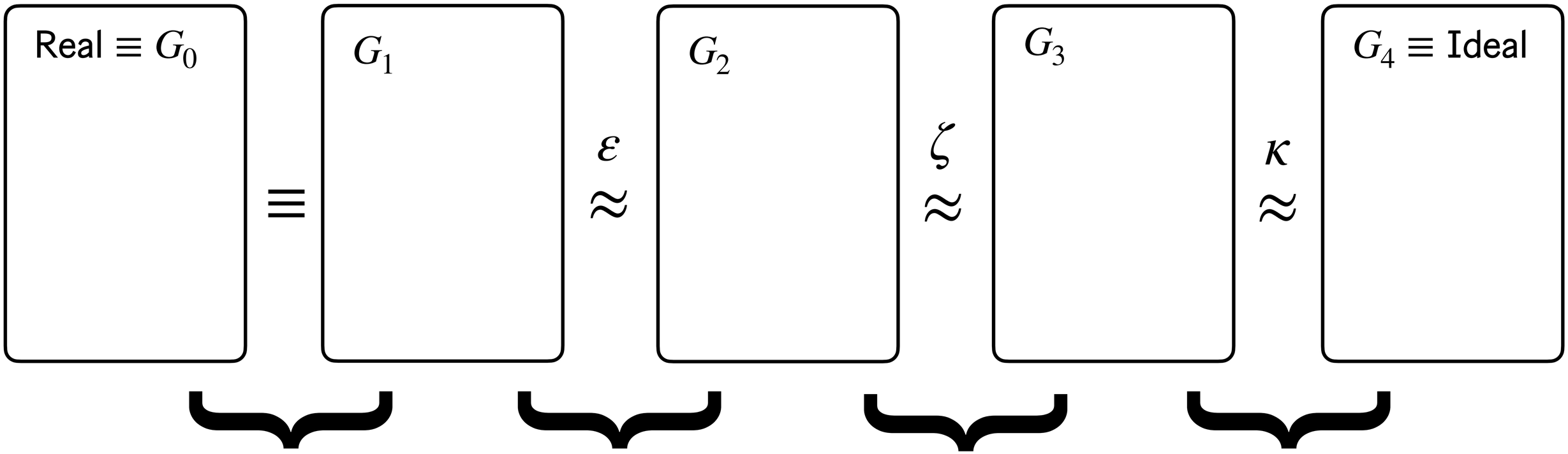
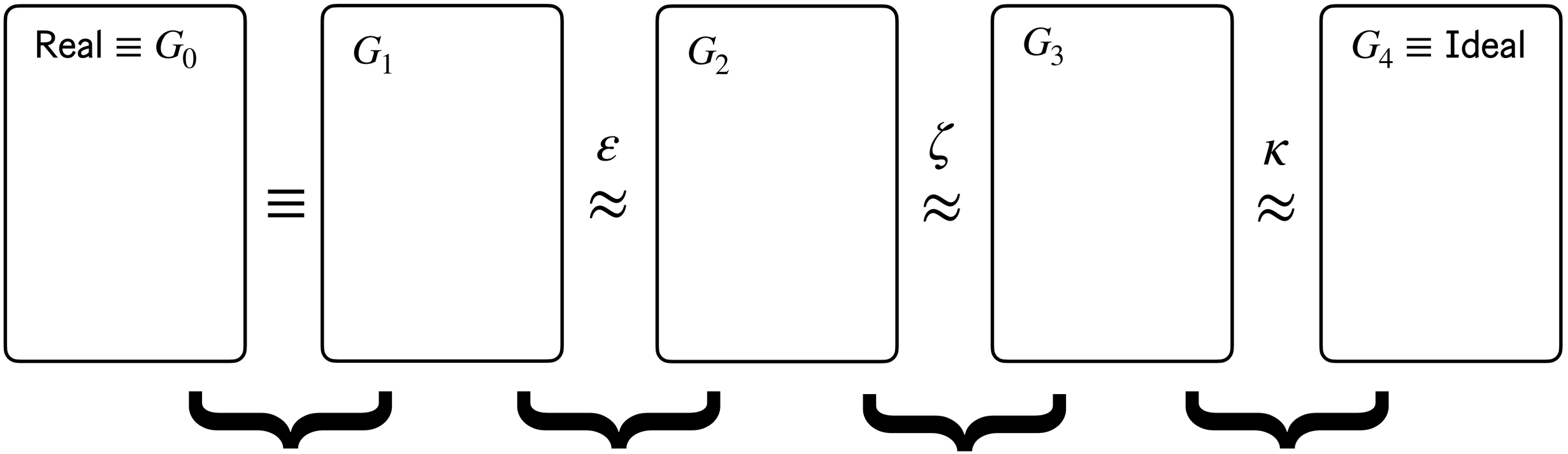


UC-friendly $\Longrightarrow$ UC-secure

UC-friendly properties exactly defined for these game hops



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SIAM J. COMPUT.
Vol. 30, No. 4, pp. 1253–1298

COMPUTATIONALLY SOUND PROOFS*

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

Micali’s construction II

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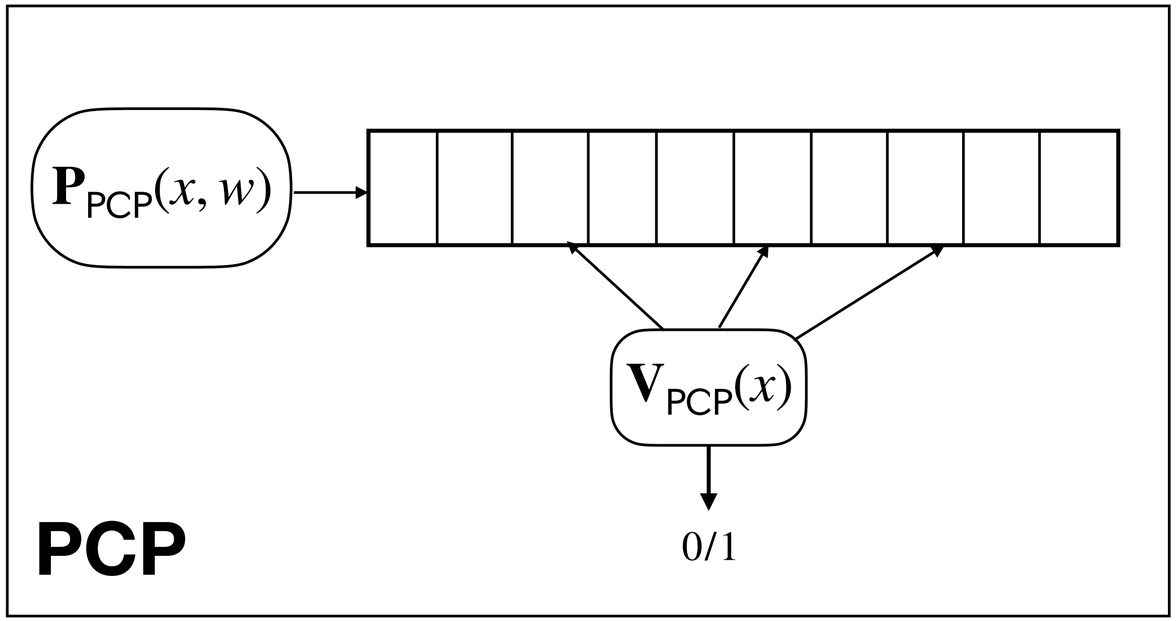

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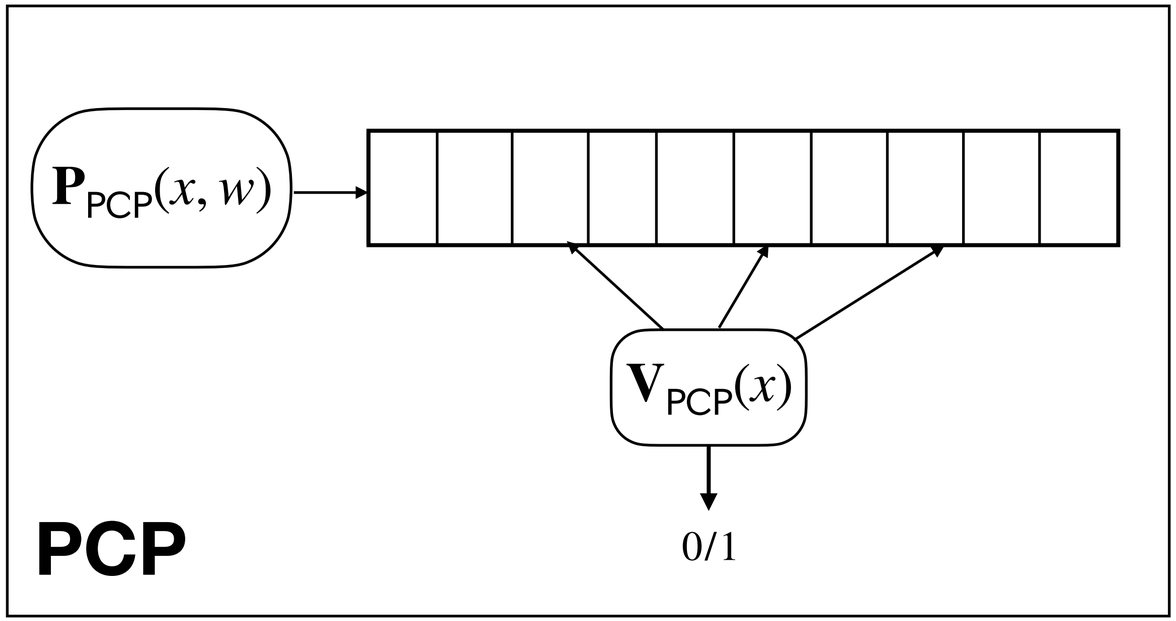

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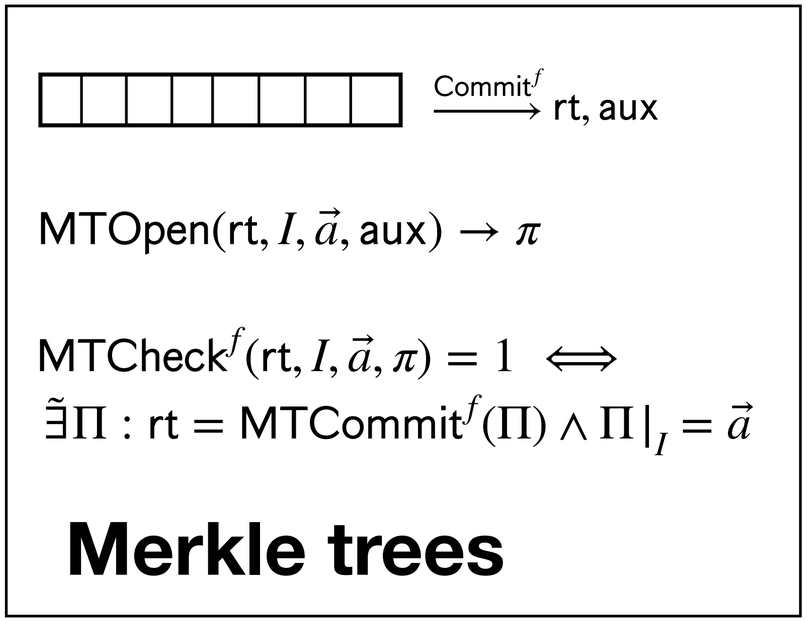

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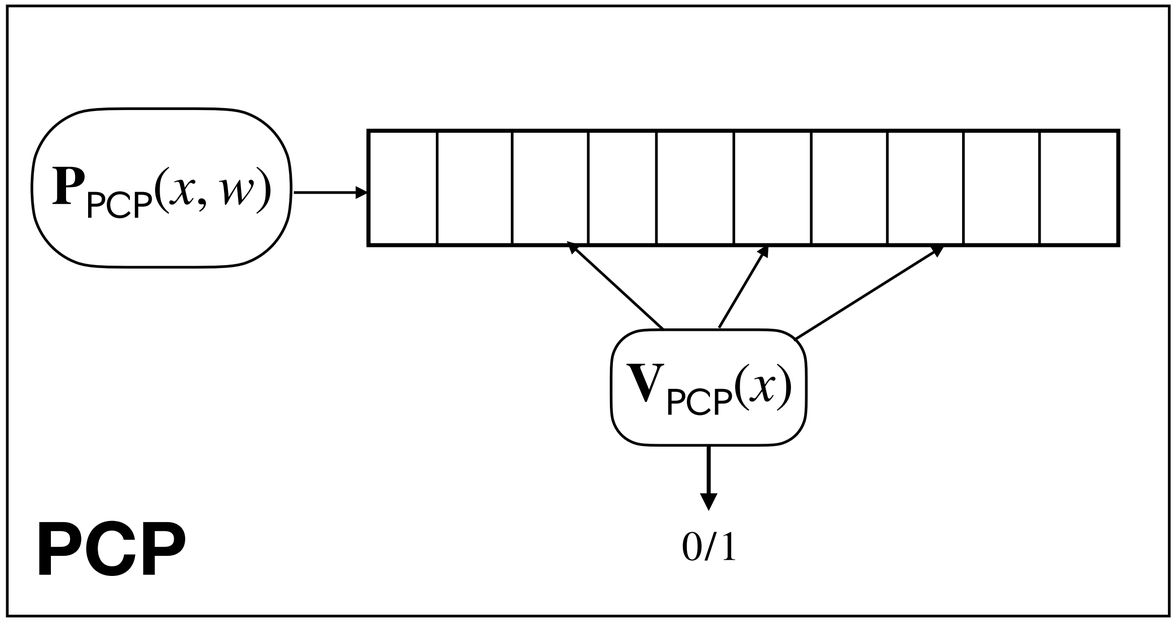

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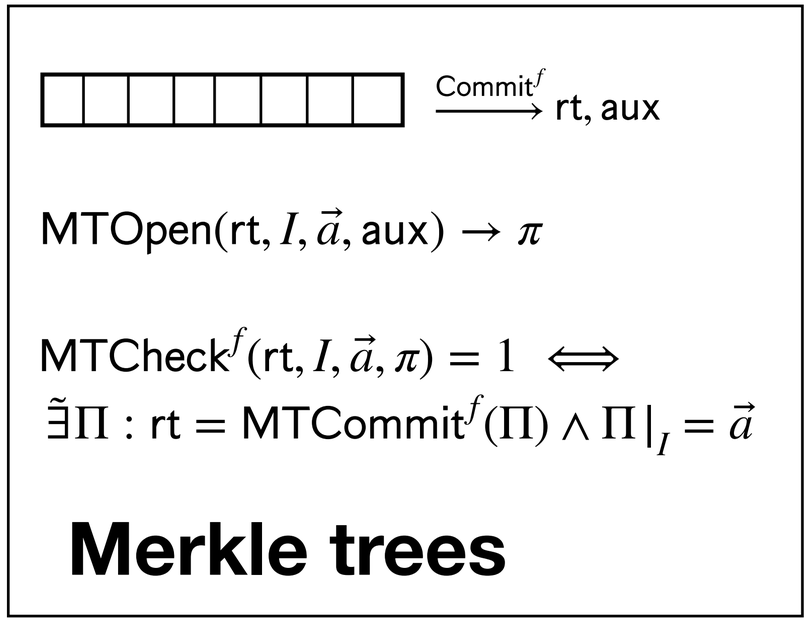

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Fiat Shamir

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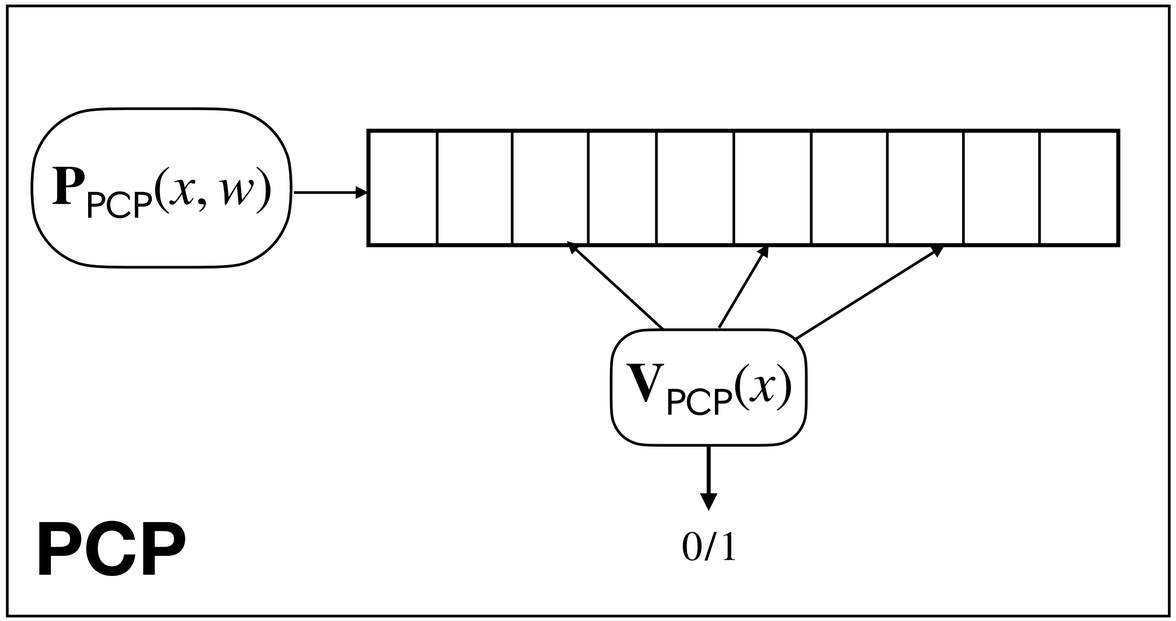

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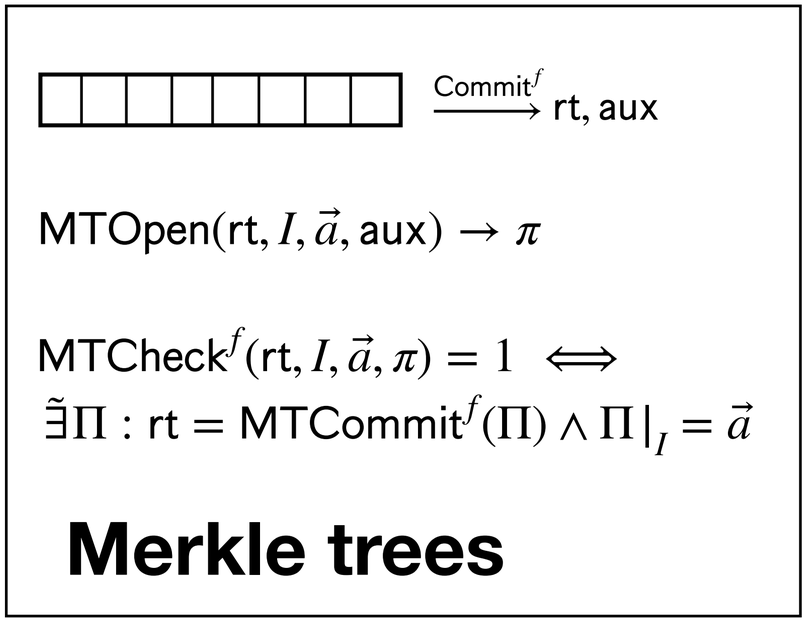

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zkSNARK in the ROM

Micali’s construction III

Commit to PCP string using MT,
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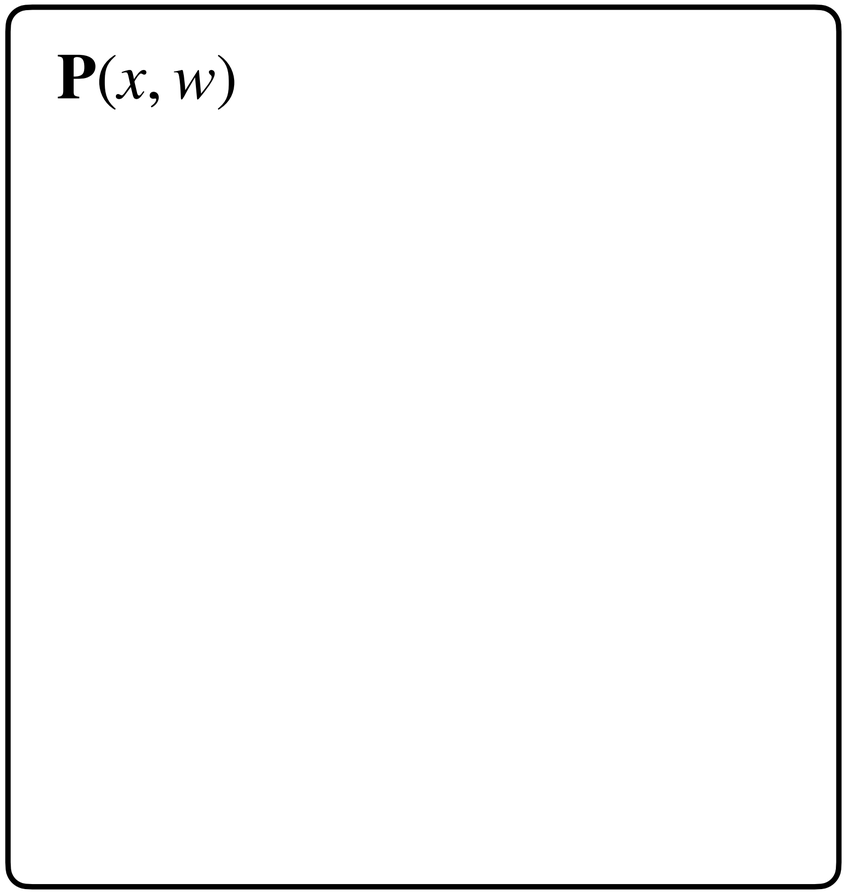

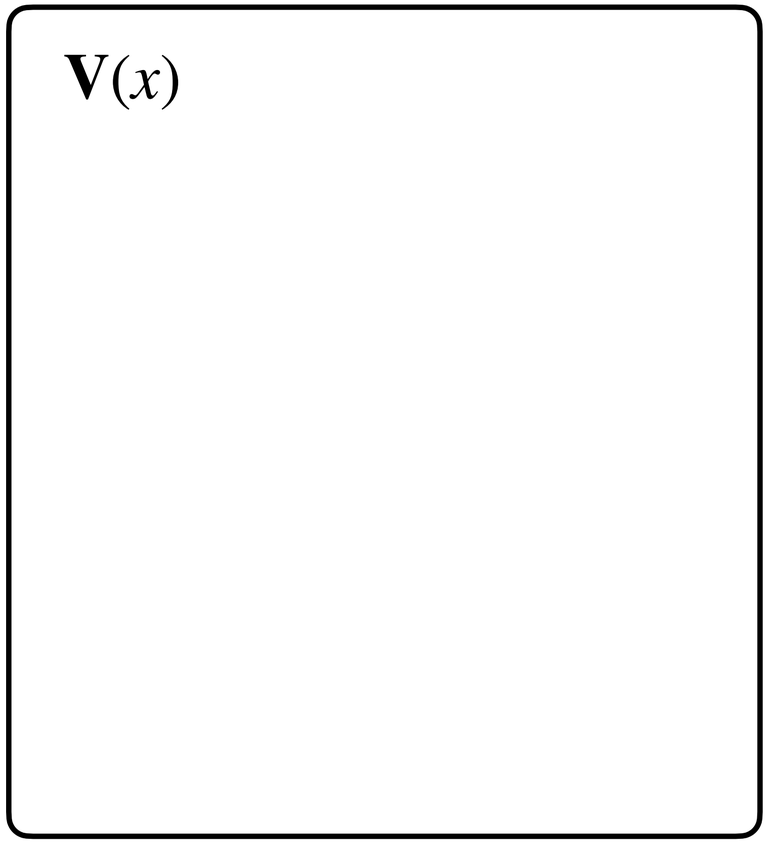

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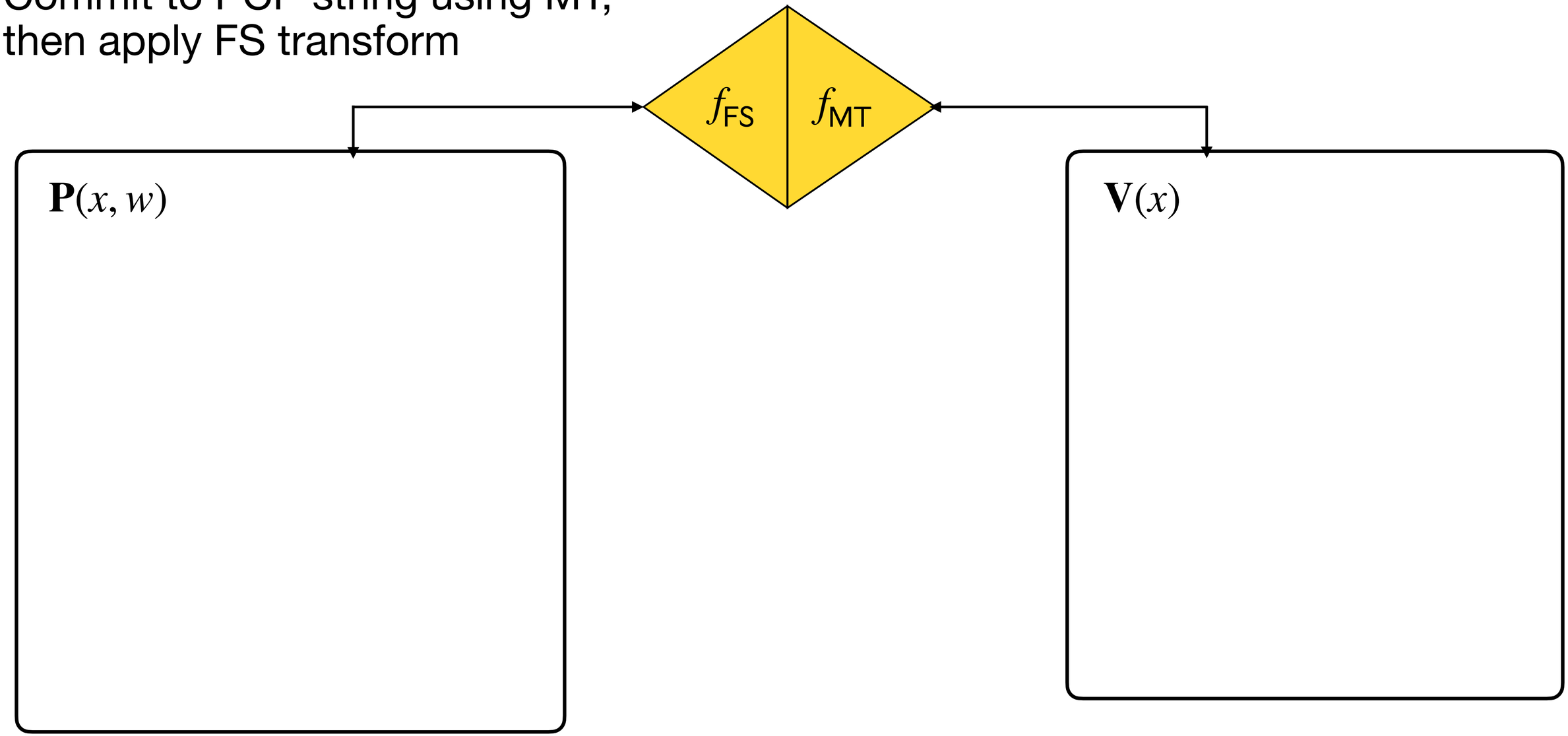

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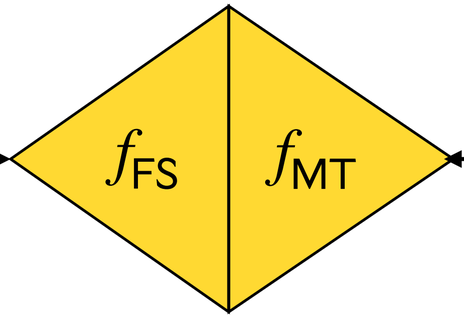

$\mathbf{P}(x, w)$

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

$\mathbf{V}(x)$

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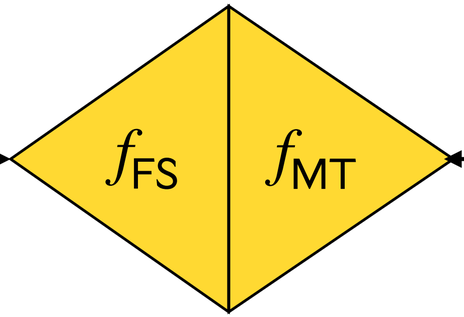

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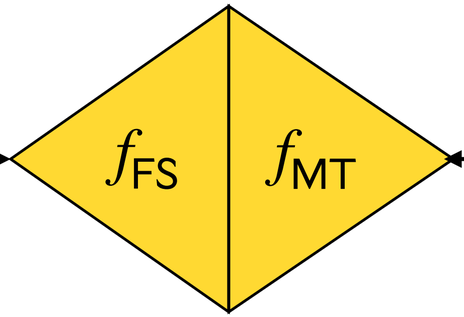

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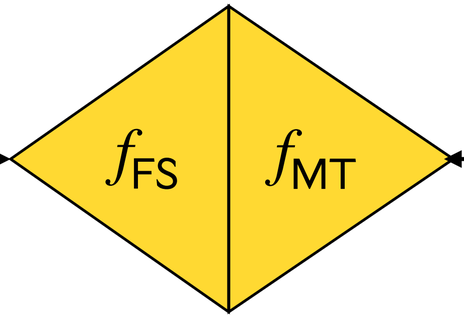

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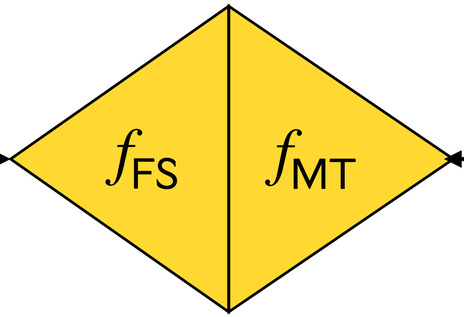

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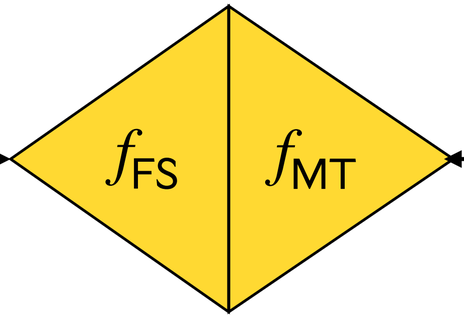

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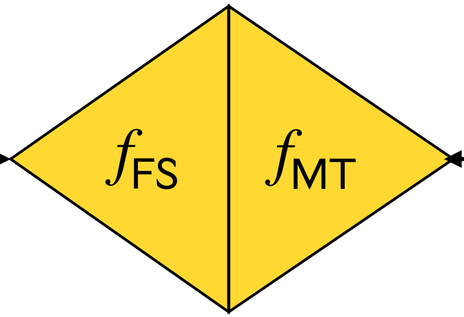

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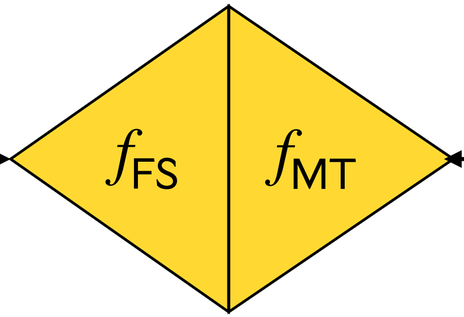

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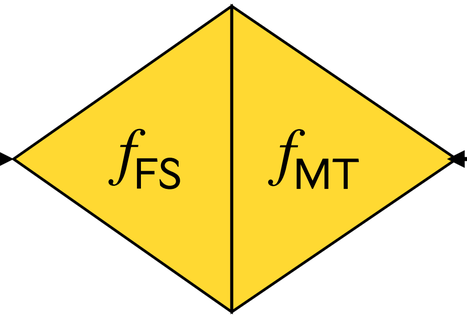

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$\mathbf{V}(x)$

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

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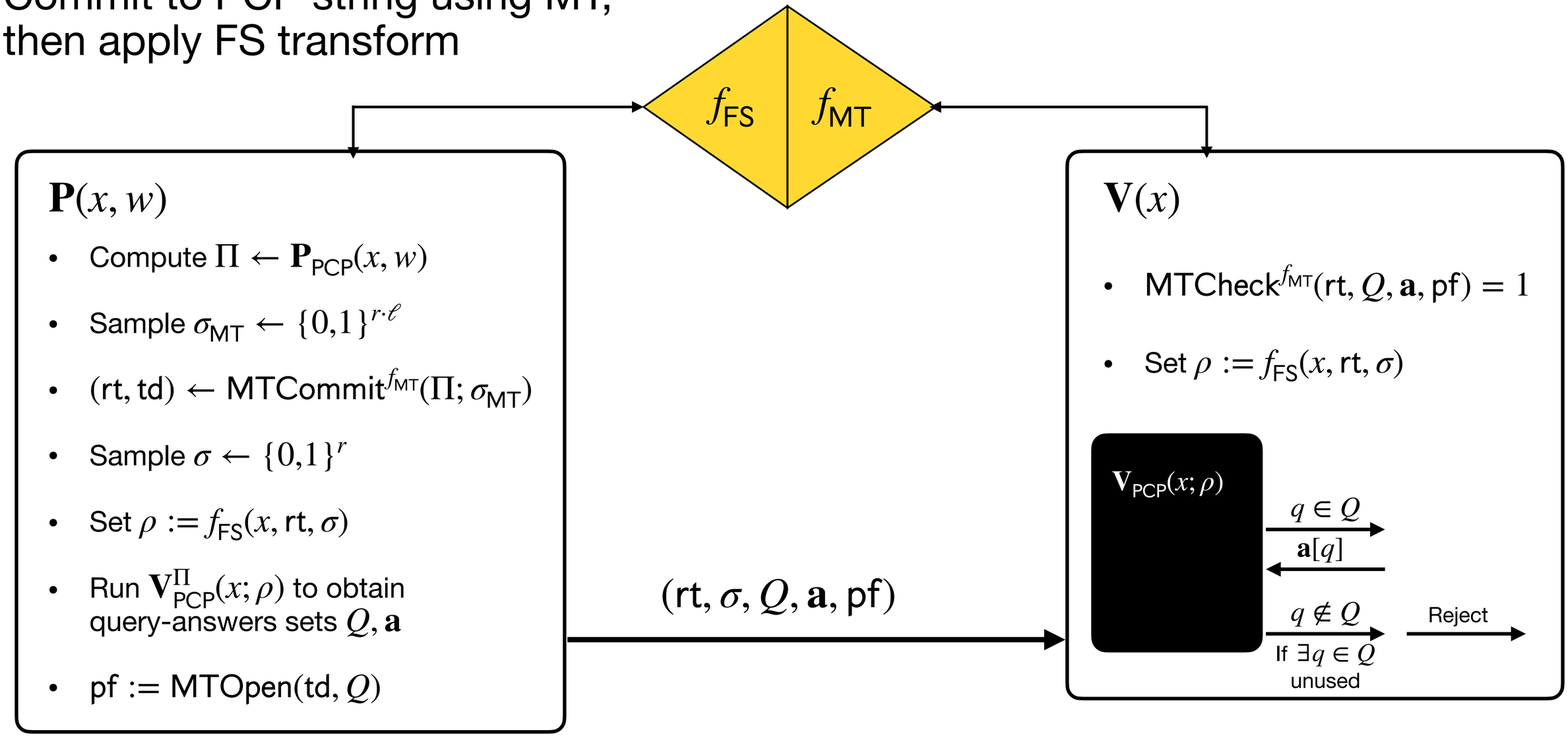

UC-friendly completeness

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

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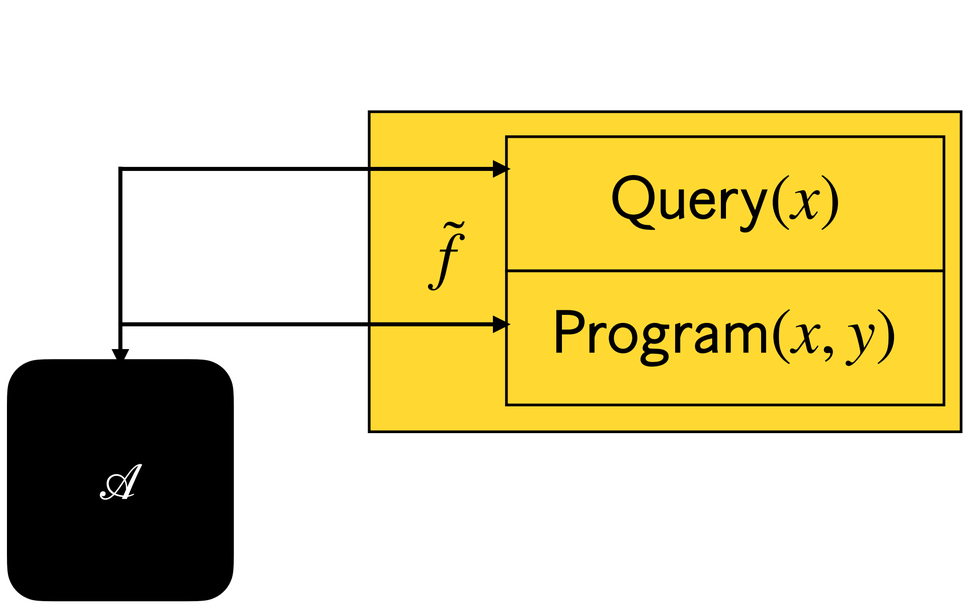

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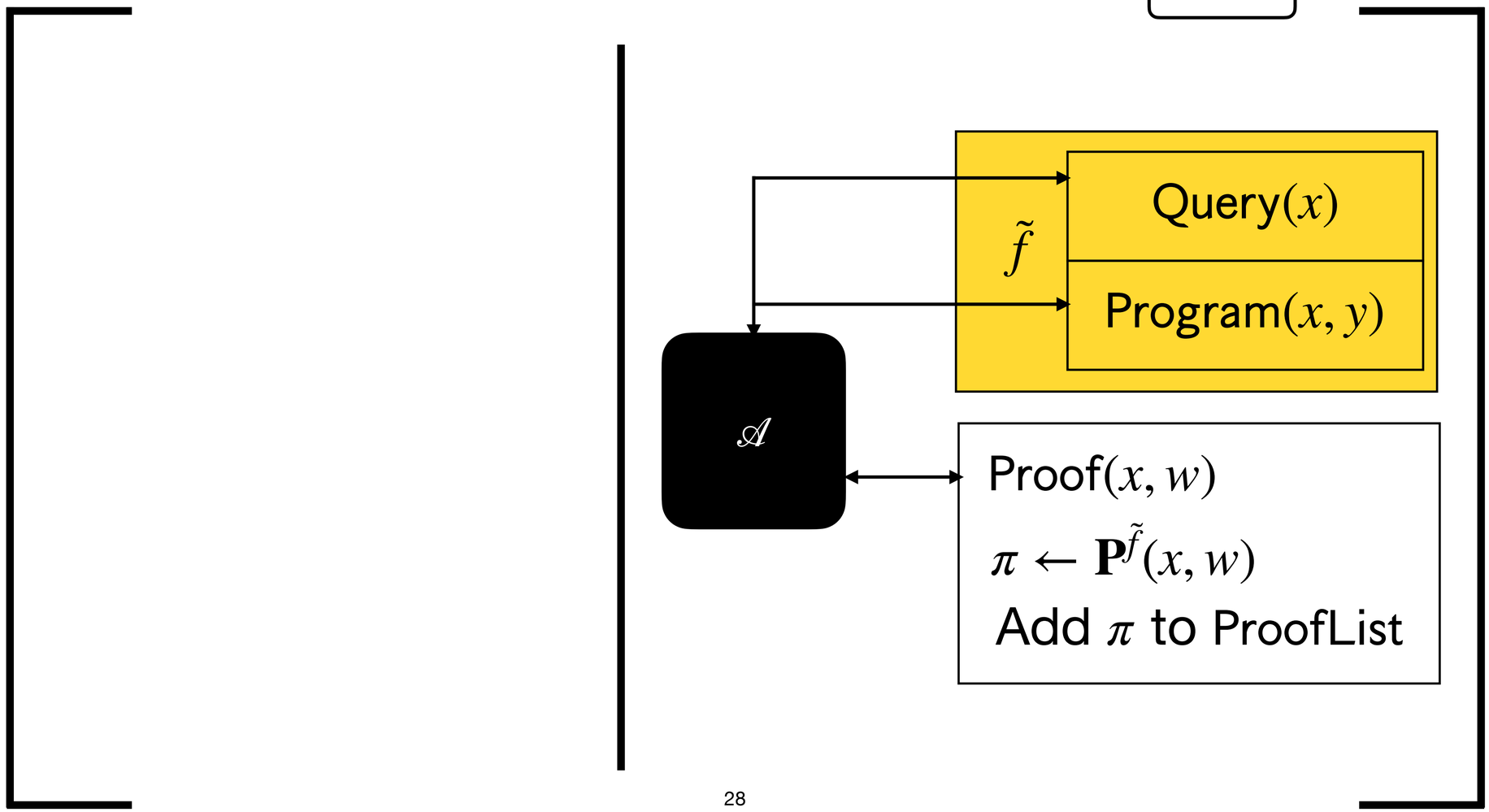

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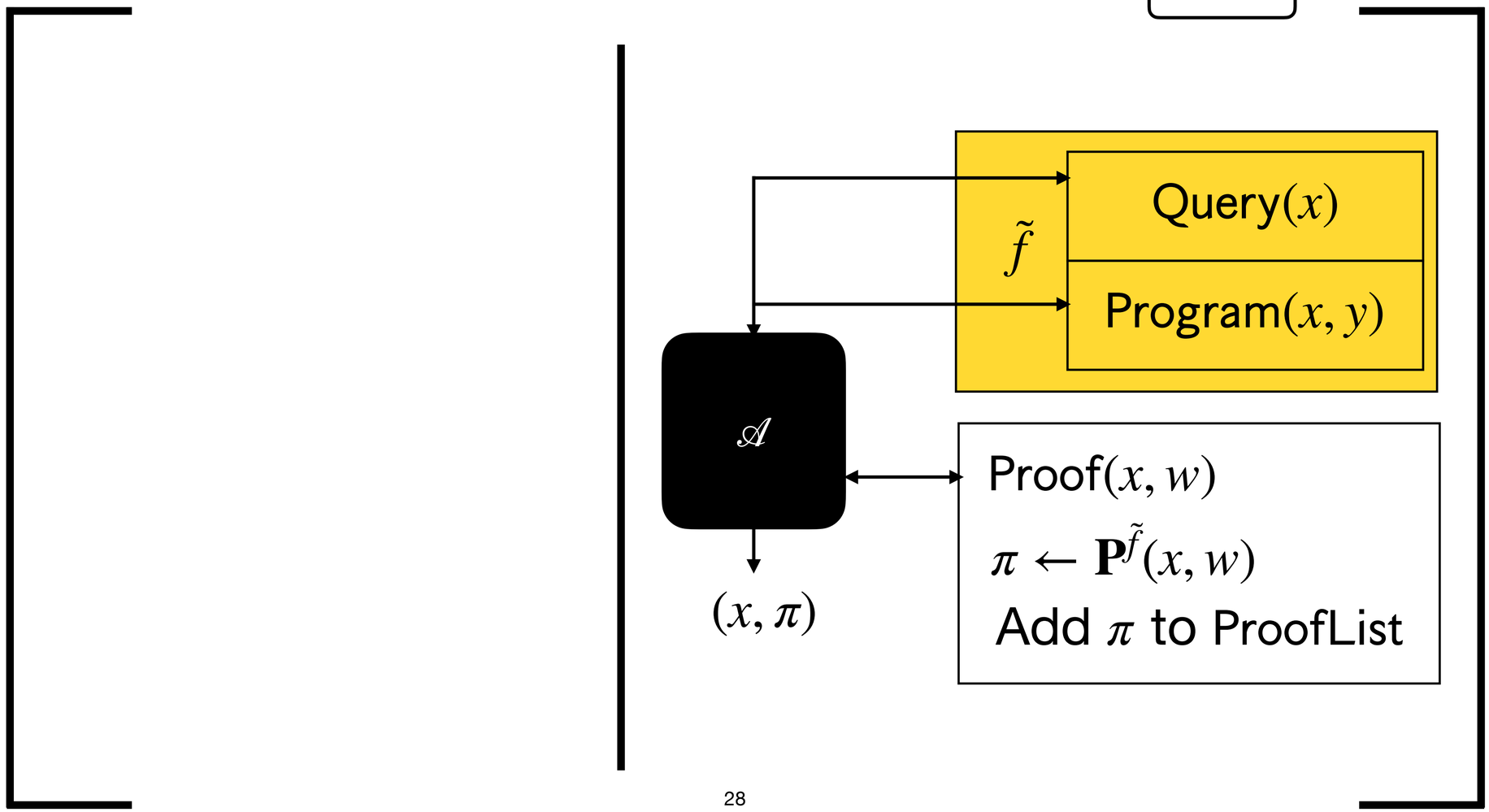

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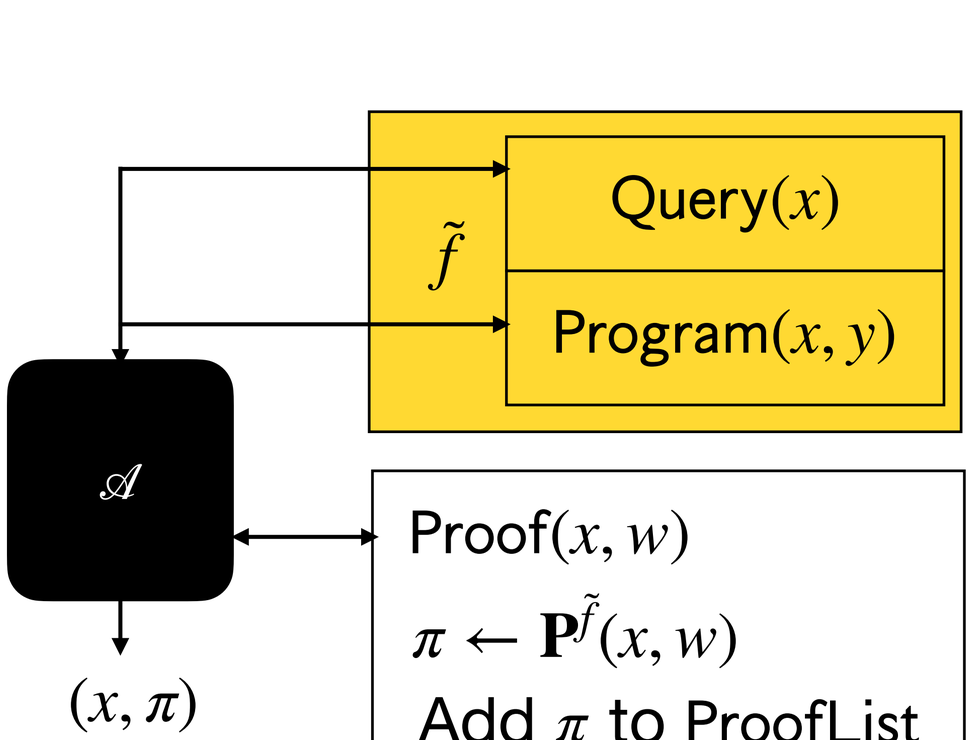

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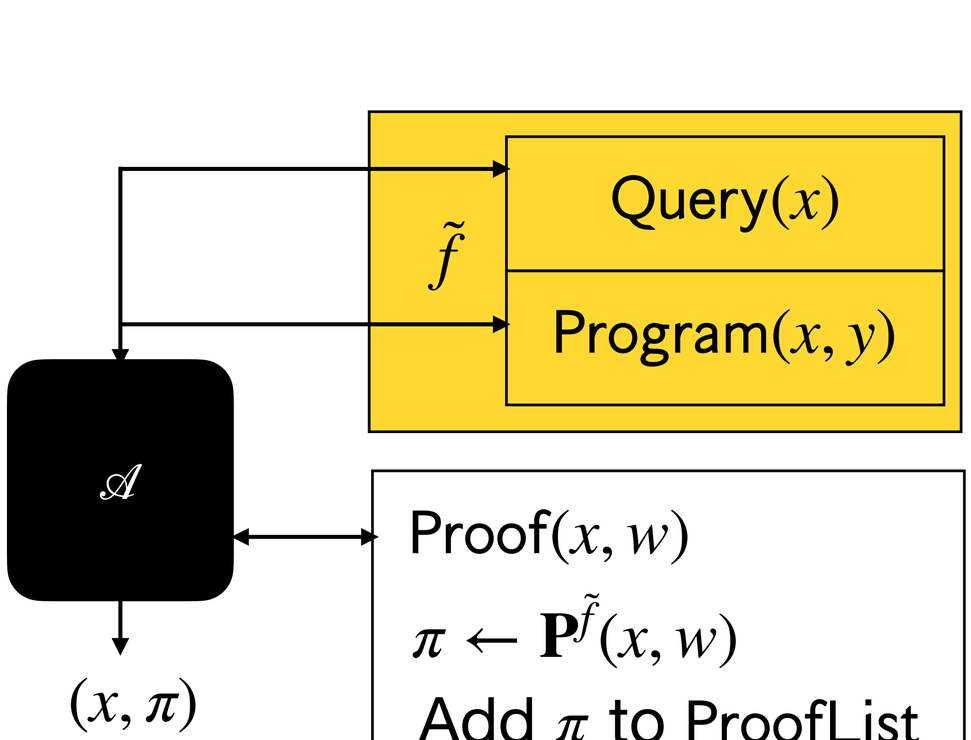

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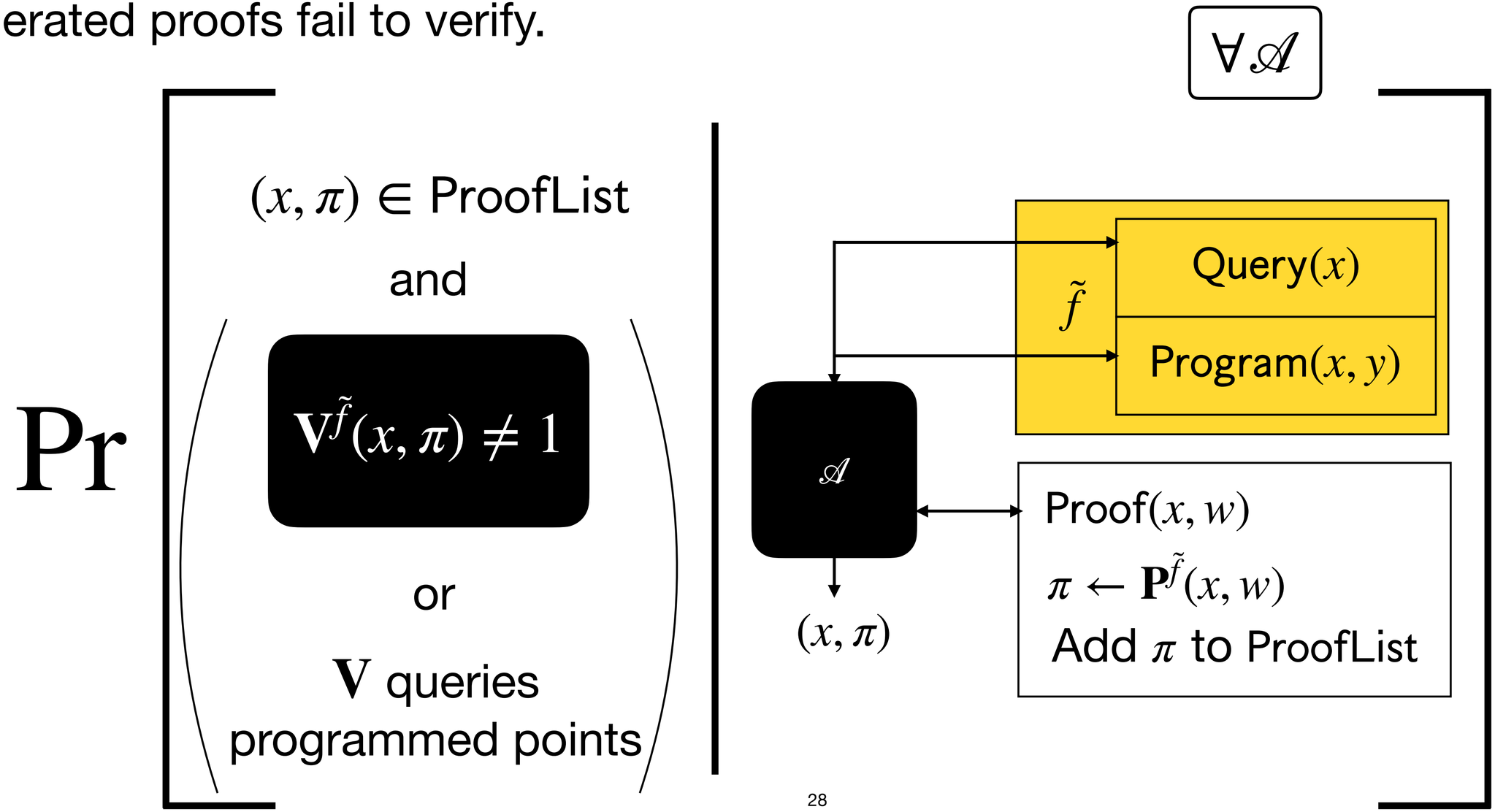

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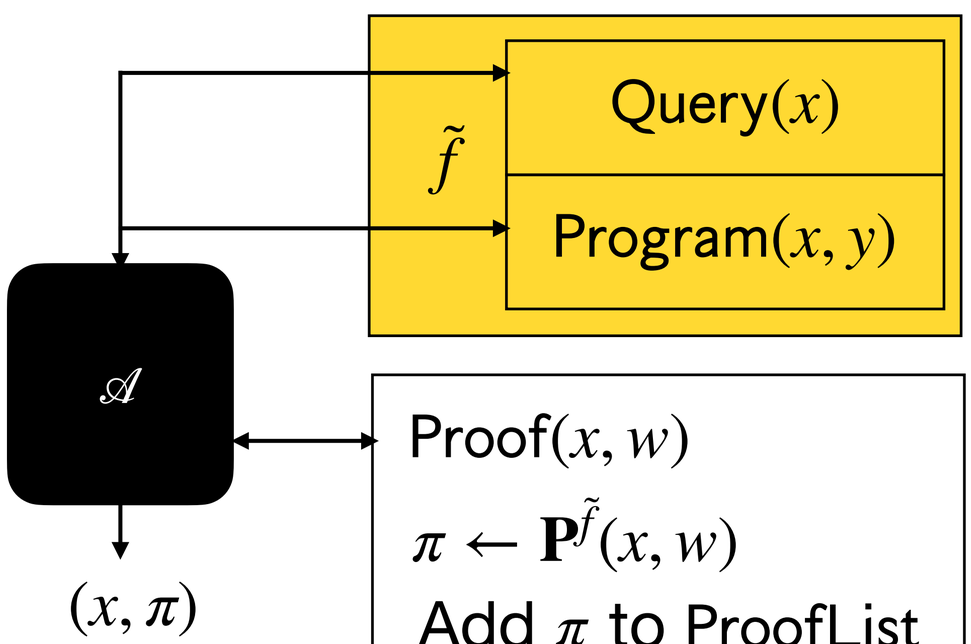

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Adversary should not be able to distinguish real and simulated proofs, even with access to a programming oracle.

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

s.t

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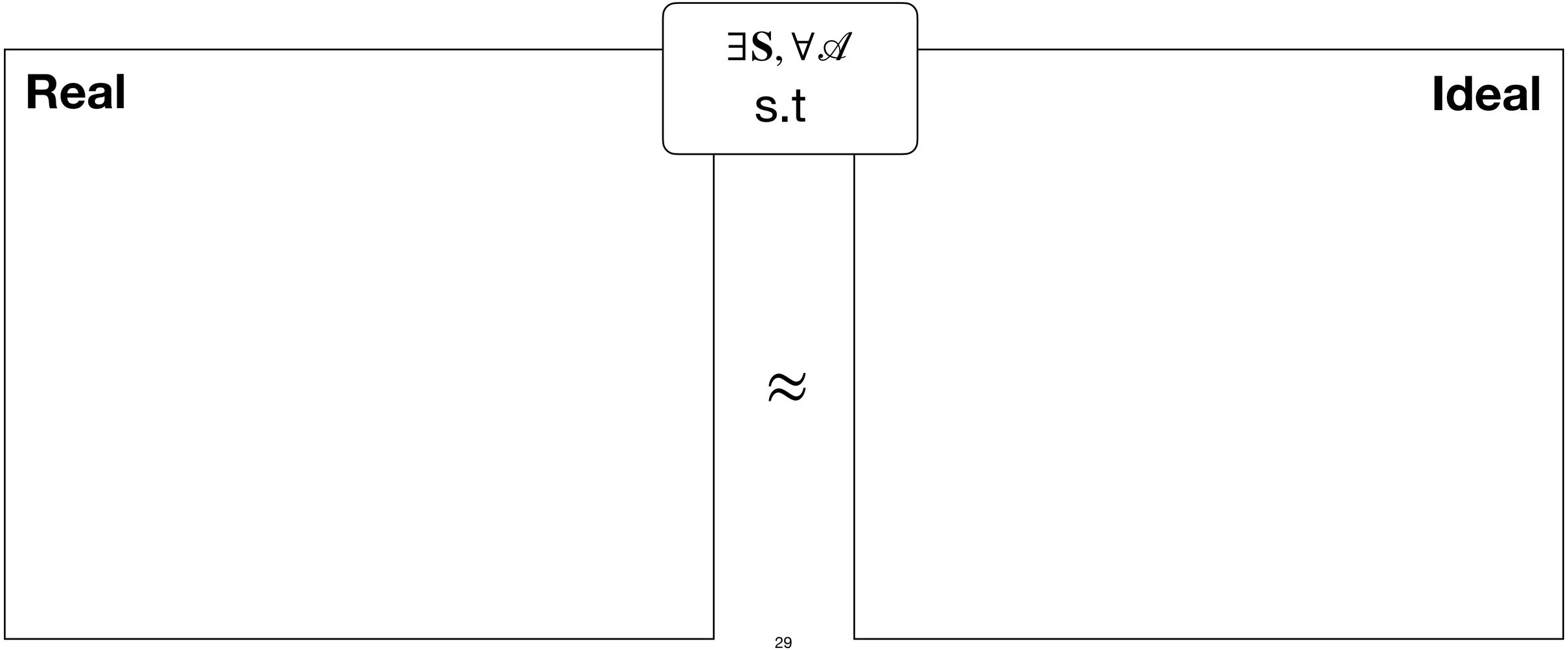

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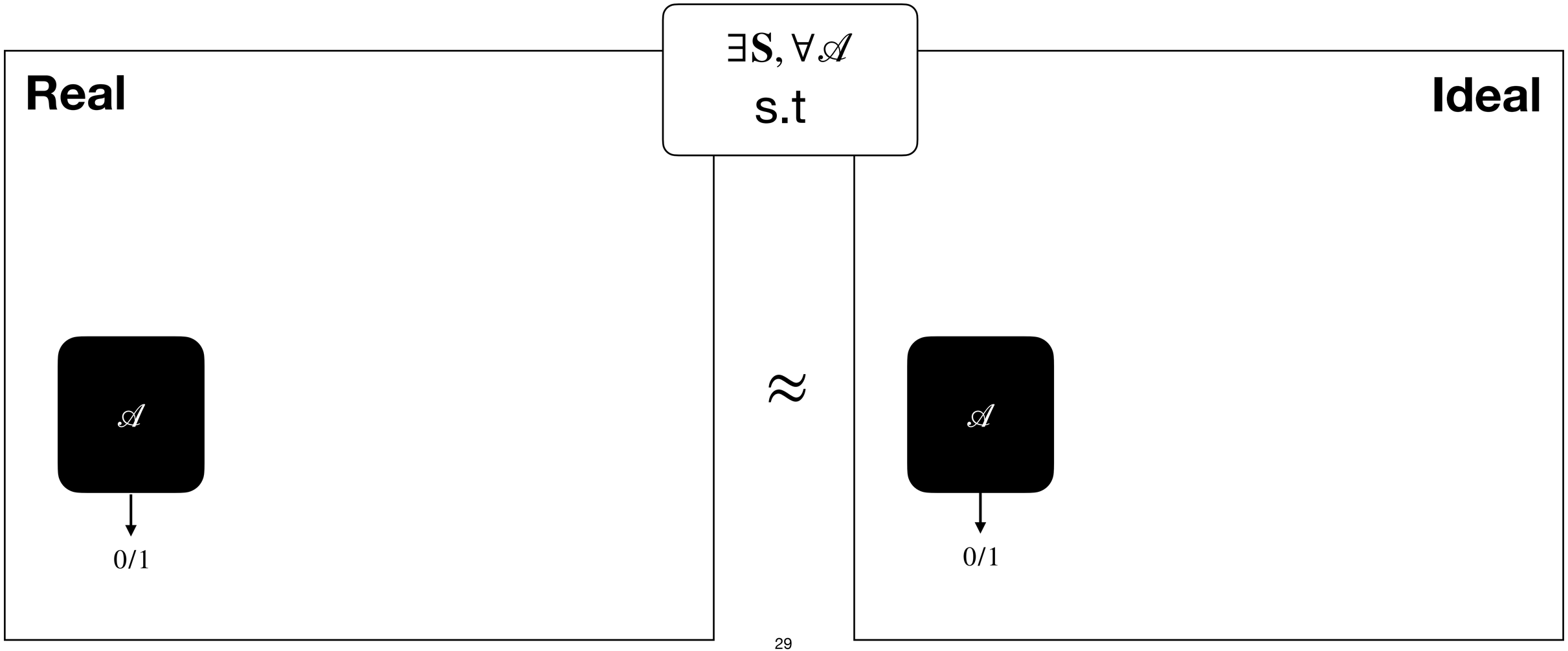

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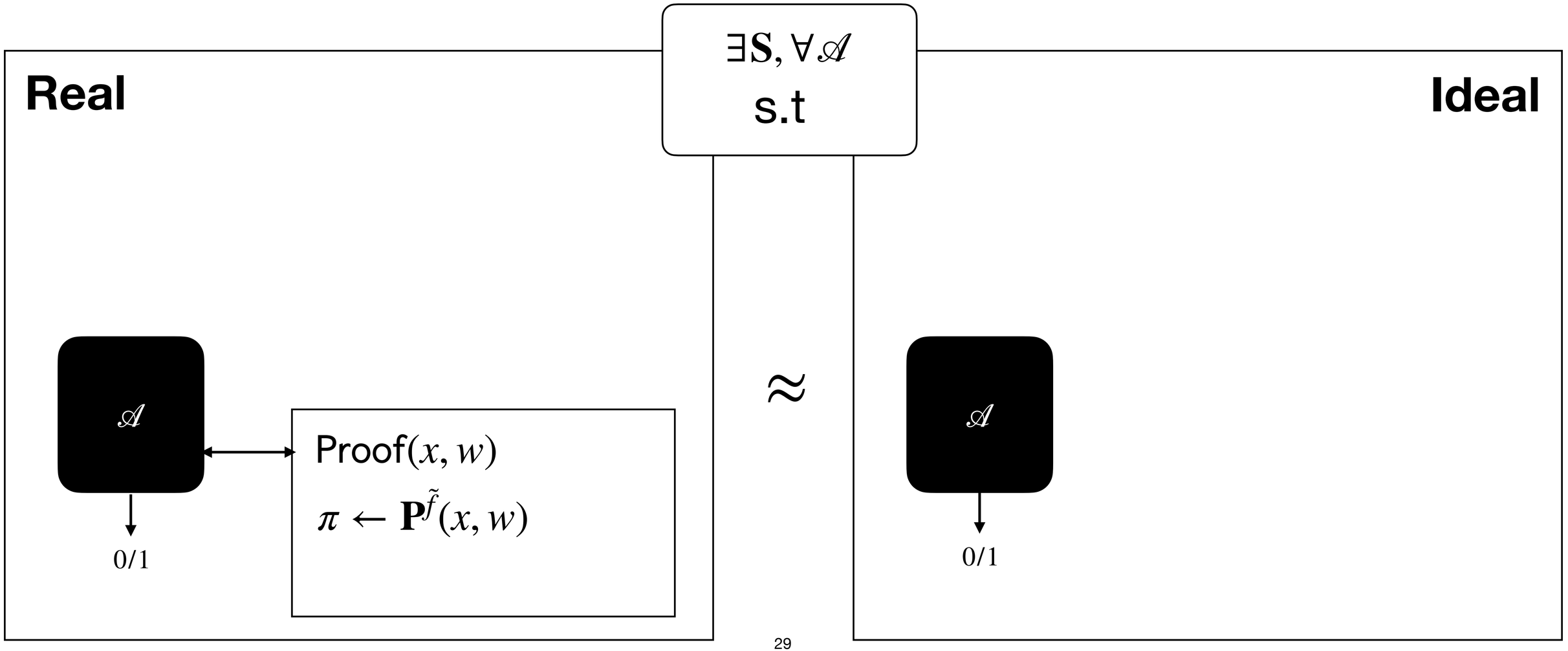

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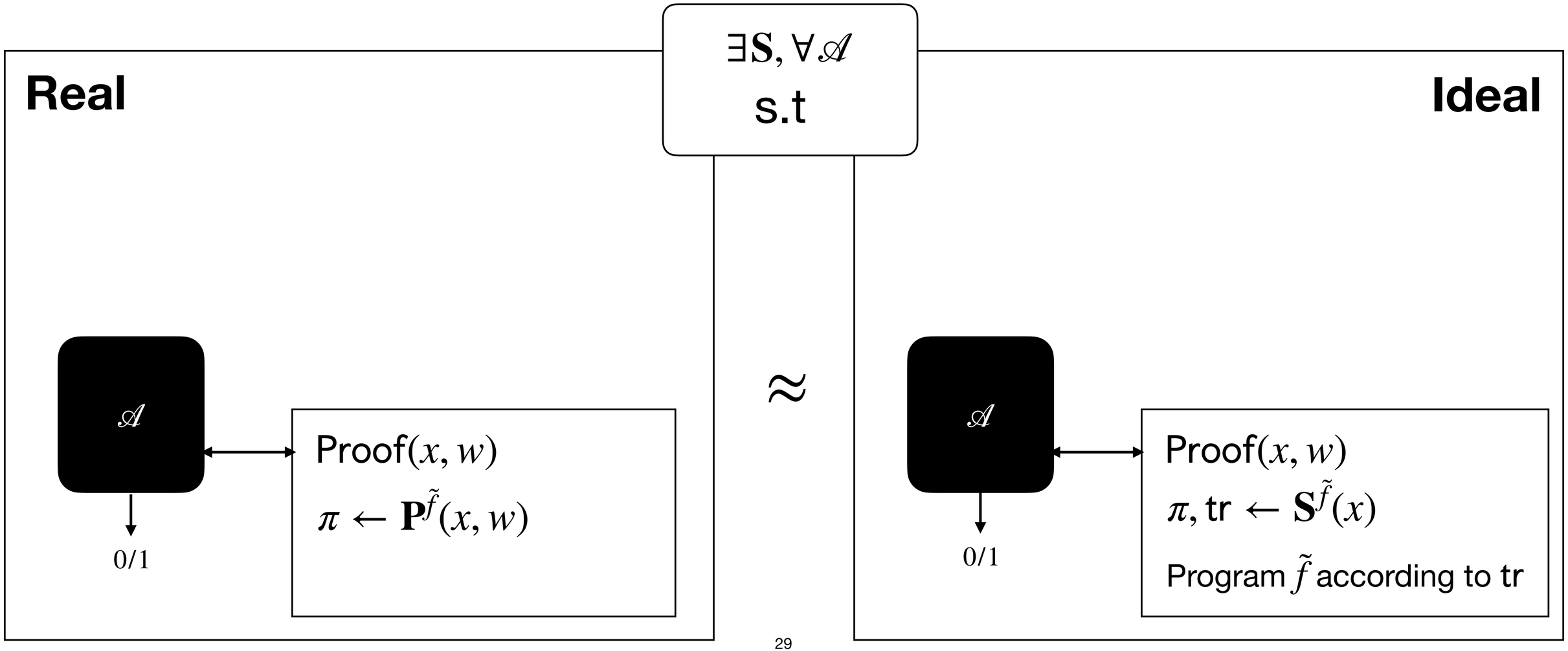

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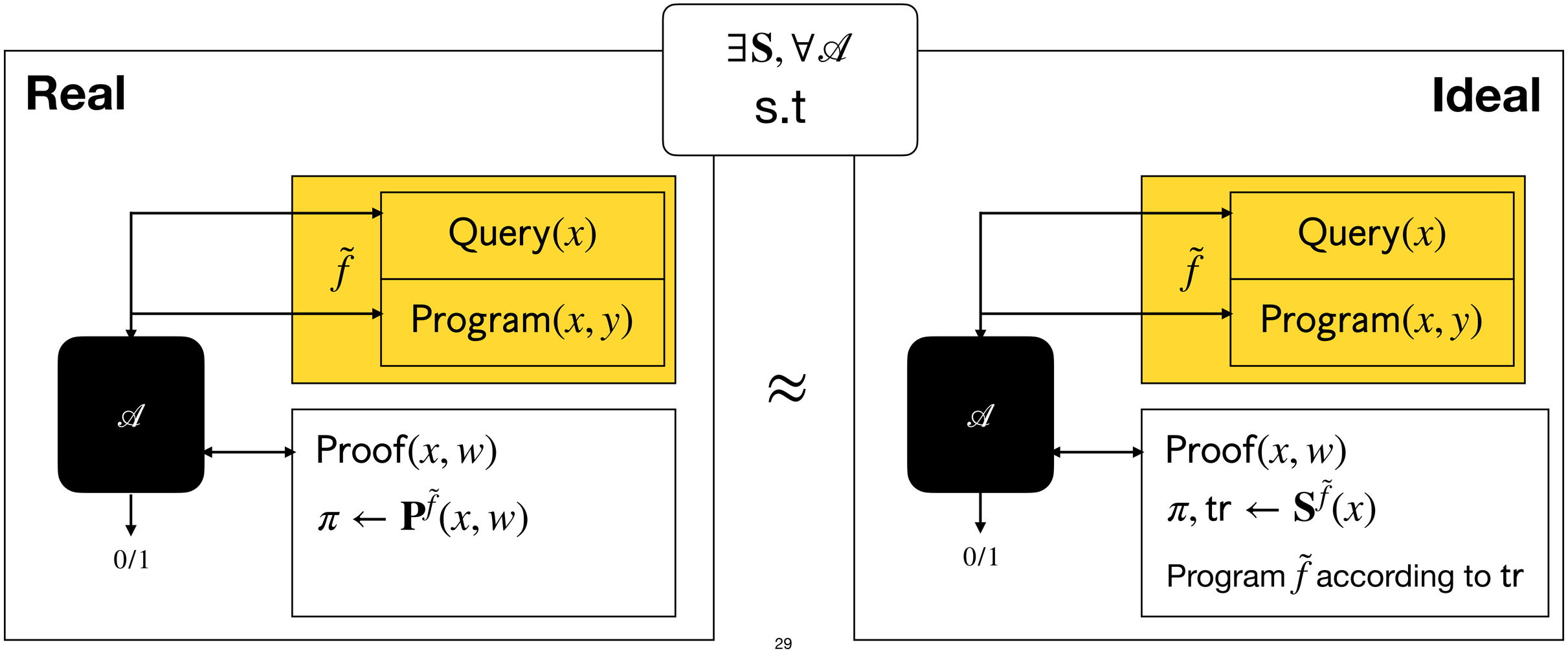

Micali has UC-friendly ZK

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Real $\equiv G_0$

Micali has UC-friendly ZK

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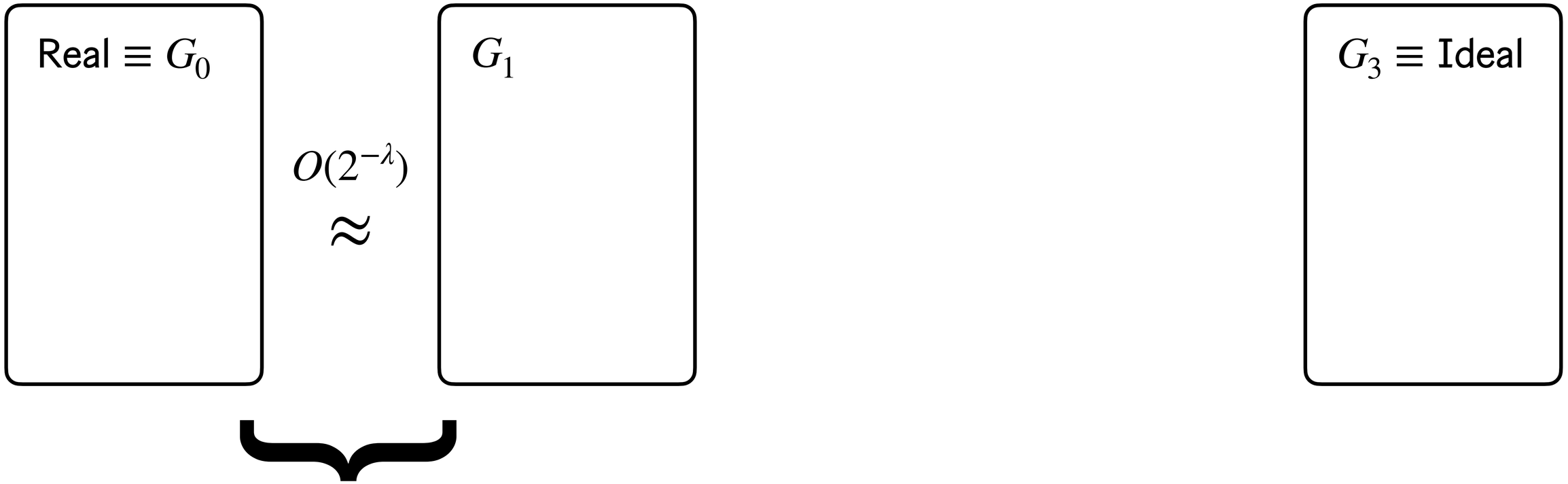
$G_3 \equiv$ Ideal

Micali has UC-friendly ZK



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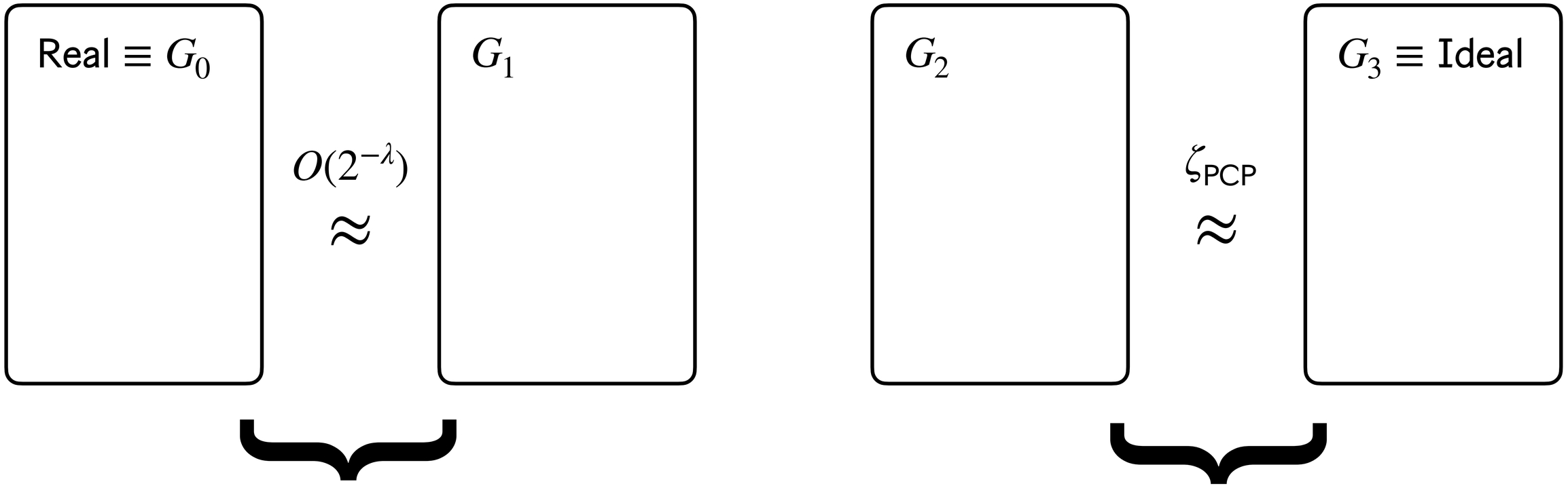
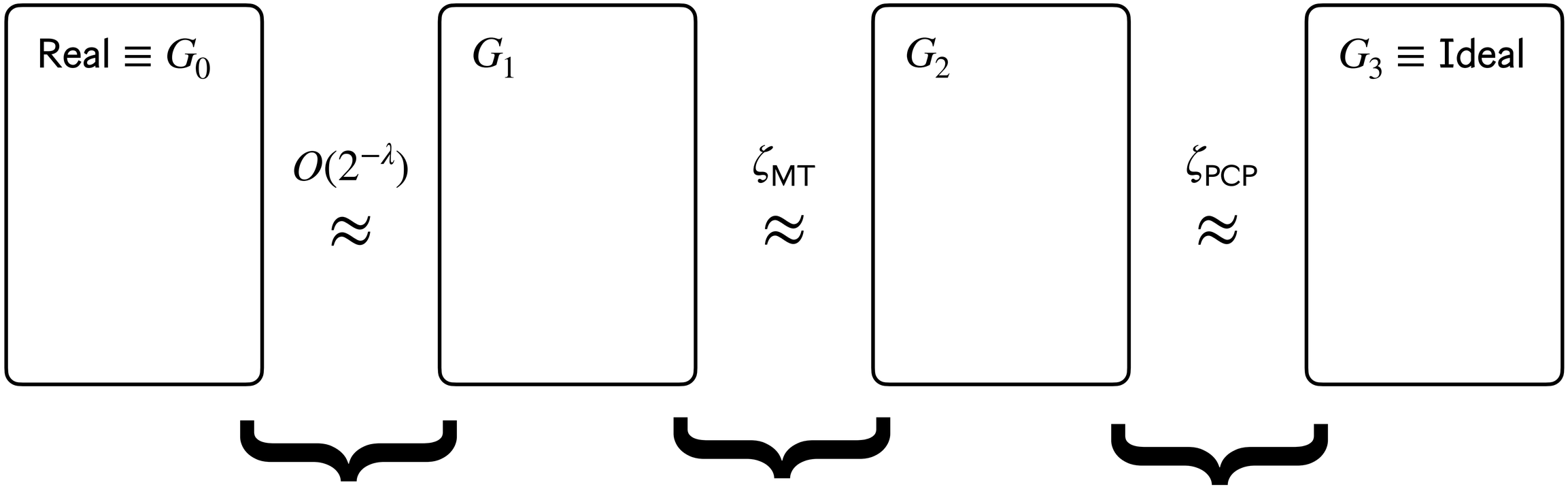


FS input hard to predict

PCP honest-verifier ZK

Micali has UC-friendly ZK



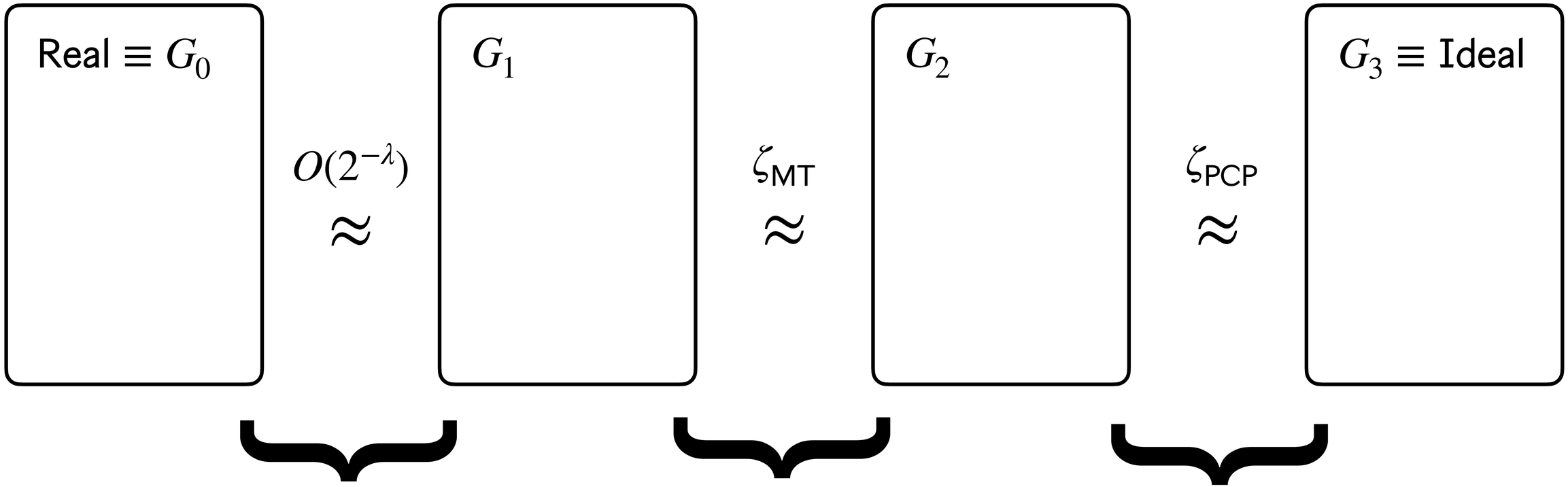
FS input hard to predict

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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UC-friendly knowledge soundness

Adversary should not be able to generate fresh proofs
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$$\exists \mathscr{E} \forall \mathscr{A}$$

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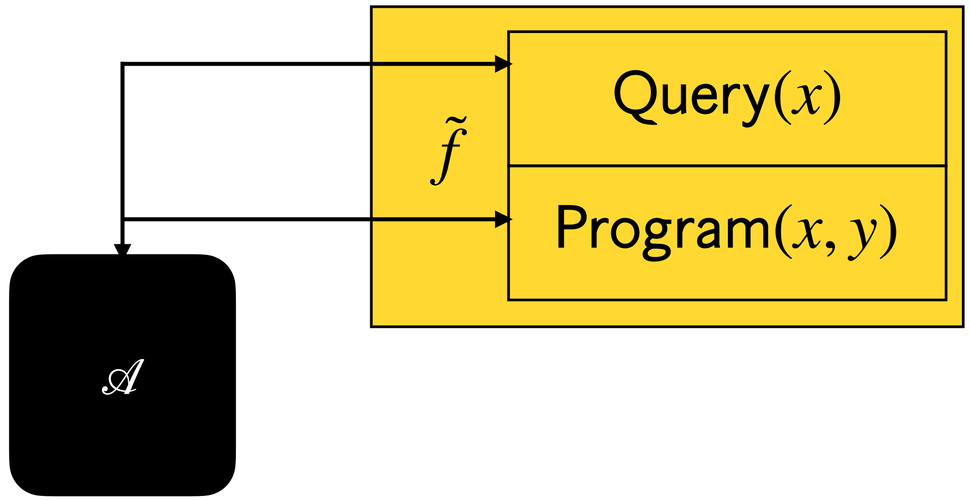

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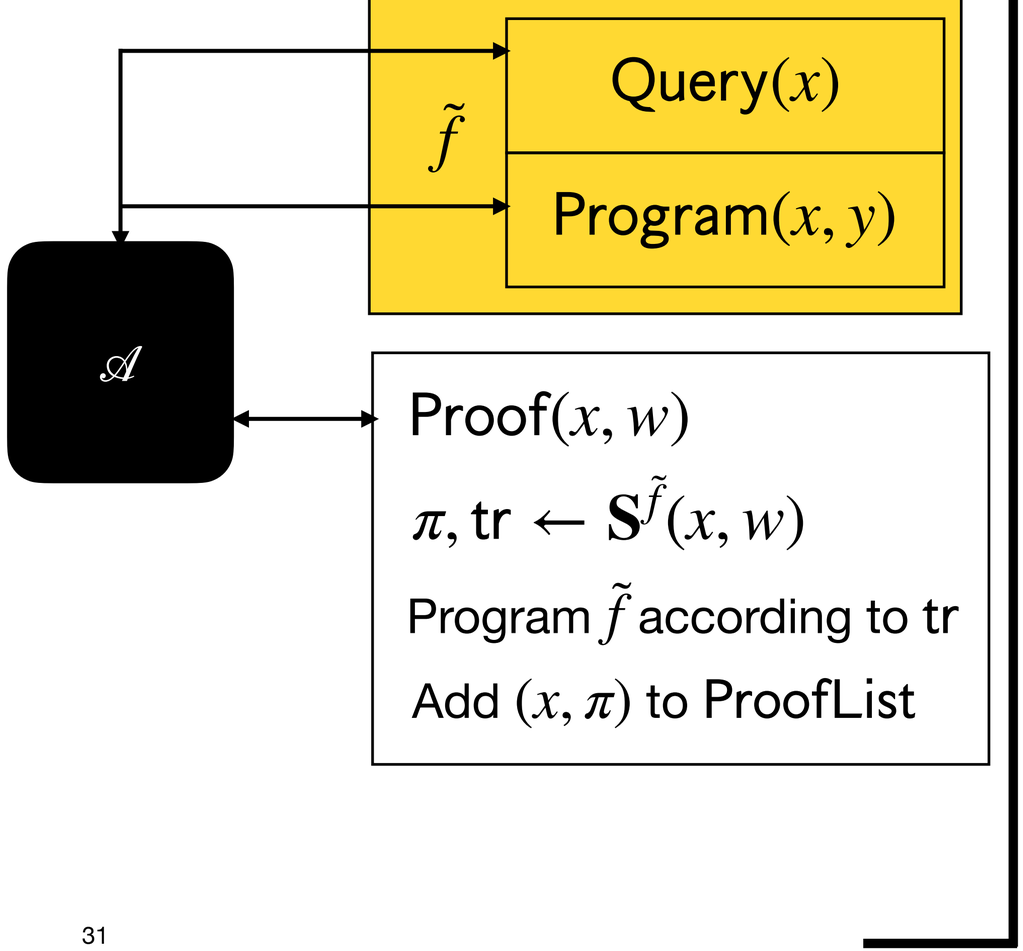

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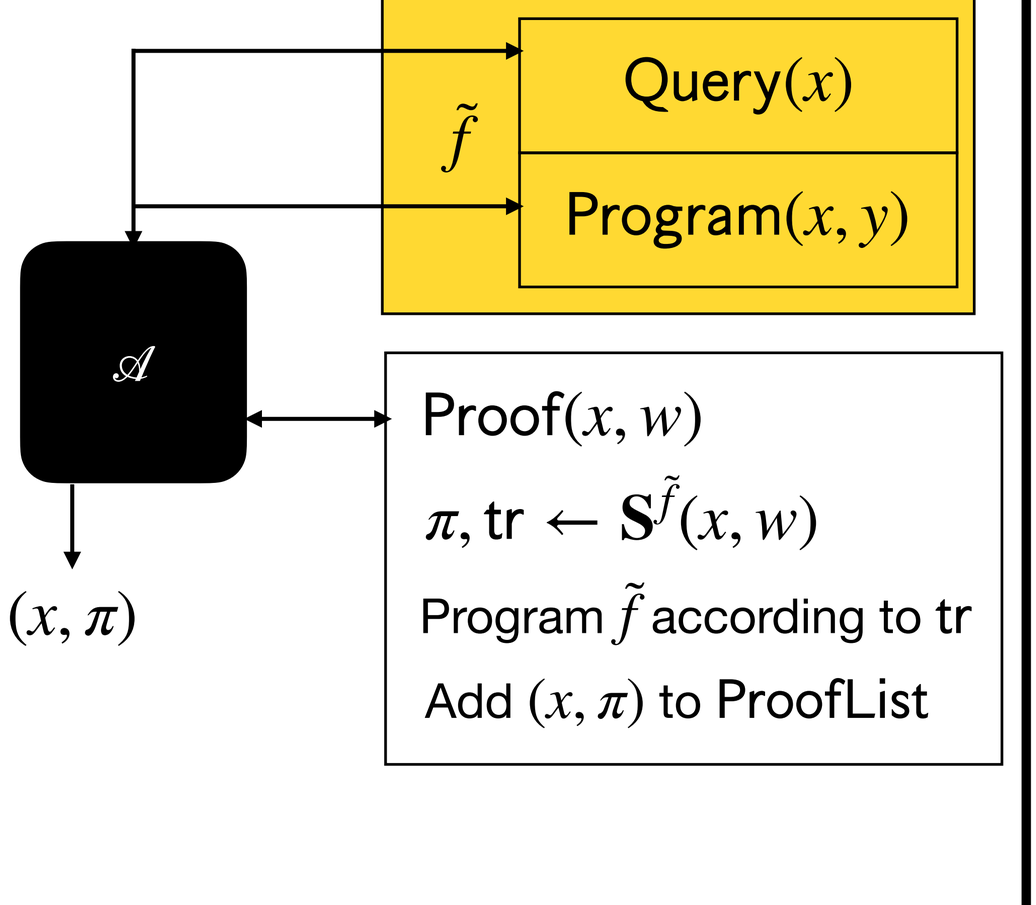

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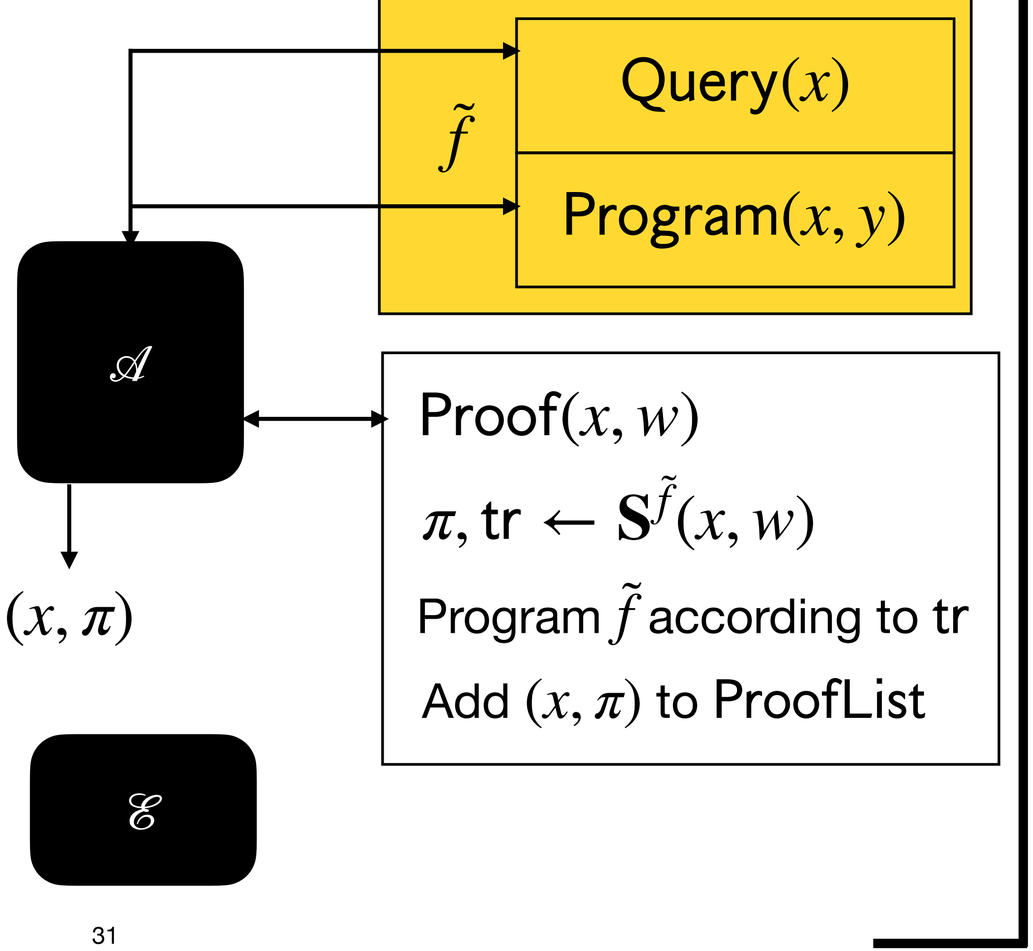
$\exists \mathscr{E} \forall \mathscr{A}$

$$\Pr\Big[$$



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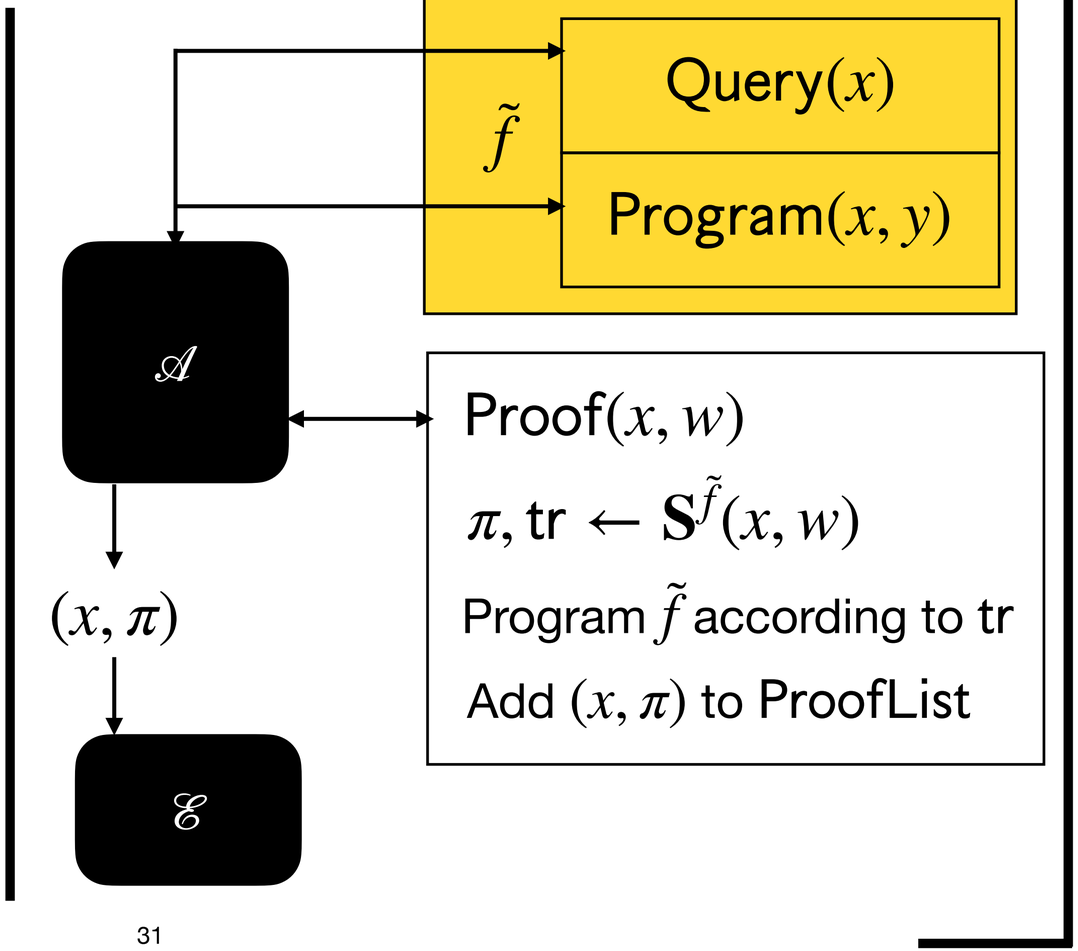

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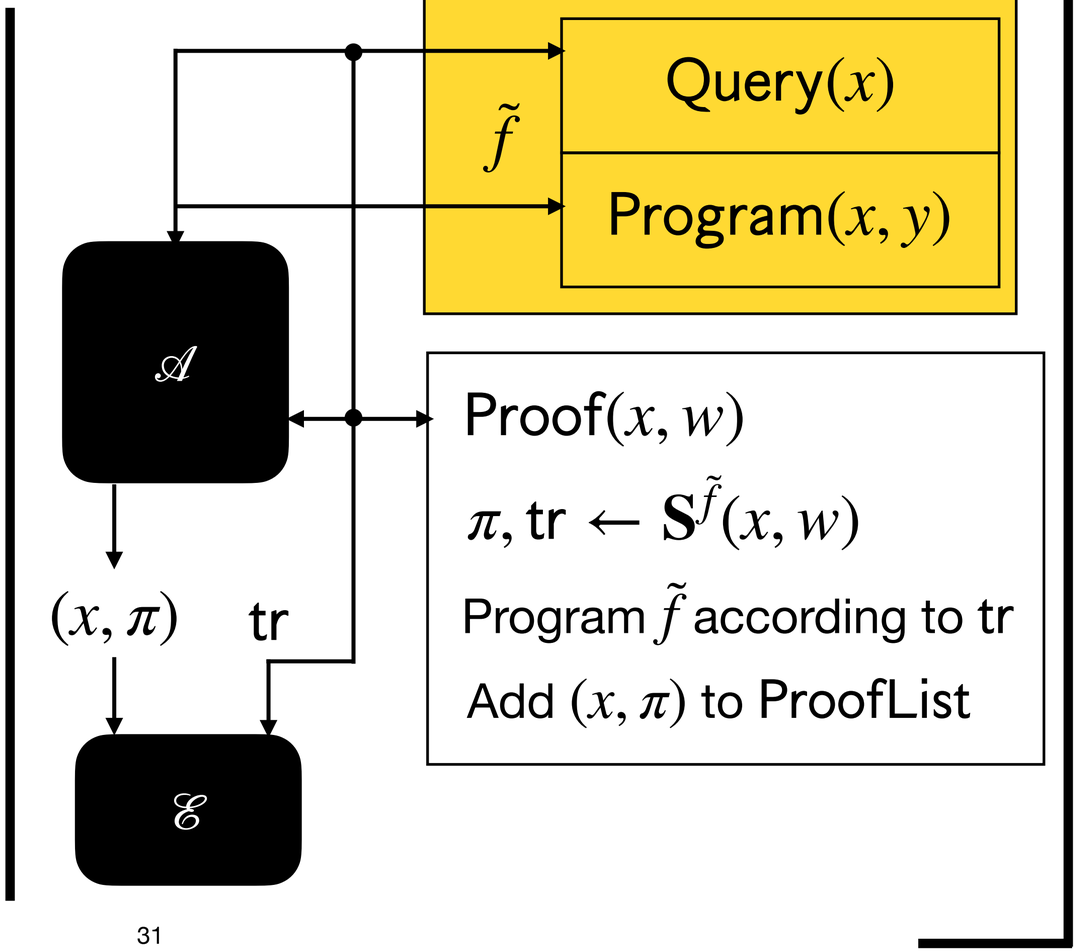

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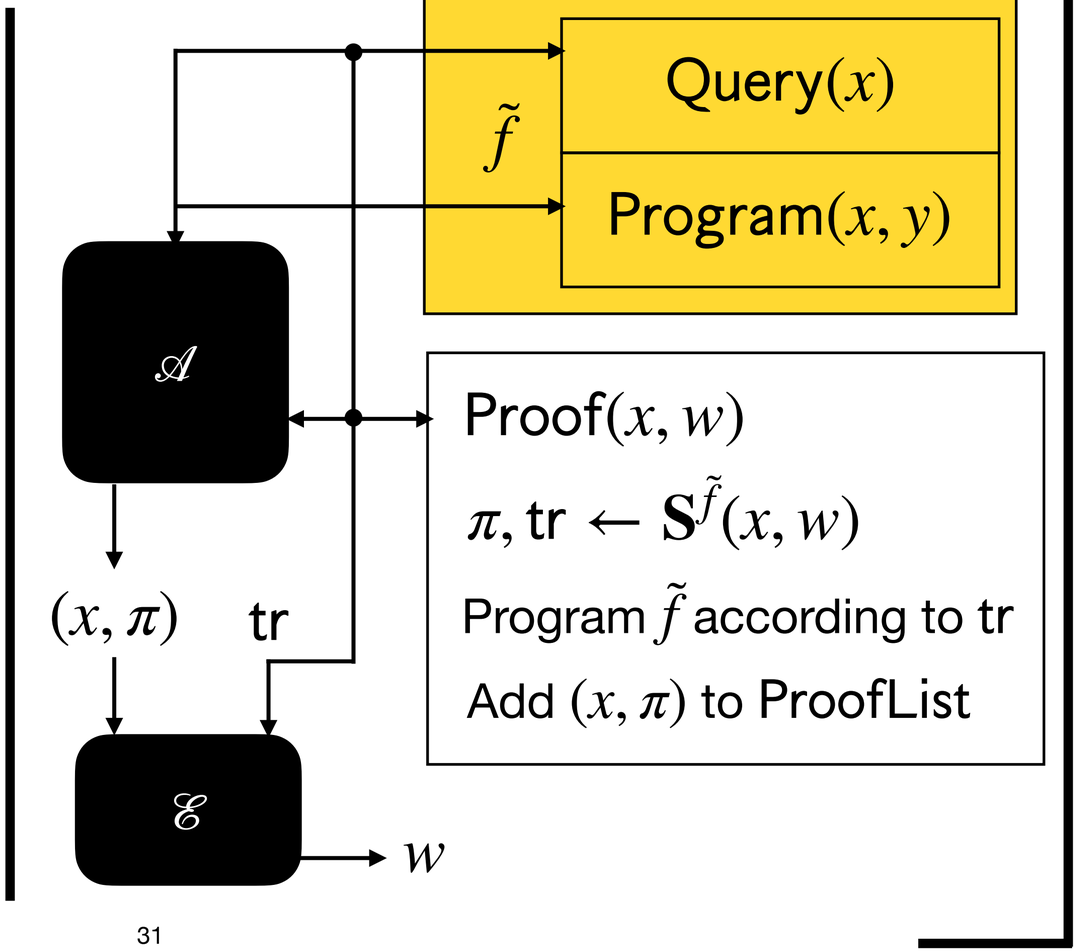


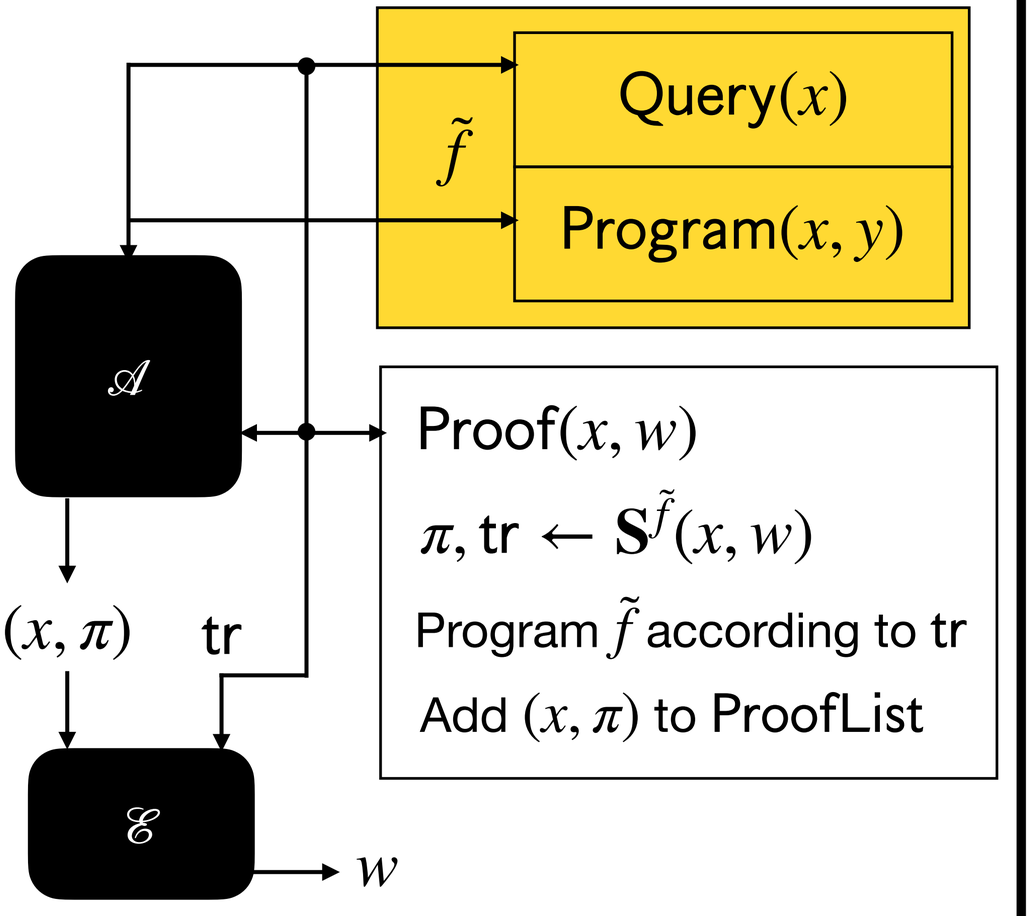
$$\Big]$$

UC-friendly knowledge soundness

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

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

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

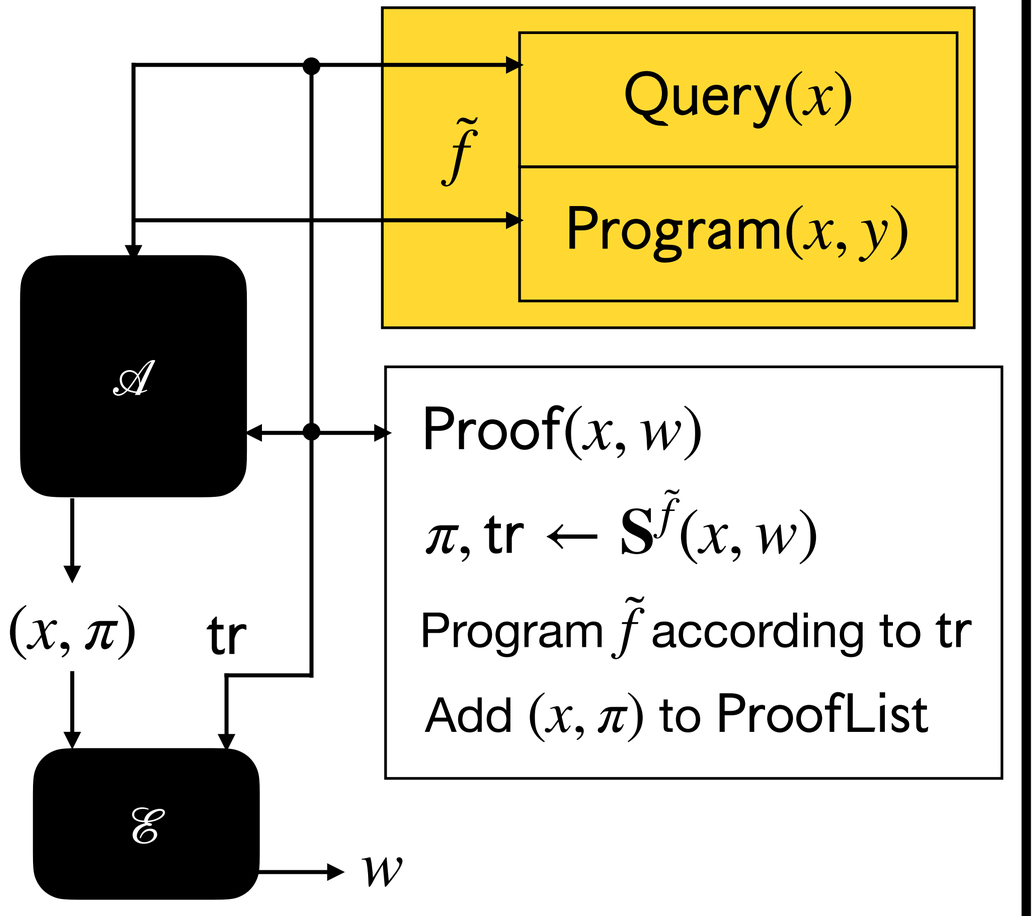


UC-friendly knowledge soundness

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

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

$$\Pr\left[\mathbf{V}^{\tilde{f}}(x,\pi) = 1 \;\text{ and }\; \mathbf{V} \text{ does not query programmed points}\right]$$

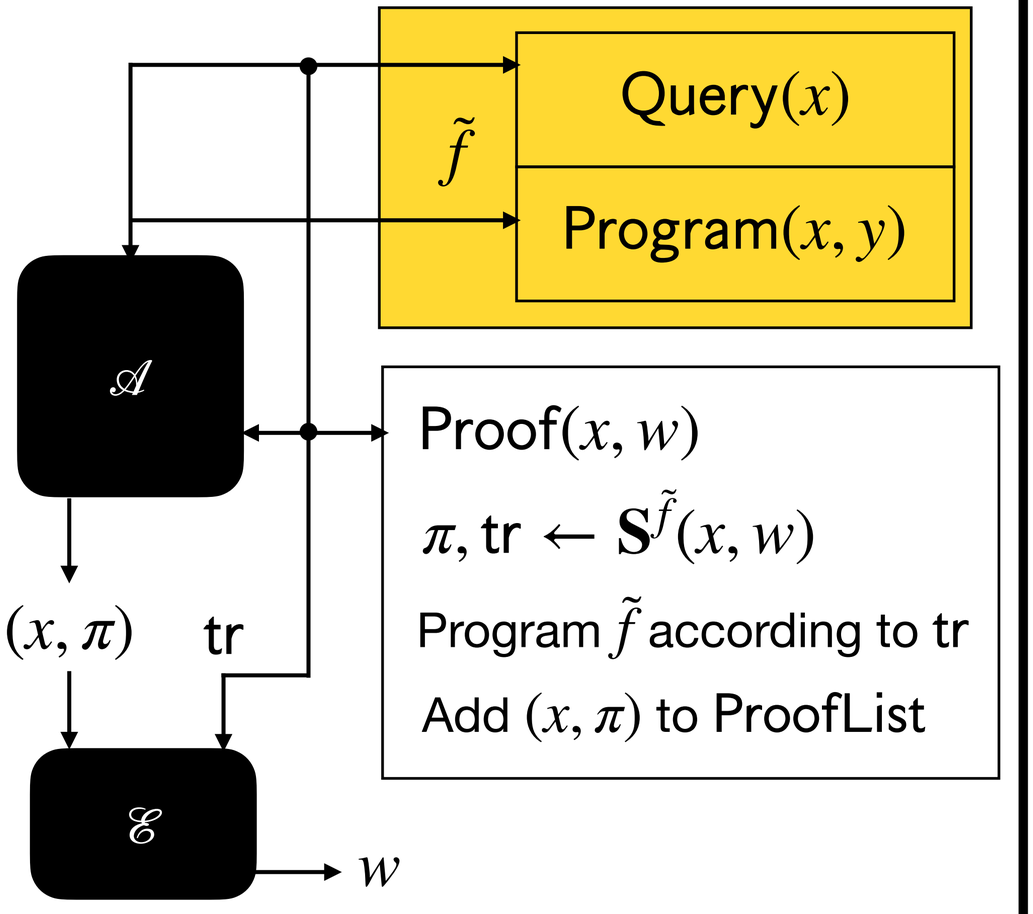


UC-friendly knowledge soundness

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

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

$$\Pr\left[\mathbf{V}^{\tilde{f}}(x,\pi) = 1 \;\wedge\; \mathbf{V} \text{ does not query programmed points} \;\wedge\; (x,\pi) \notin \text{ProofList}\right]$$

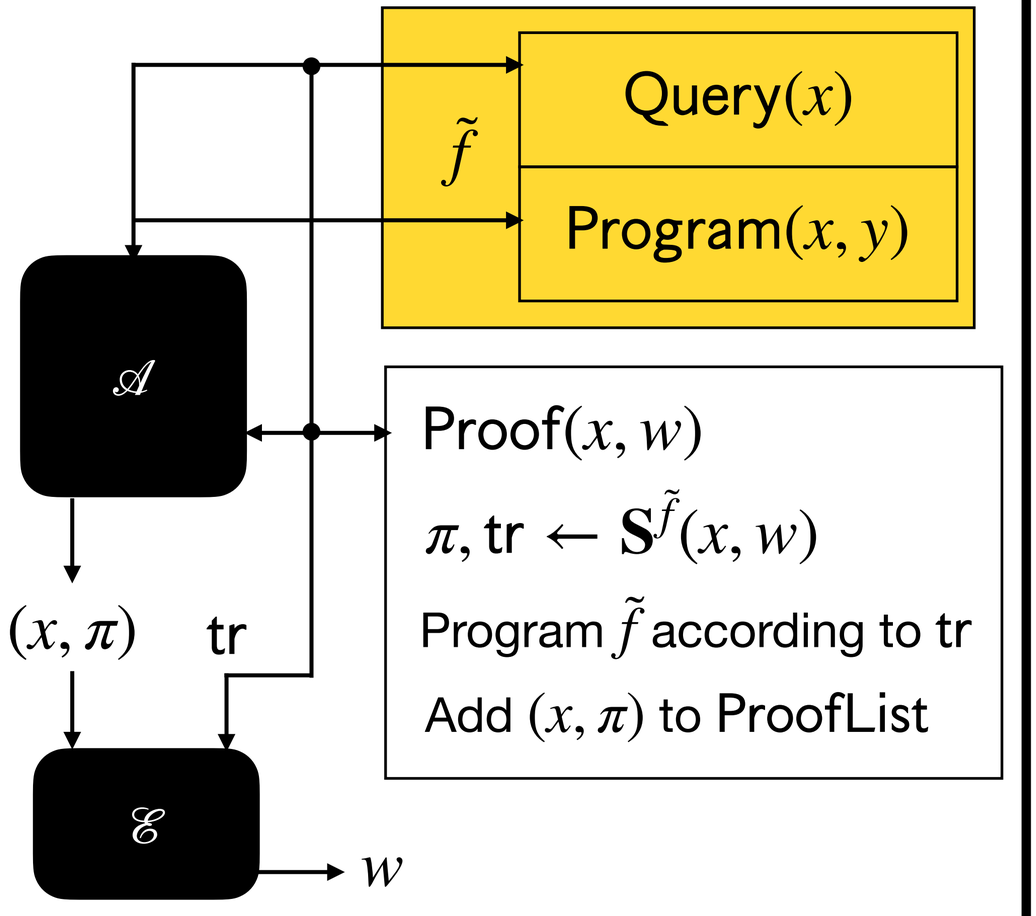


UC-friendly knowledge soundness

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

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

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



UC-friendly knowledge soundness

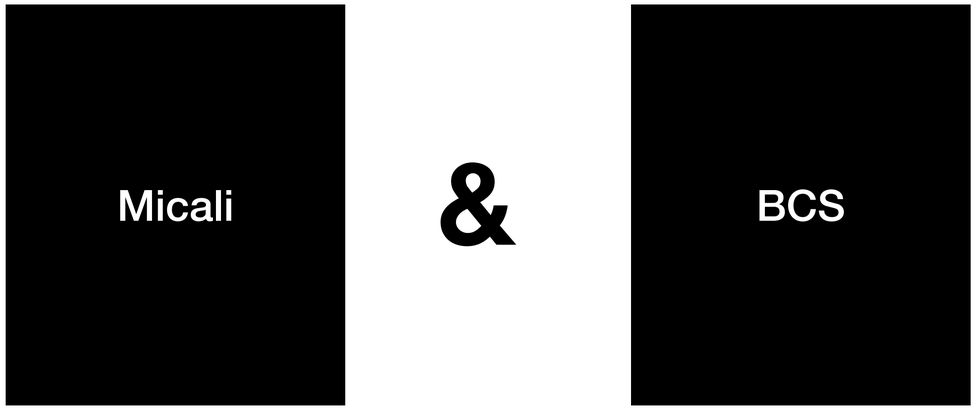
Adversary should not be able to generate fresh proofs that the extractor cannot extract a witness from

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

$$\Pr\left[\begin{array}{l} \mathbf{V}^{\tilde{f}}(x,\pi) = 1 \\ \\ \mathbf{V} \text{ does not query programmed points} \\ \\ (x,\pi) \notin \text{ProofList} \\ \\ (x,w) \notin R \end{array} \;\middle|\; \begin{array}{l} \mathscr{A} \text{ has oracle access to } \tilde{f}, \text{Query}(x), \text{Program}(x,y) \\ \\ \text{Proof}(x,w): \\ \pi, \text{tr} \leftarrow \mathbf{S}^{\tilde{f}}(x,w) \\ \text{Program } \tilde{f} \text{ according to tr} \\ \text{Add } (x,\pi) \text{ to ProofList} \\ \\ (x,\pi) \rightarrow \mathscr{E}, \quad \text{tr} \rightarrow \mathscr{E} \\ \\ \mathscr{E} \rightarrow w \end{array}\right] \leq \kappa$$

Conclusion

Conclusion



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

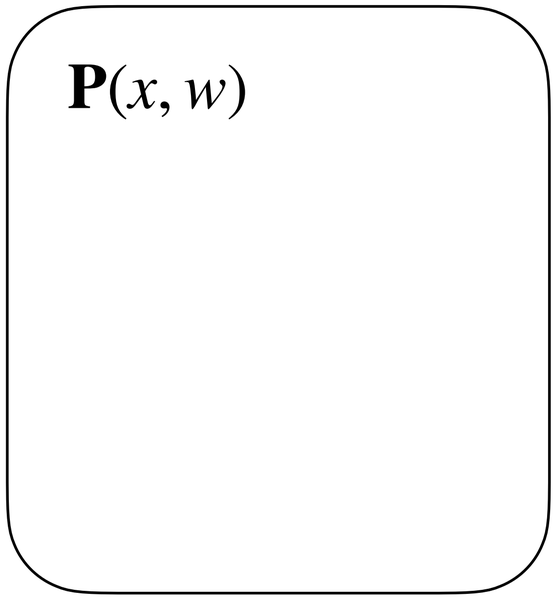
Concrete security bounds!

Thank you!

Extra slides

zkSNARKs (in the ROM)

zkSNARKs (in the ROM)



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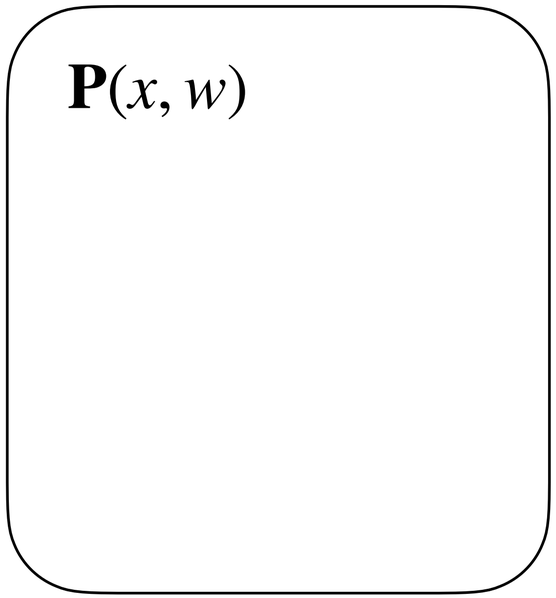

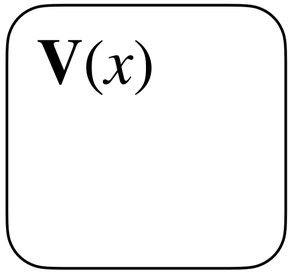

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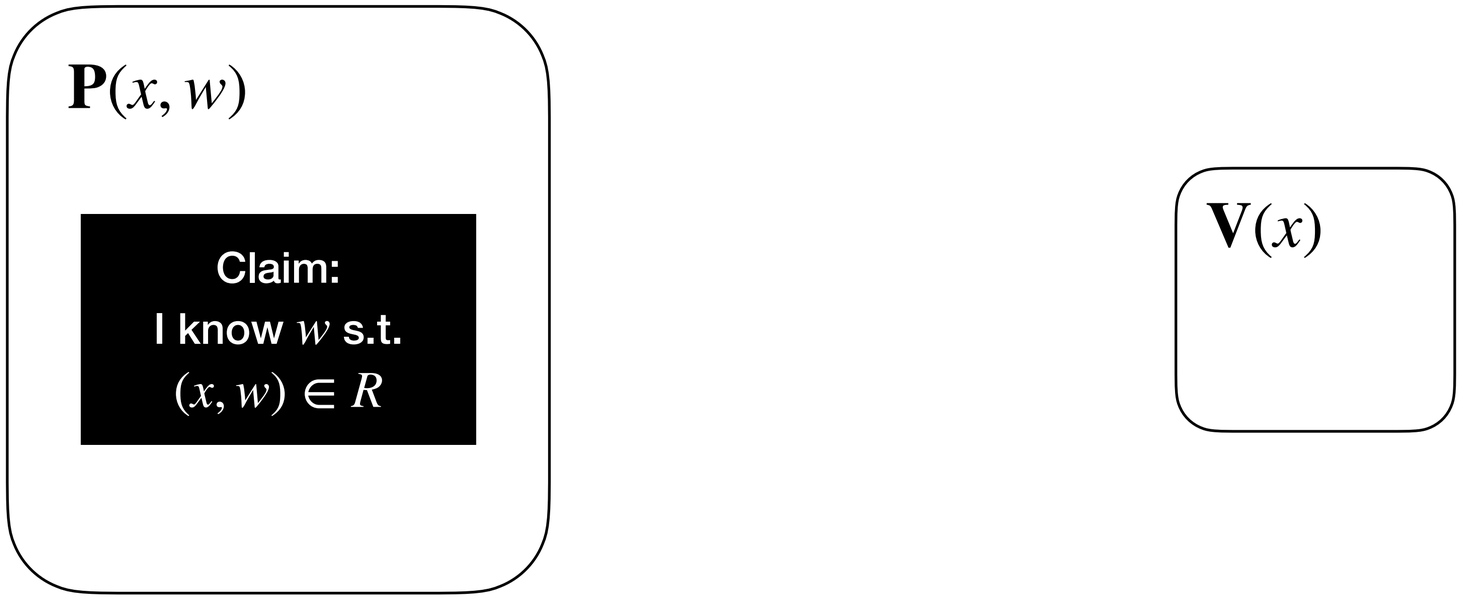

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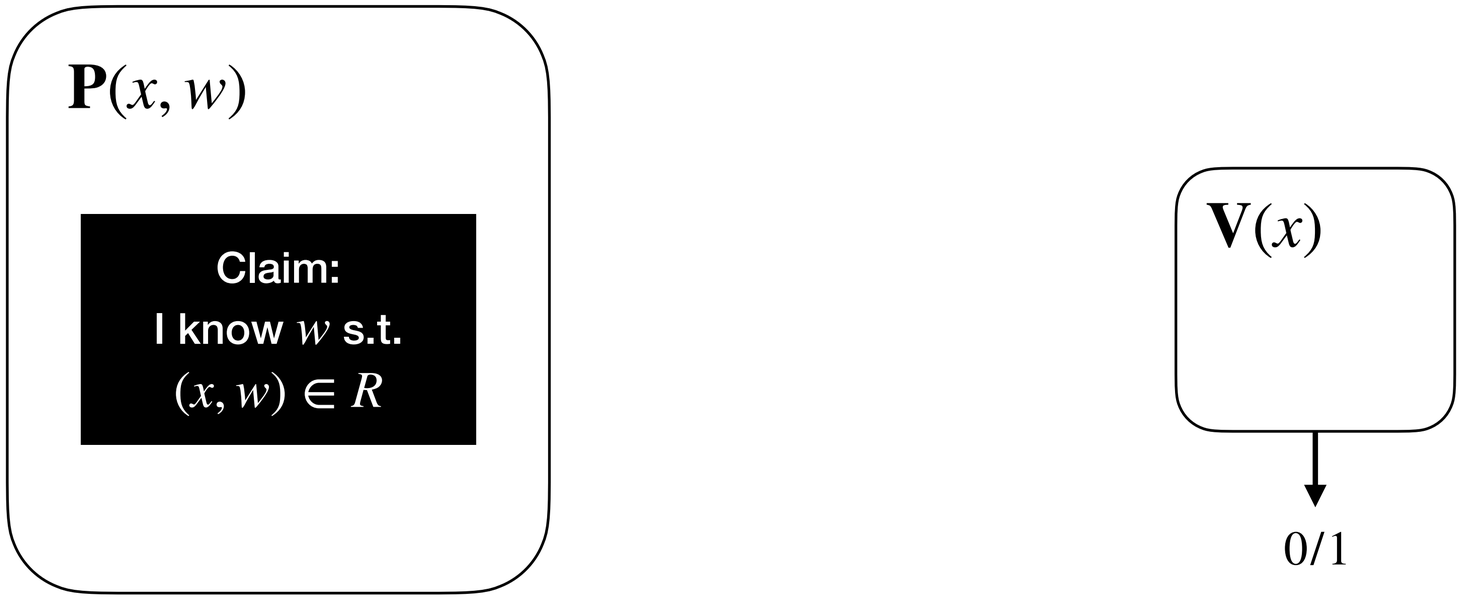

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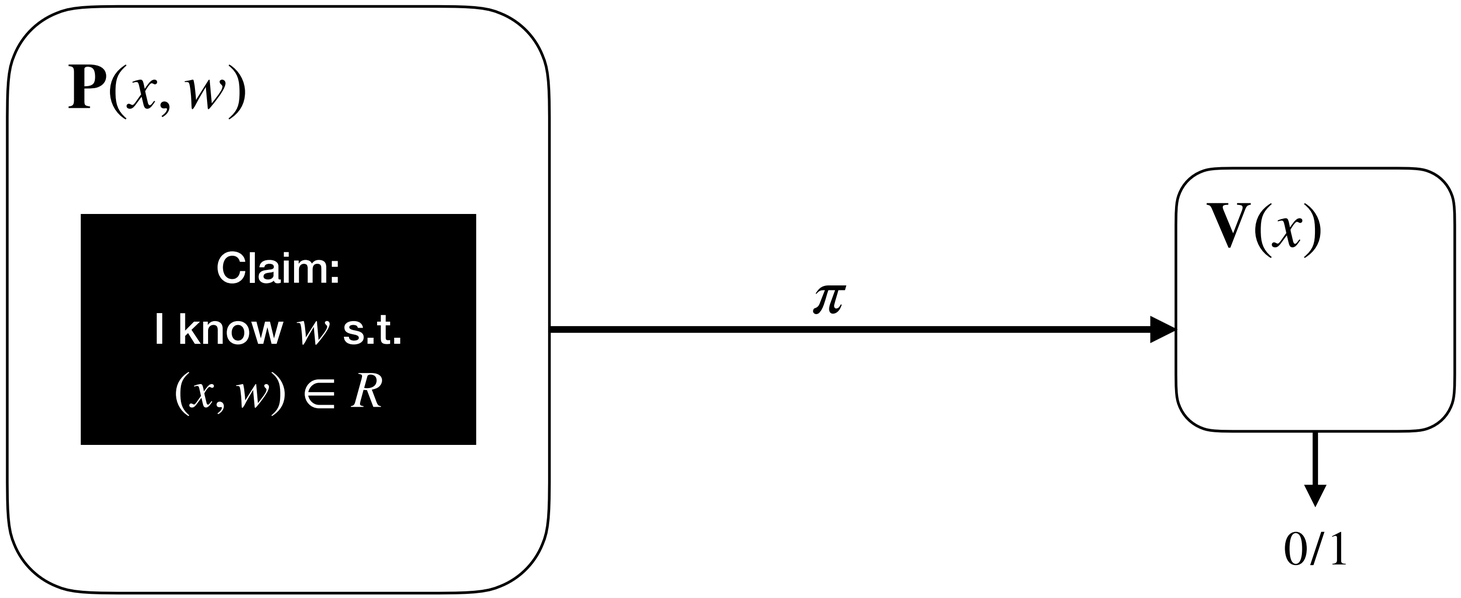

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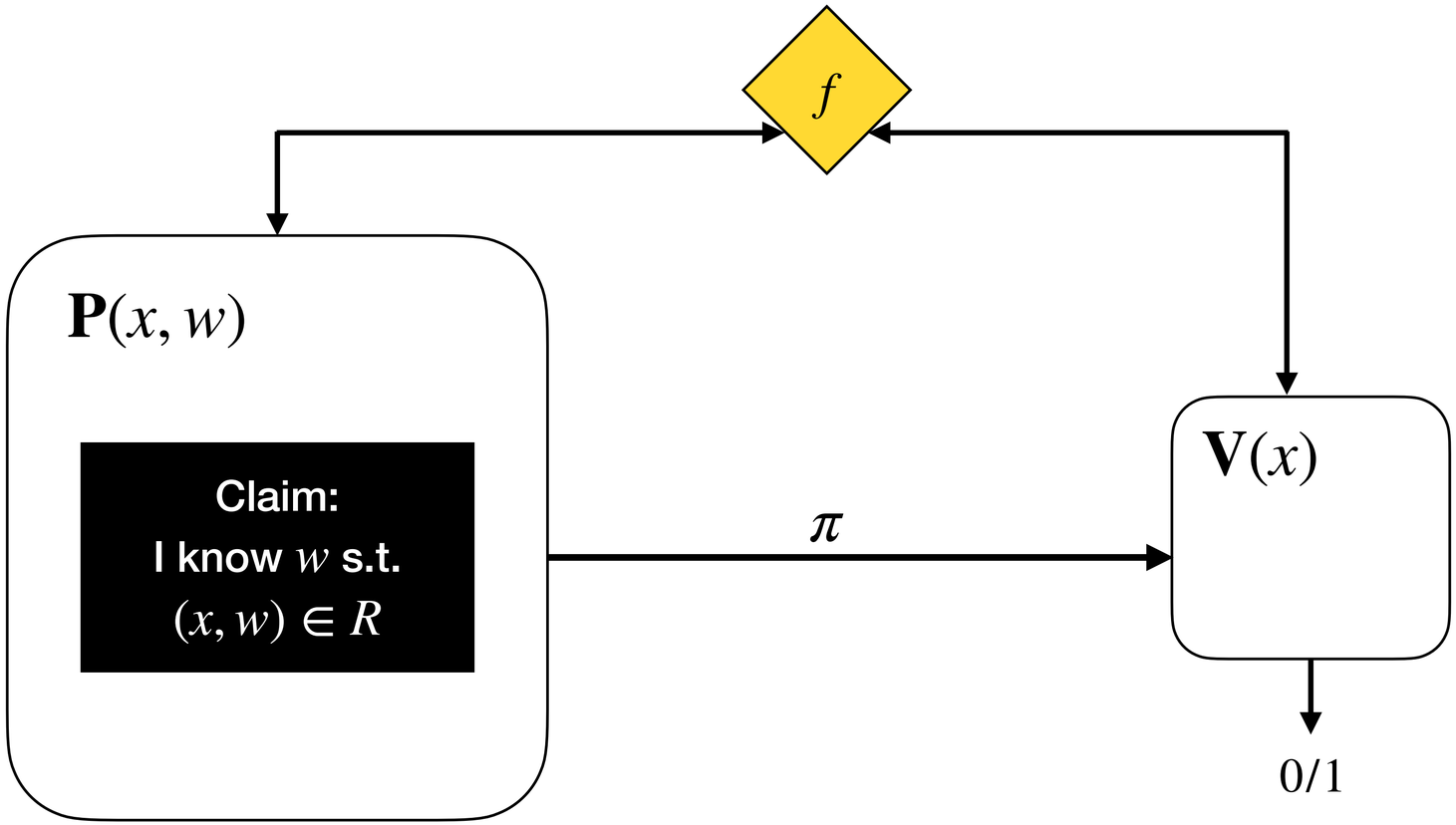
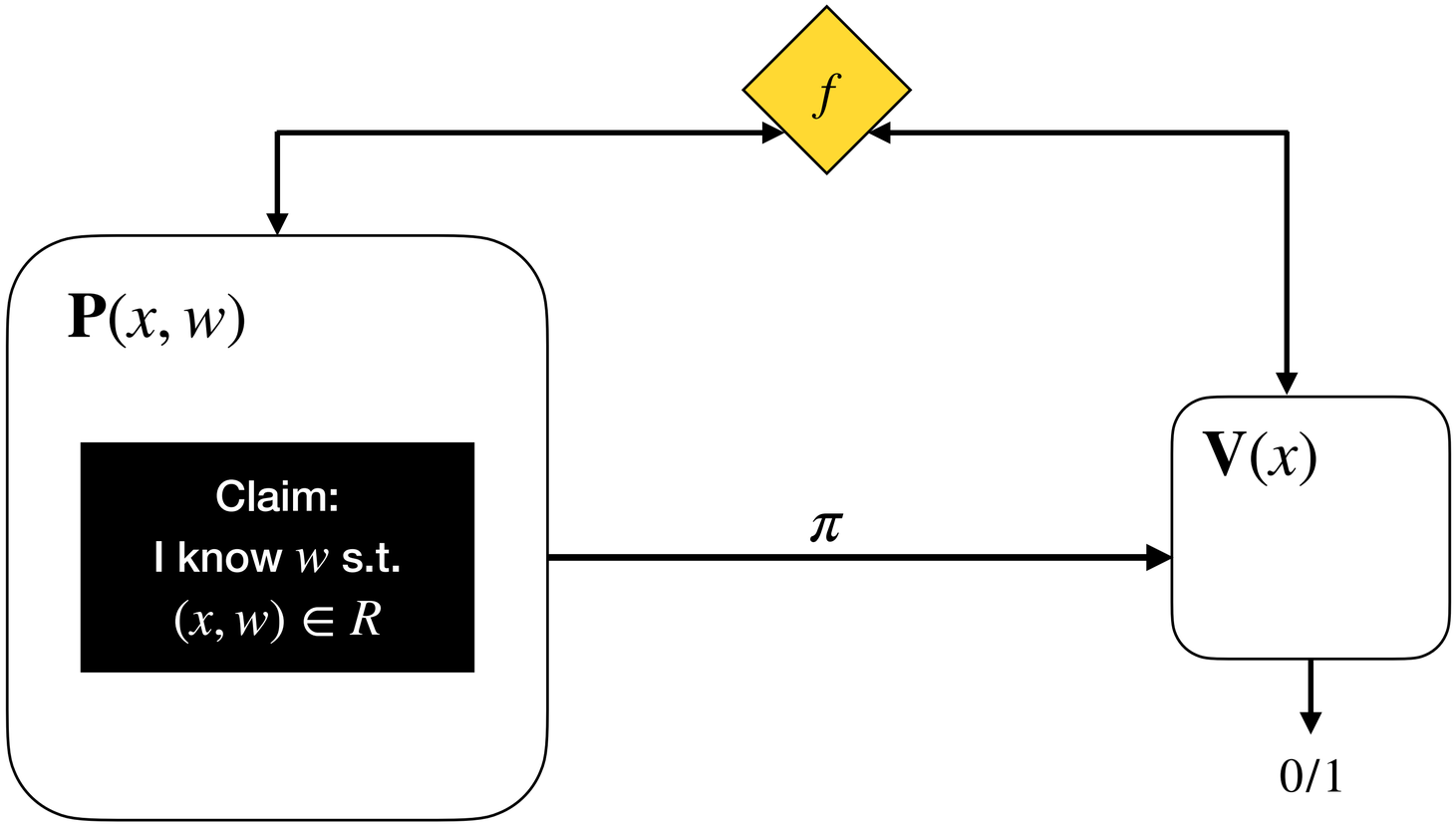
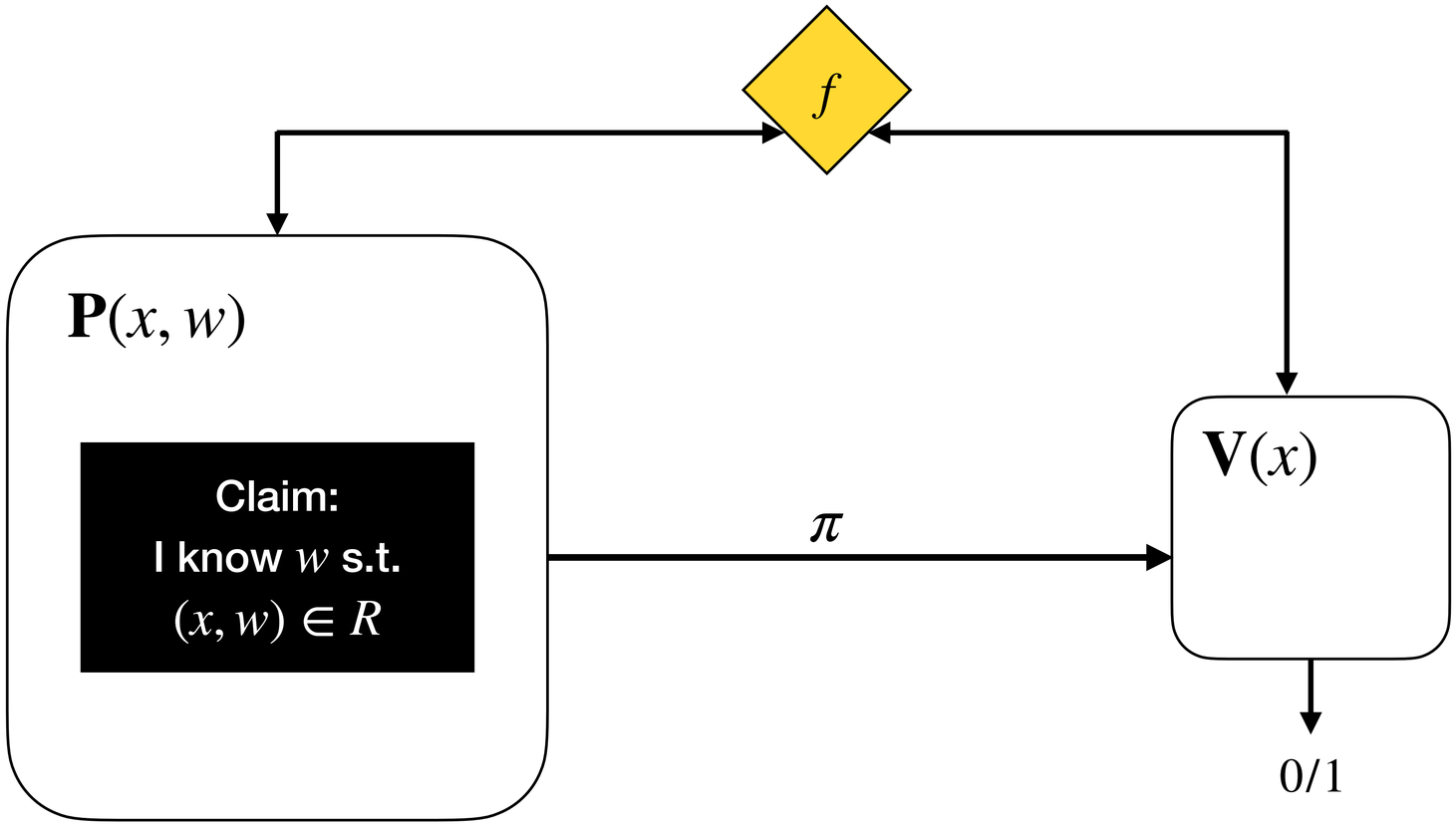


zkSNARKs (in the ROM)



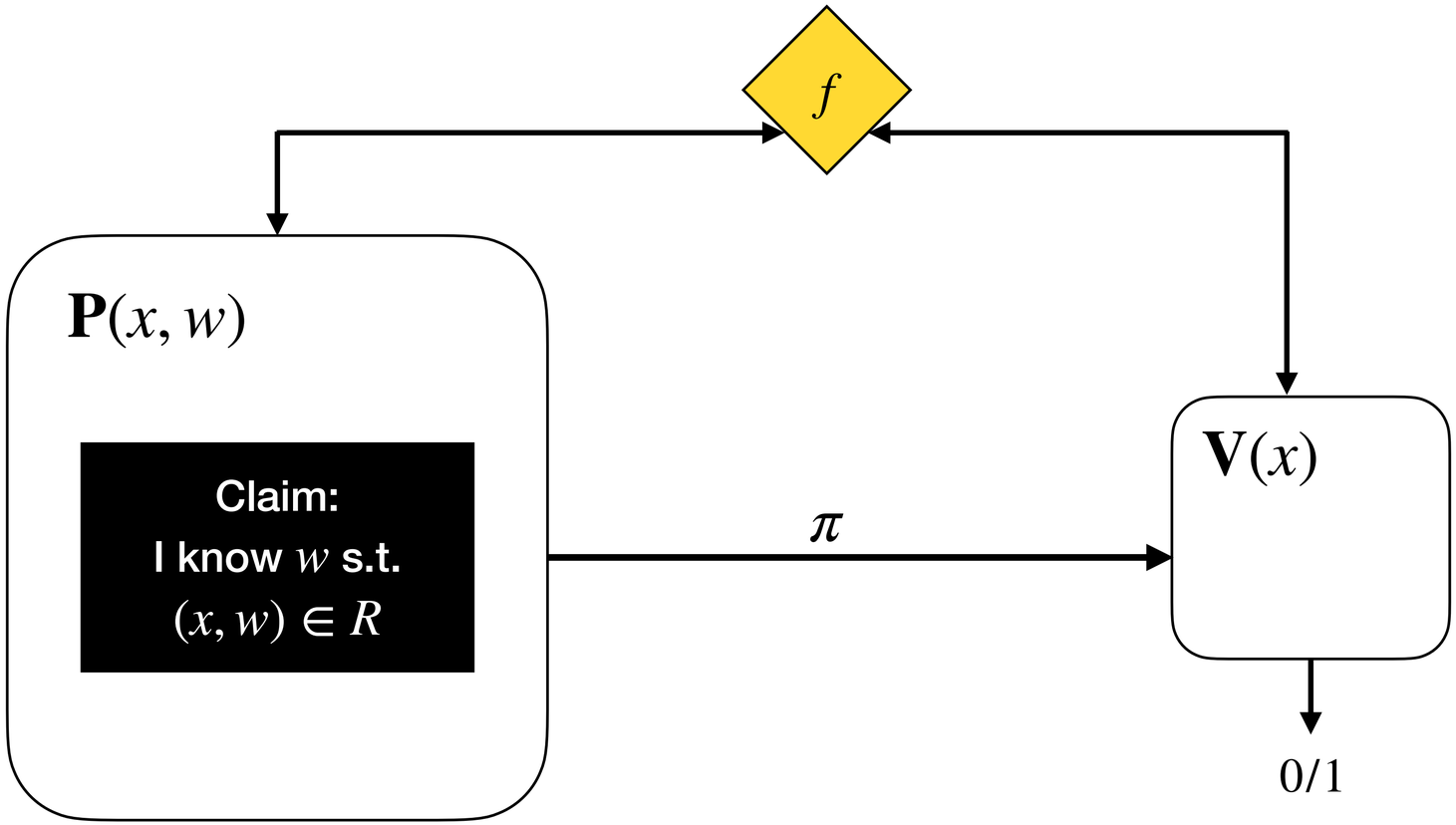
- Zero-Knowledge
  - $\exists \mathbf{S}: \ \mathbf{P}^f(x, w) \approx \mathbf{S}^f(x)$

zkSNARKs (in the ROM)



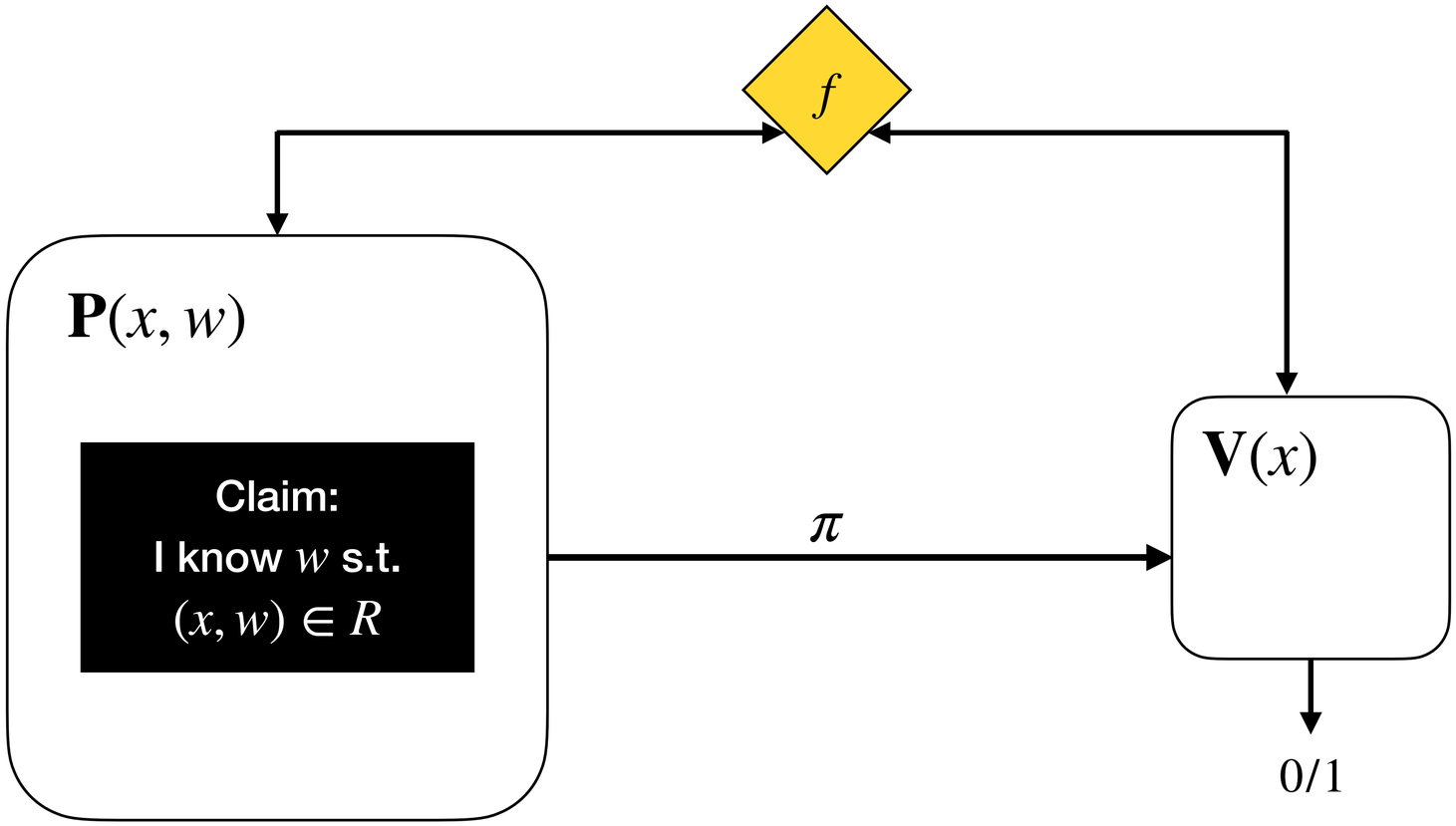
- Zero-Knowledge
  - $\exists \mathbf{S} : \ \mathbf{P}^f(x, w) \approx \mathbf{S}^f(x)$
- Succinct
  - $|\pi| \ll |w|$

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

zkSNARKs (in the ROM)



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- Argument of Knowledge

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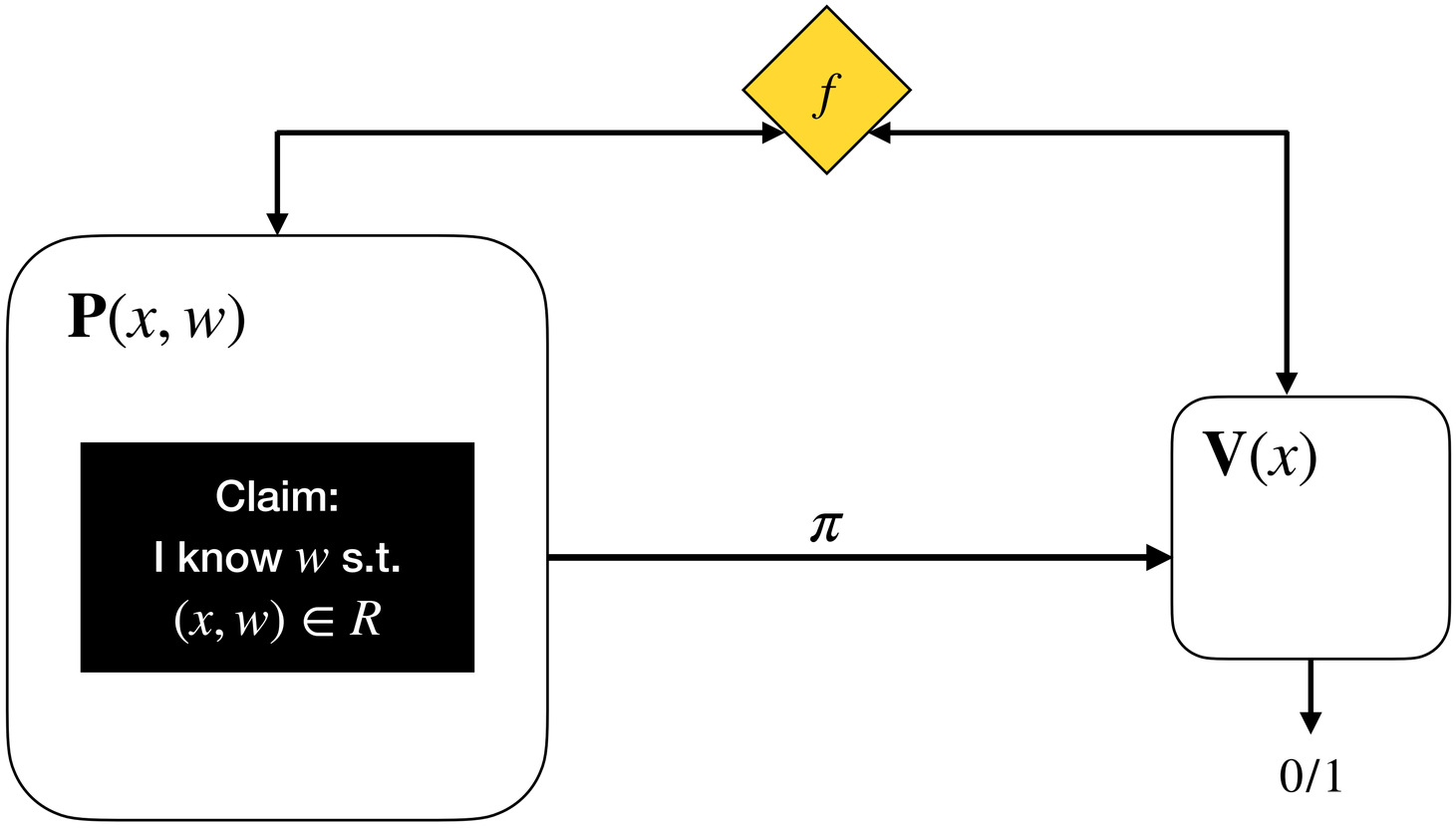
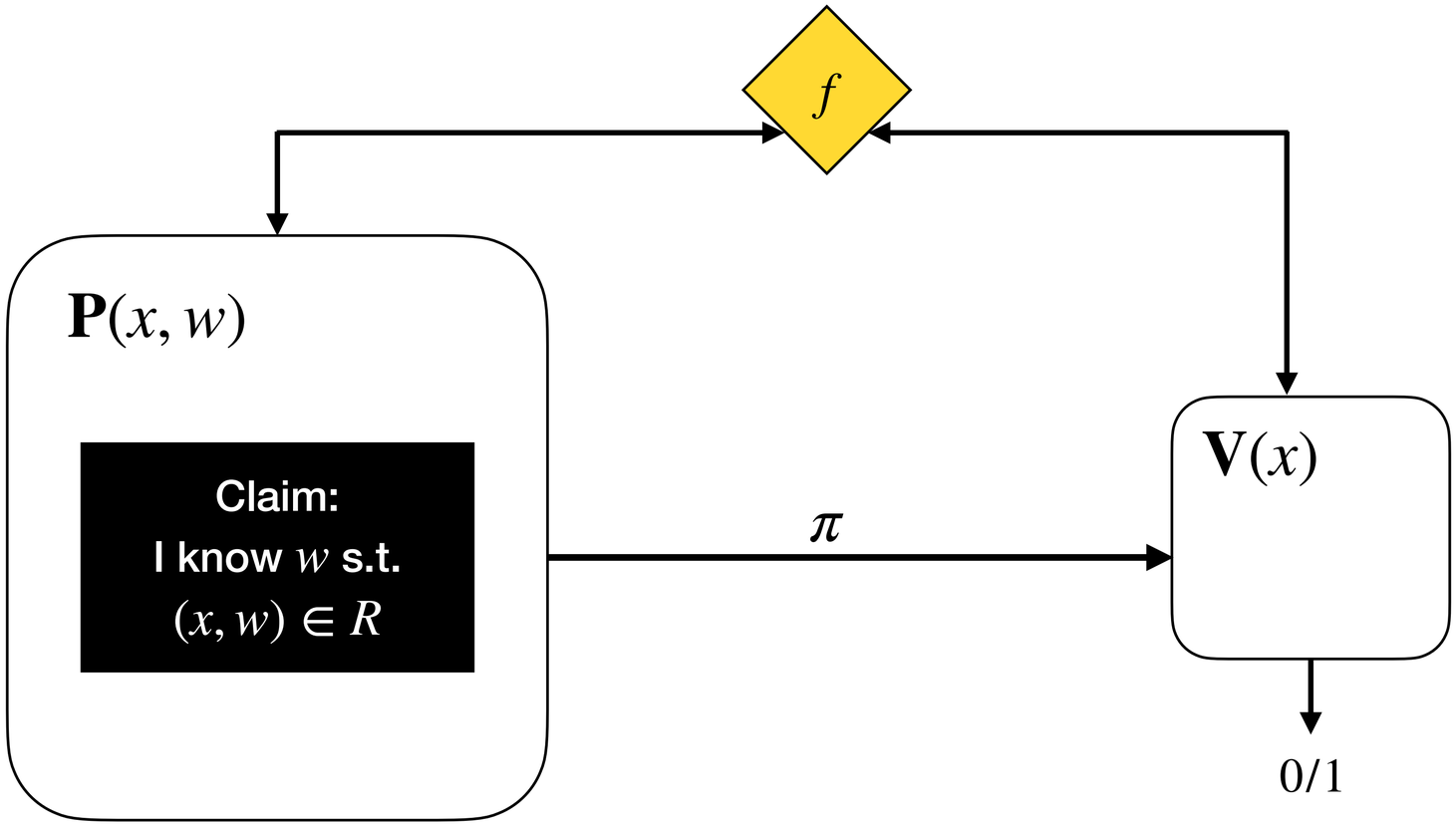


- Zero-Knowledge
  - $\exists \mathbf{S} : \ \mathbf{P}^f(x, w) \approx \mathbf{S}^f(x)$
- Succinct
  - $|\pi| \ll |w|$
- Non-interactive
- Argument of Knowledge
  - $\exists \mathbf{E} : \ \mathbf{V}^f(x, \pi \leftarrow \tilde{\mathbf{P}}) = 1$

zkSNARKs (in the ROM)



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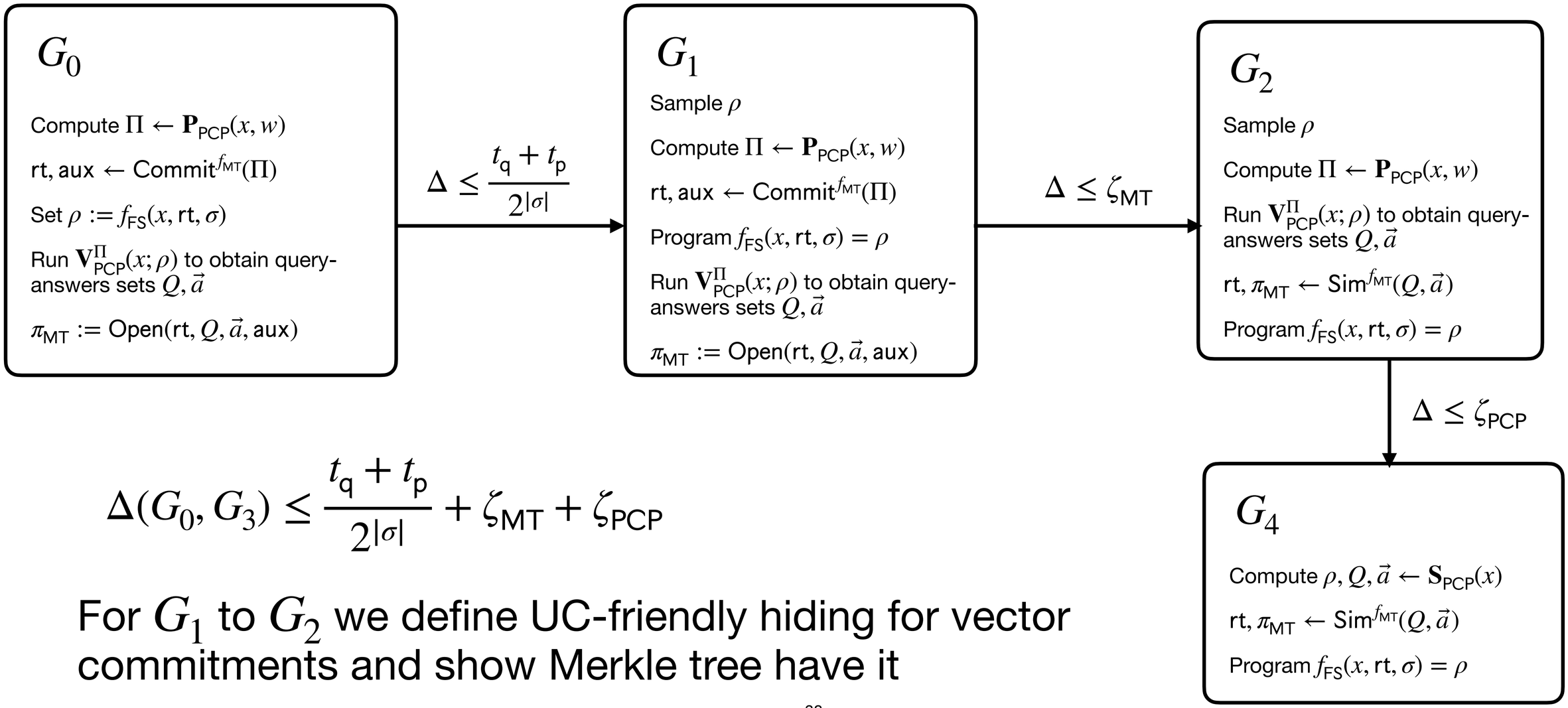
  - $\exists \mathbf{S} : \ \mathbf{P}^f(x, w) \approx \mathbf{S}^f(x)$
- Succinct
  - $|\pi| \ll |w|$
- Non-interactive
- Argument of Knowledge
  - $\exists \mathbf{E} : \ \mathbf{V}^f(x, \pi \leftarrow \tilde{\mathbf{P}}) = 1$
    $\implies (x, \mathbf{E}(x, \pi, \mathsf{tr}_{\tilde{\mathbf{P}}})) \in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

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



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

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

Micali has UC-friendly completeness

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UC-friendly completeness

Perfect completeness
of the PCP

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:

UC-friendly completeness

Perfect completeness
of the PCP

Micali has UC-friendly completeness

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

UC-friendly completeness

Perfect completeness
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Micali has UC-friendly completeness

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- 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)

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Micali has UC-friendly KS

UC-friendly KS of Micali

Micali has UC-friendly KS

- UC-friendly KS implies simulation-extractability.

UC-friendly KS of Micali

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- Merkle trees are **non-malleable** already.

UC-friendly KS of Micali

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- In Micali, makes proofs **non-malleable**.

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

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UC-friendly KS of Micali

Merkle trees are UC-friendly extractable

Micali has UC-friendly KS

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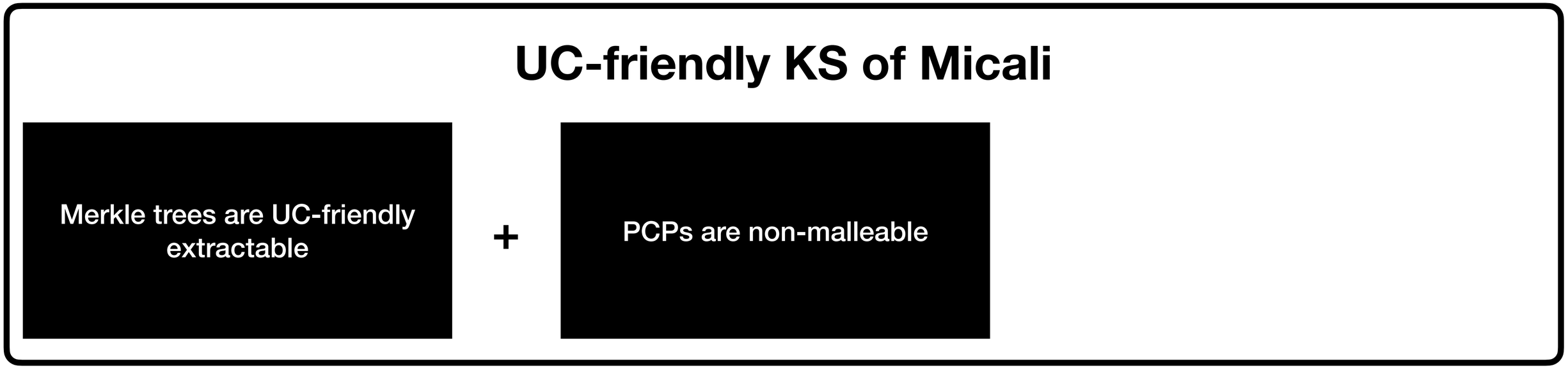

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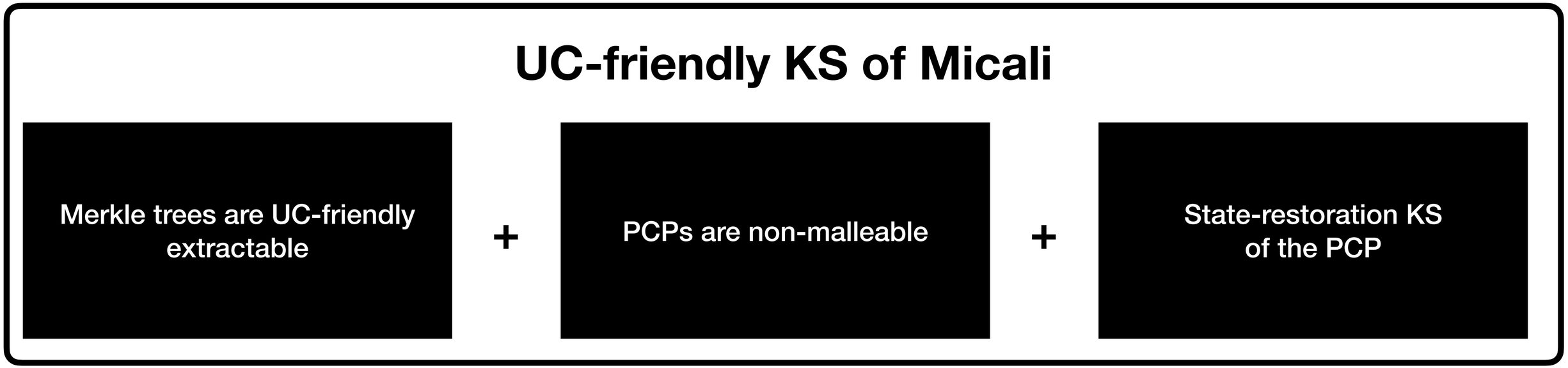


Related works

Known UC-secure zkSNARKs

Related works

Known UC-secure zkSNARKs

Non-Witness Succinct

Related works

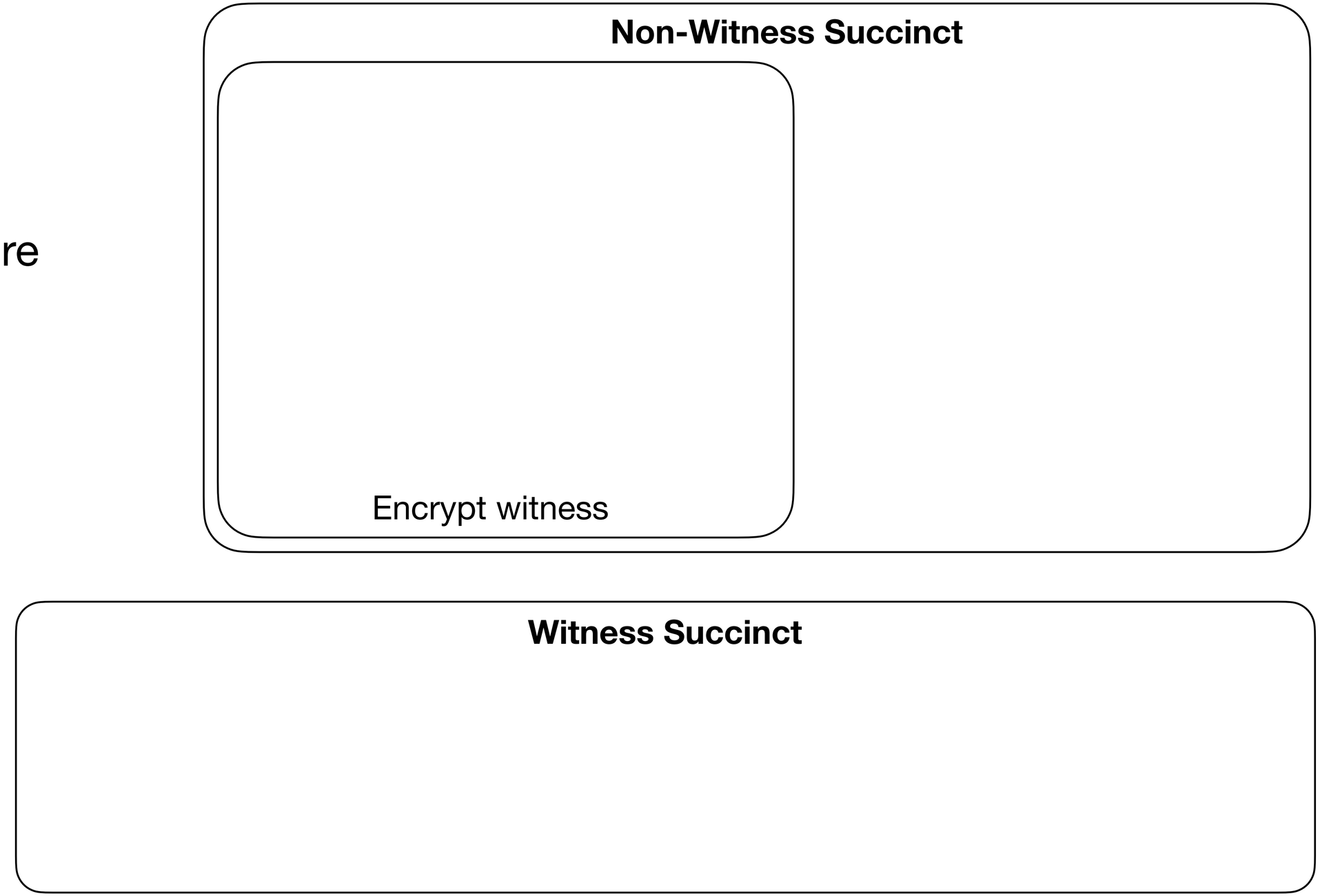
Known UC-secure zkSNARKs

Non-Witness Succinct

Witness Succinct

Related works

Known UC-secure zkSNARKs



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

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

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Encrypt witness

Witness Succinct

Related works

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Encrypt witness

Compile Σ-protocol

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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
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Encrypt witness

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

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

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

Commit witness using PCS

Related works

Known UC-secure zkSNARKs

Non-Witness Succinct

C∅C∅: 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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zkSNARKs in the ROM with Unconditional UC-Security

Alessandro Chiesa
alessandro.chiesa@epfl.ch
EPFL

Giacomo Fenzi
giacomo.fenzi@epfl.ch
EPFL

This work!

Challenge I

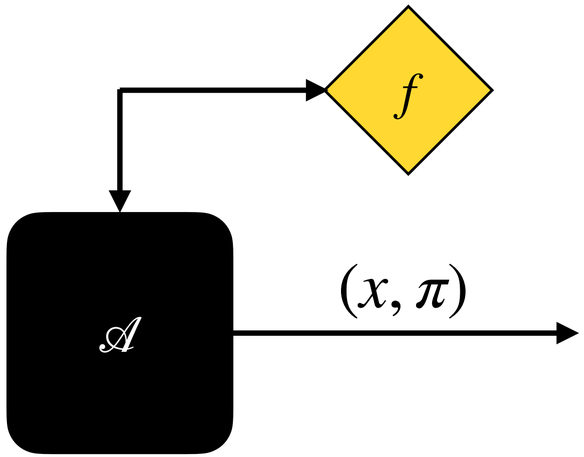
Challenge I

Rewinding

extractor

Challenge I

Rewinding extractor



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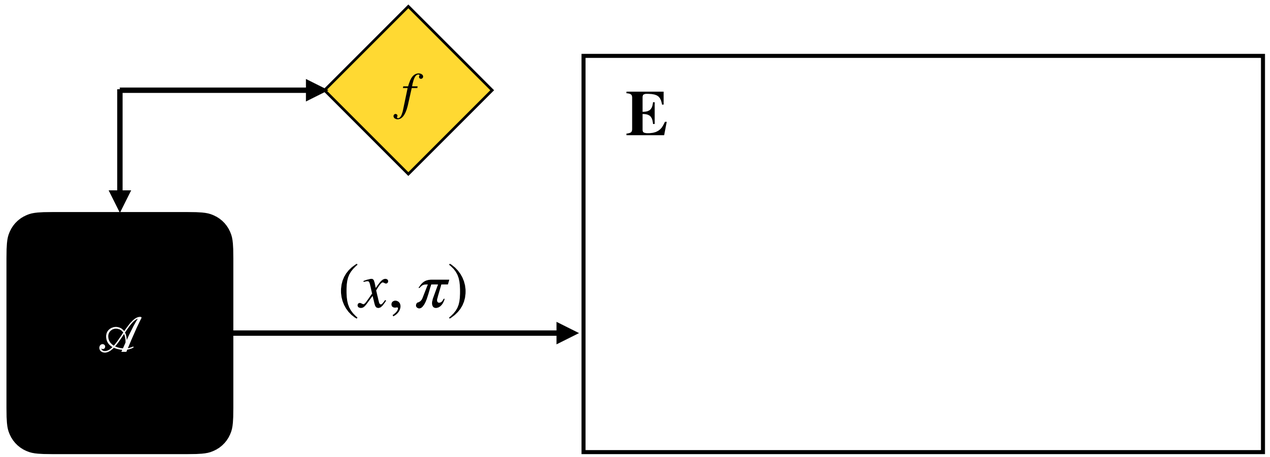

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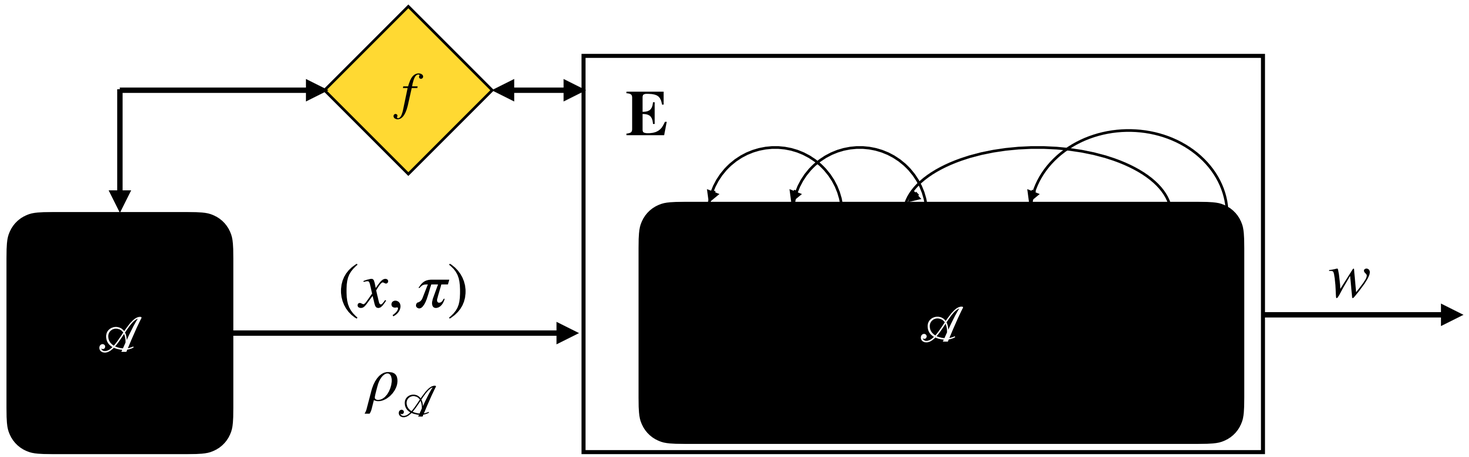

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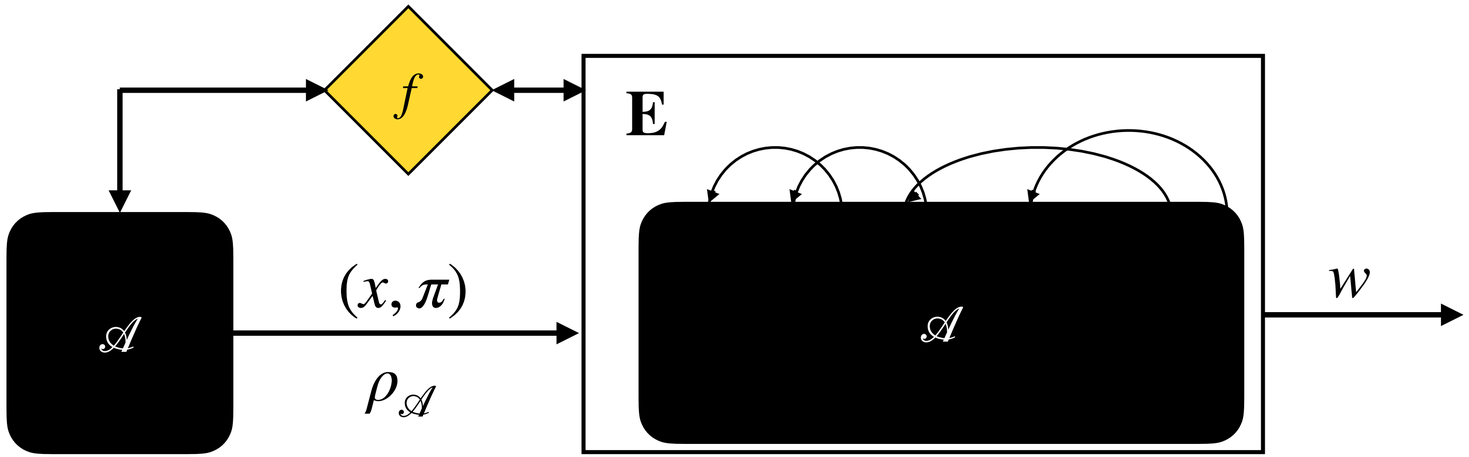

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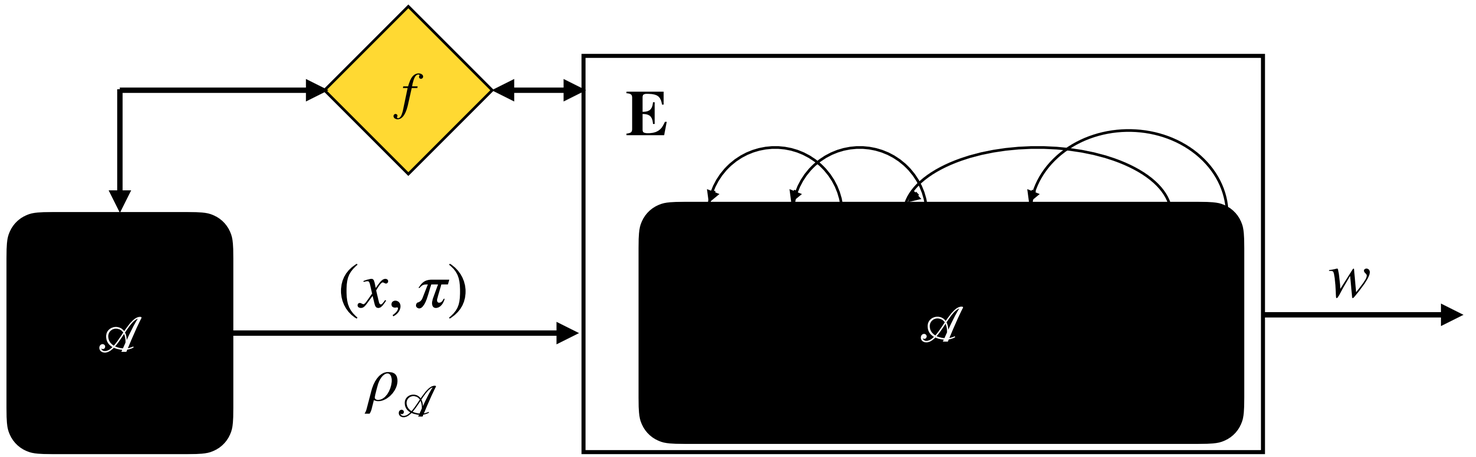

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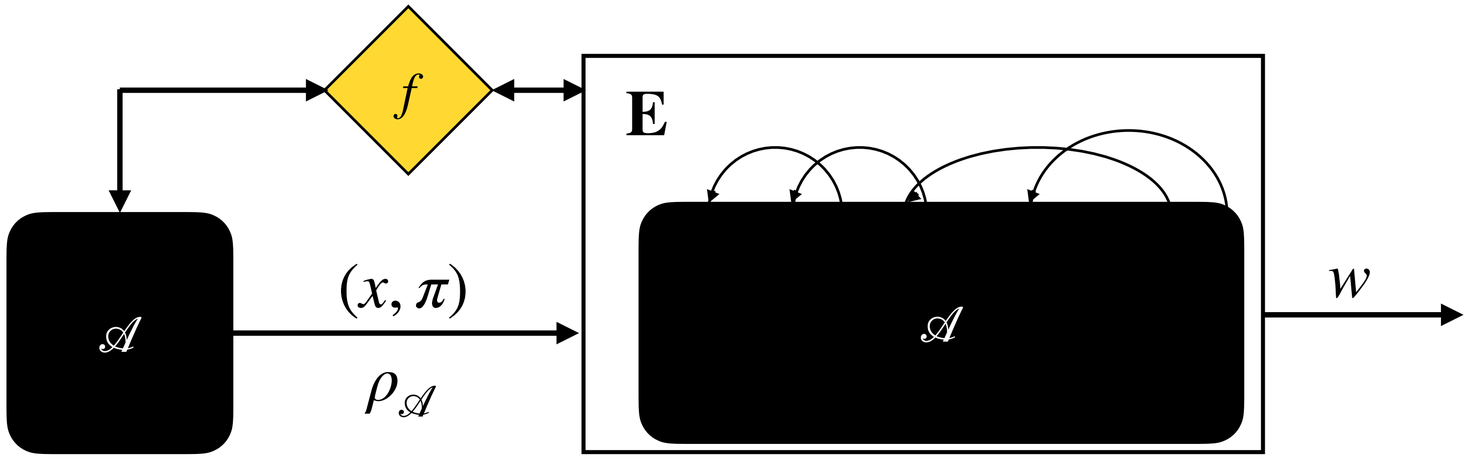

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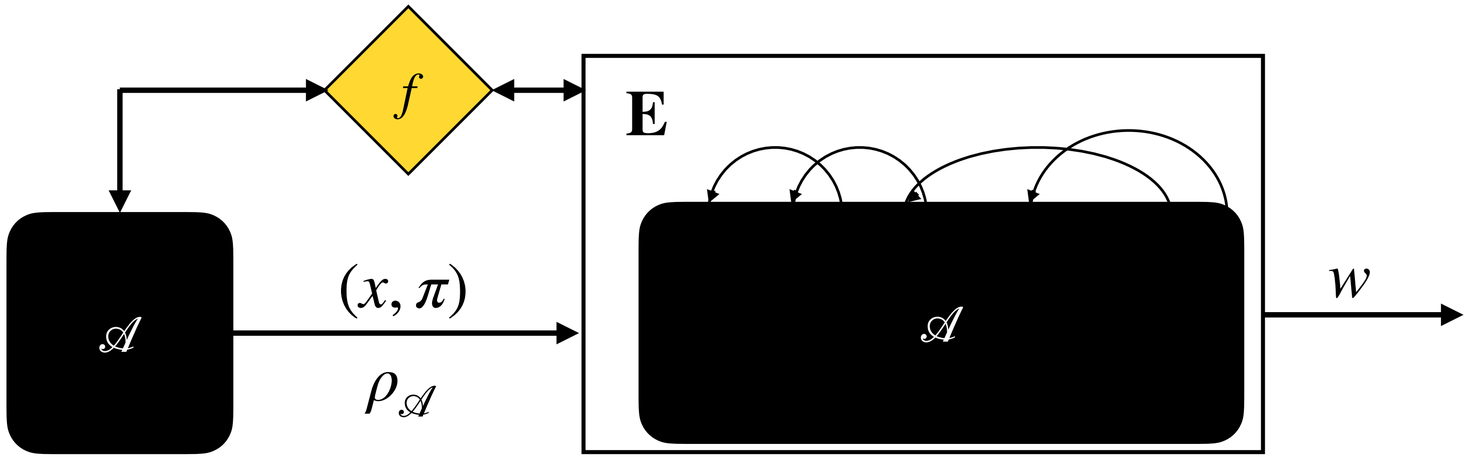

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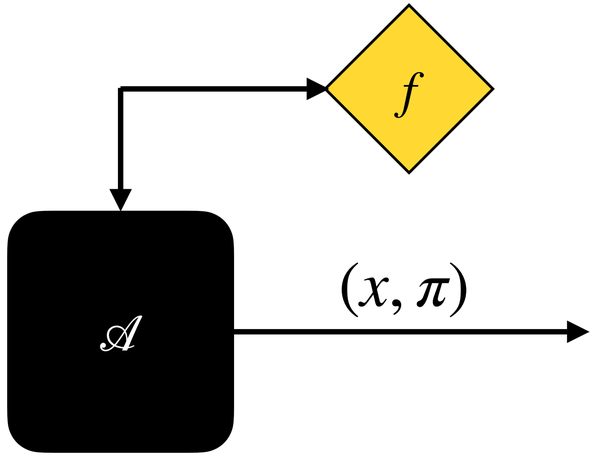

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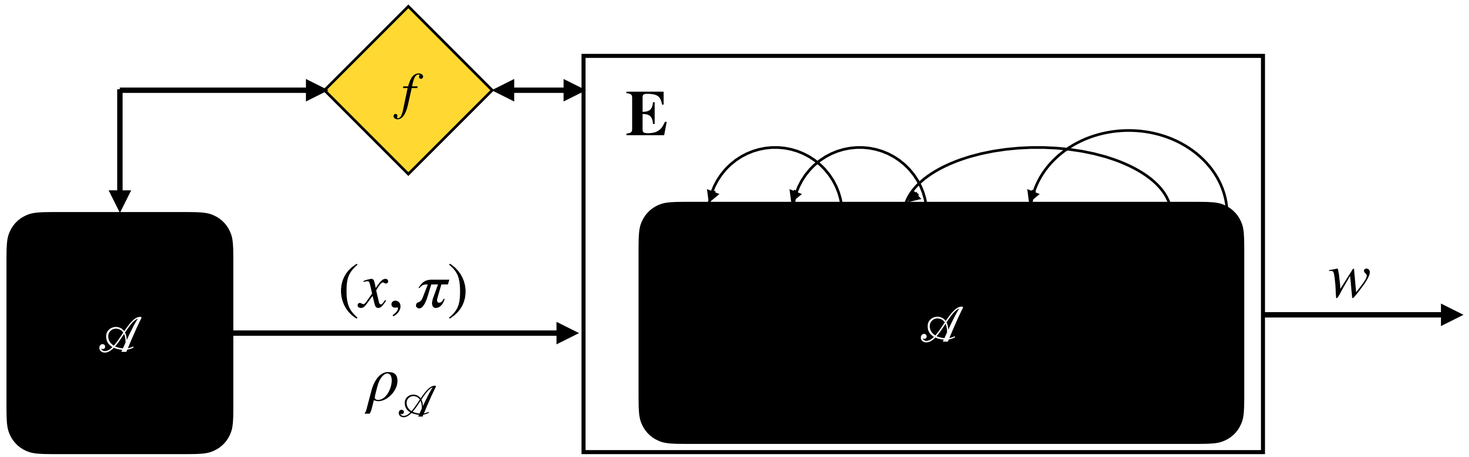

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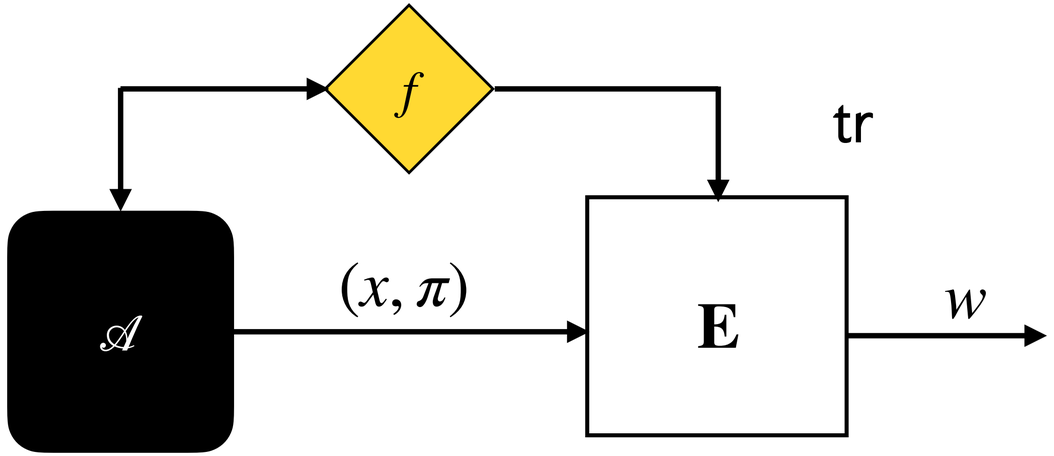

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$$\Pr\left[\begin{array}{l} \mathbf{Sim}(x) \\ \pi, \mathsf{tr}_\pi \leftarrow \mathbf{S}^f(x), \mathcal{Q} := \mathcal{Q} \cup \{\pi\} \\ \text{Program } f \text{ according to } \mathsf{tr}_\pi \\ \mathcal{A} \leftrightarrow f \end{array}\right] \leq \kappa$$

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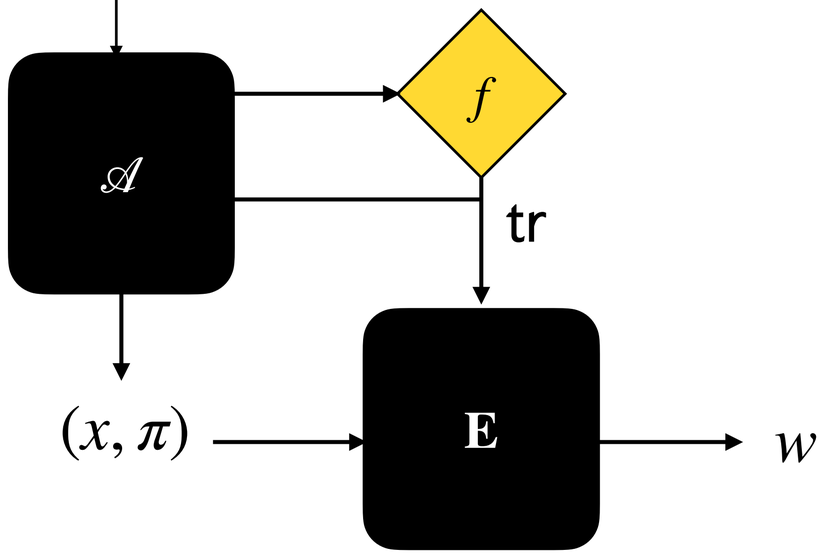

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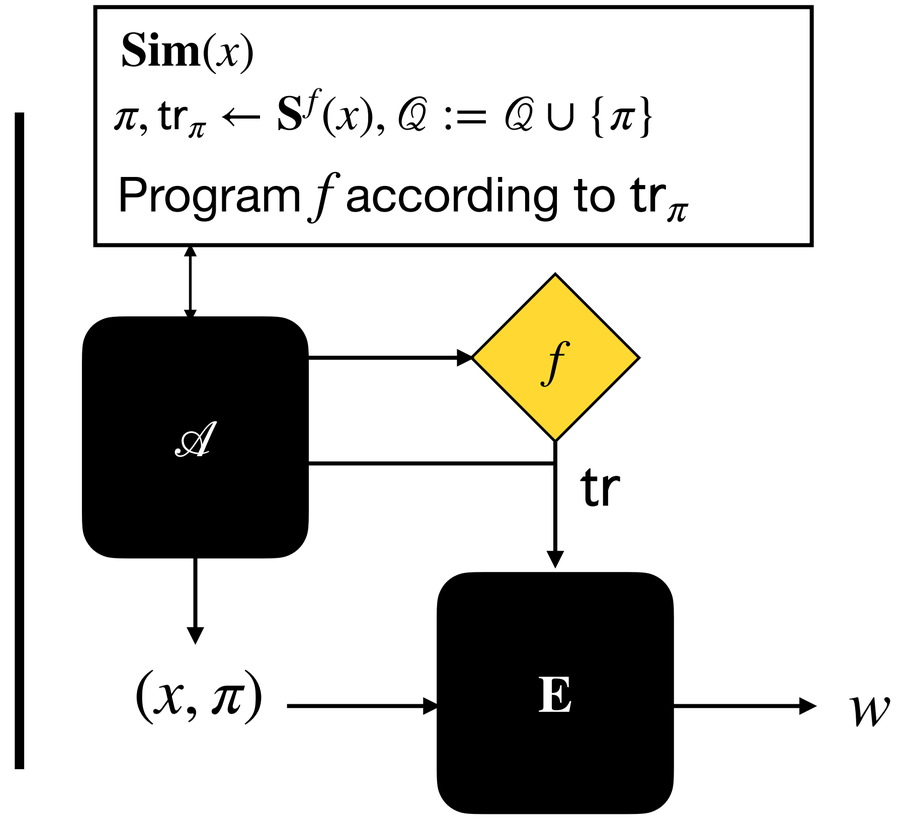

UC with Budgets

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

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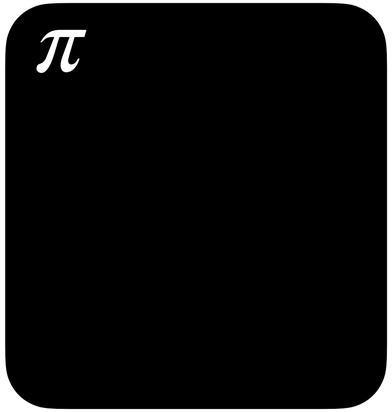

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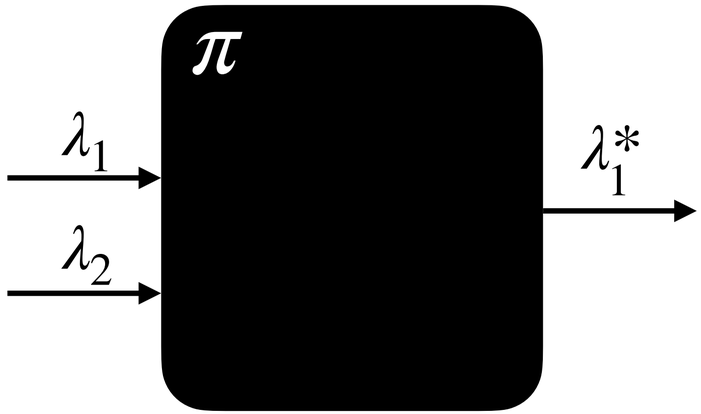

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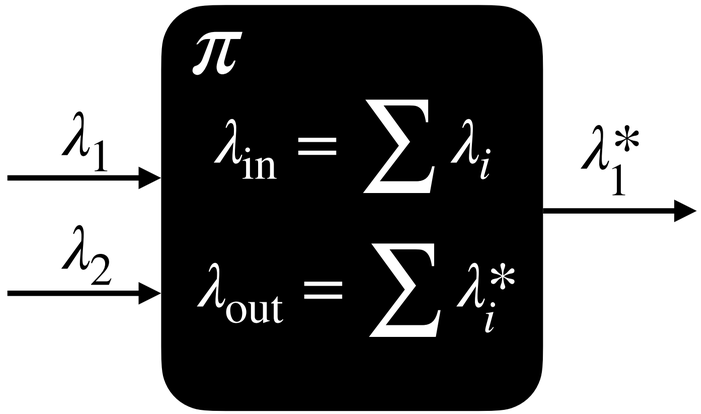

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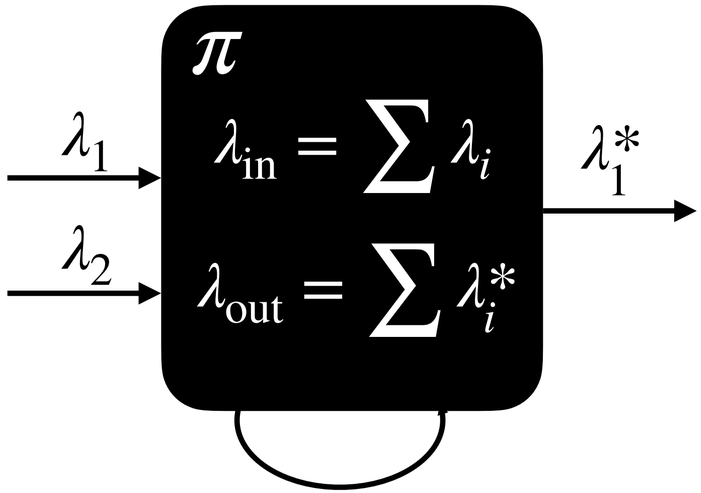

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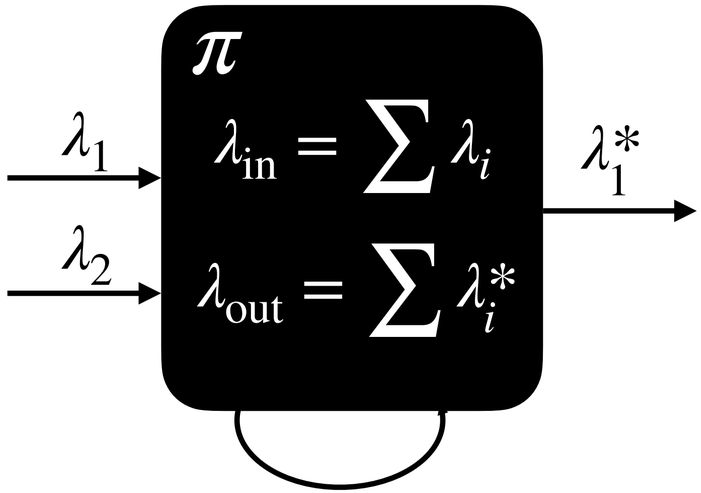

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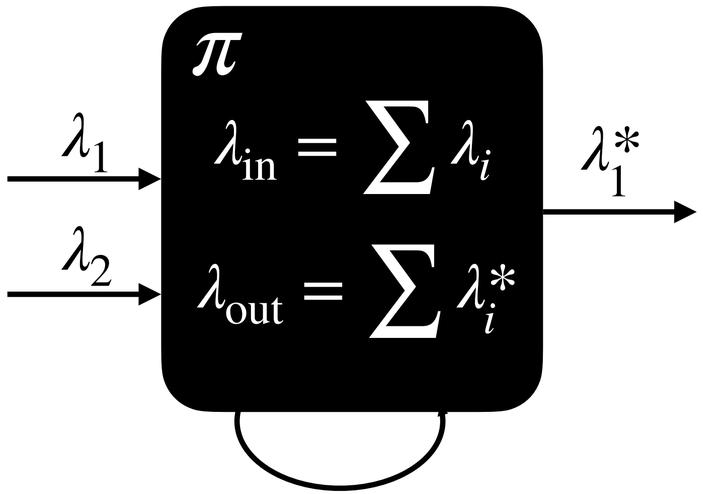

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π

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

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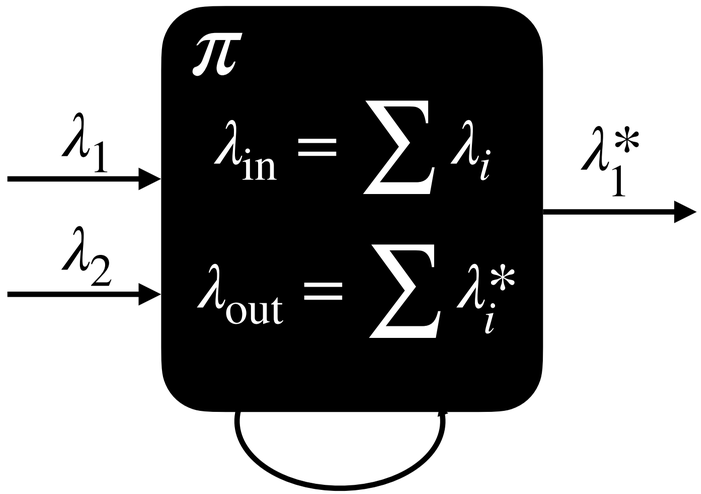

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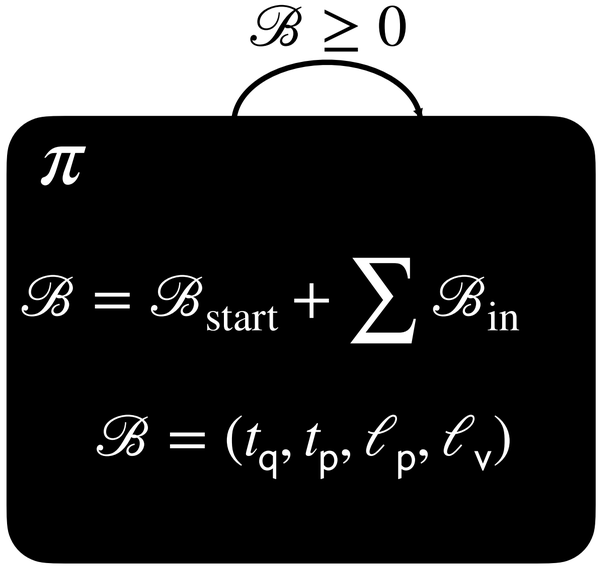

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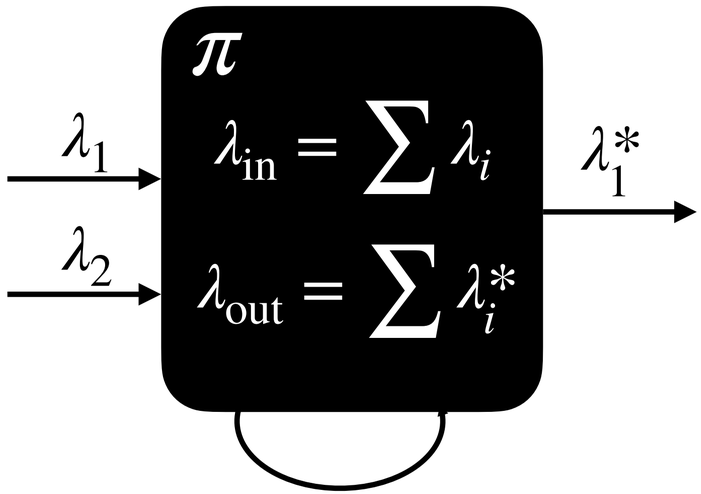

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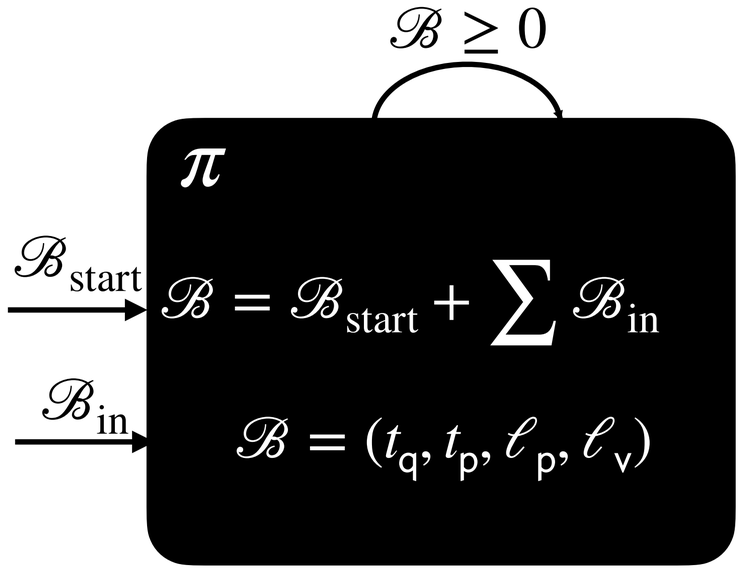

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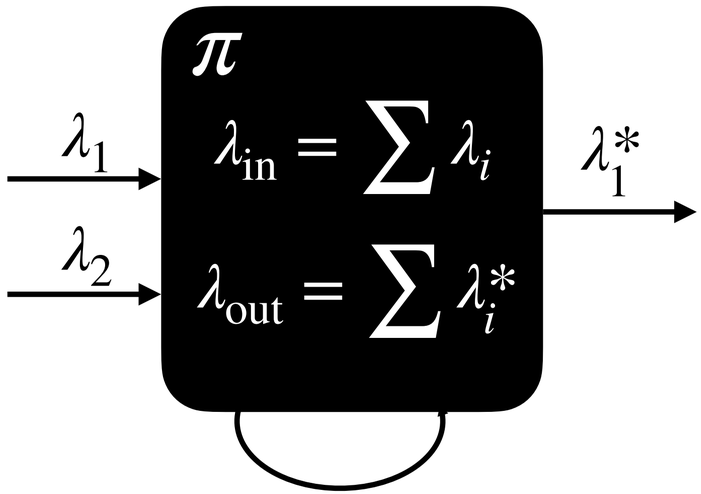

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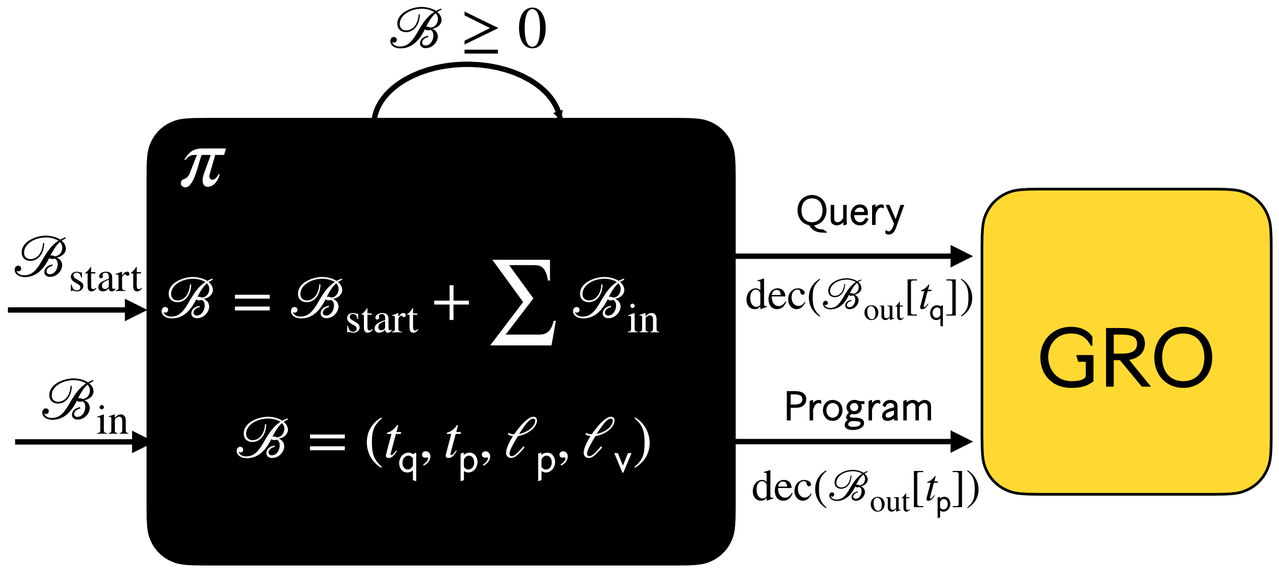

$\text{dec}(x) := x \leftarrow x - 1$

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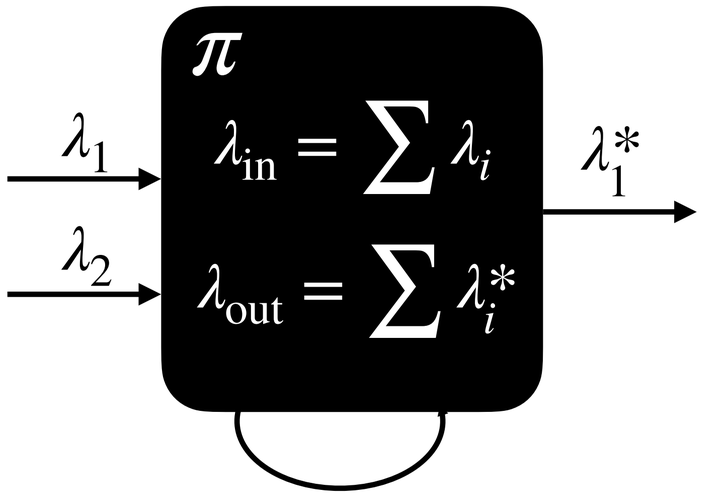

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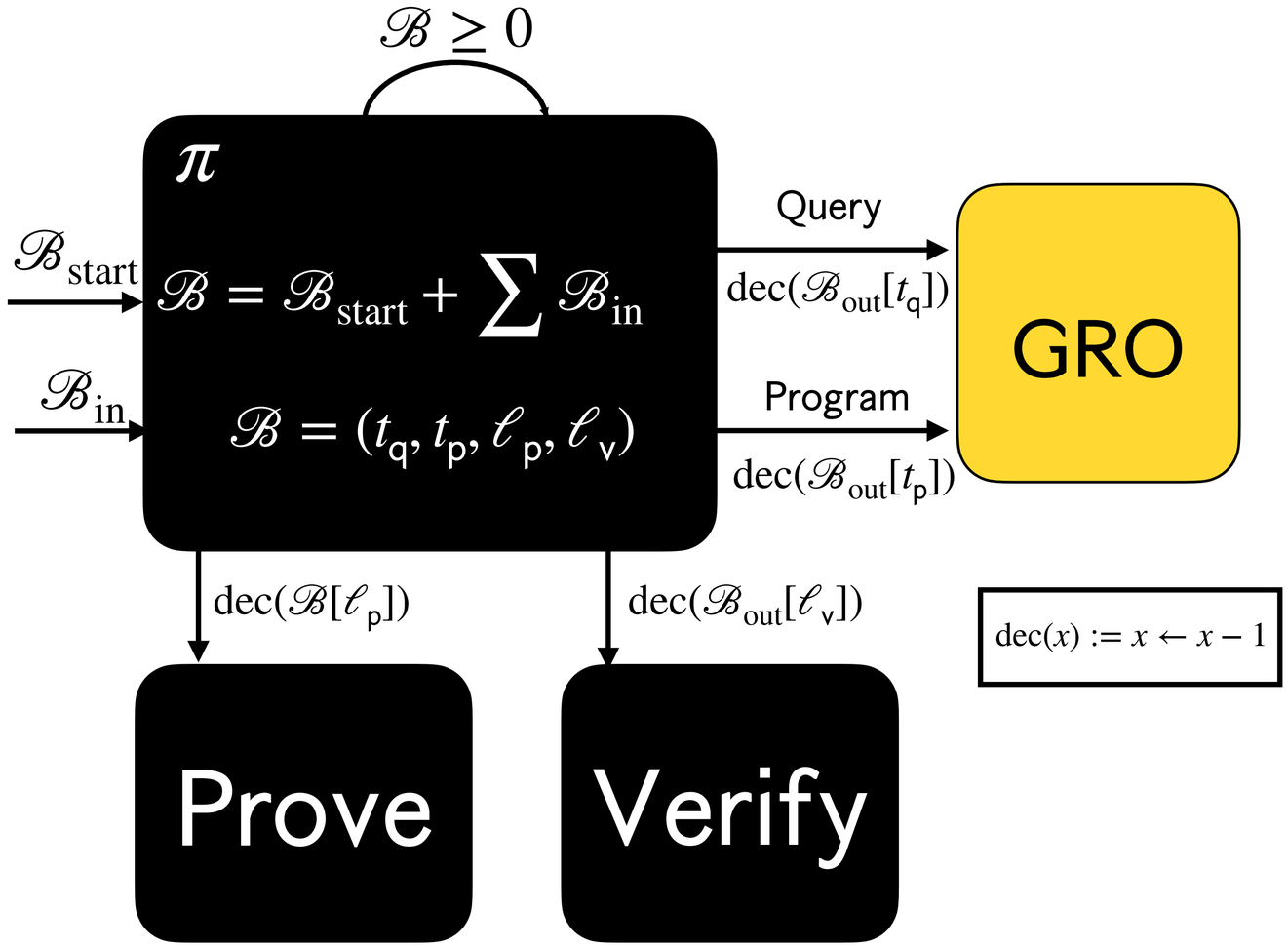

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