How to Bootstrap a SNARK *in Public*

Nir Bitansky, Ran Canetti, Alessandro Chiesa, Eran Tromer

How quickly can we verify the result of long computations?

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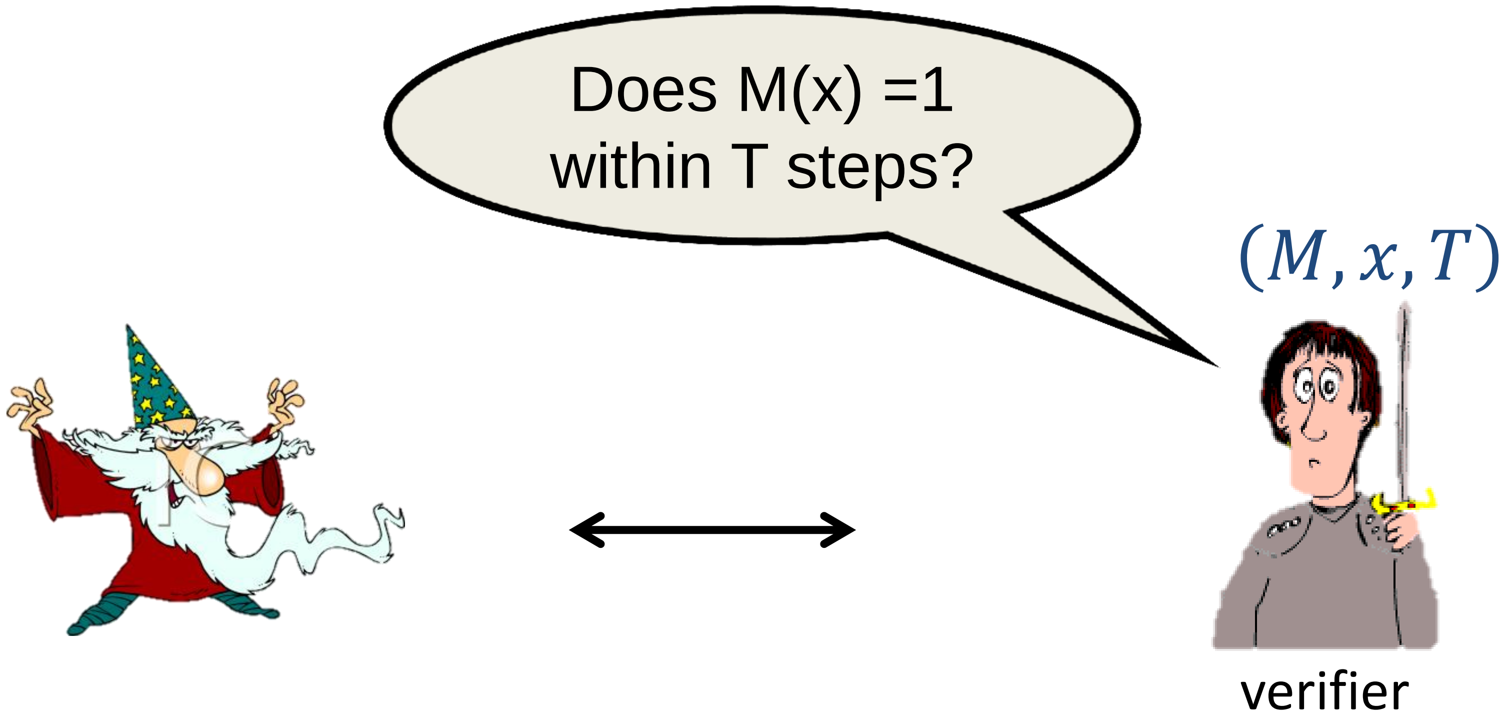
(Plain version)



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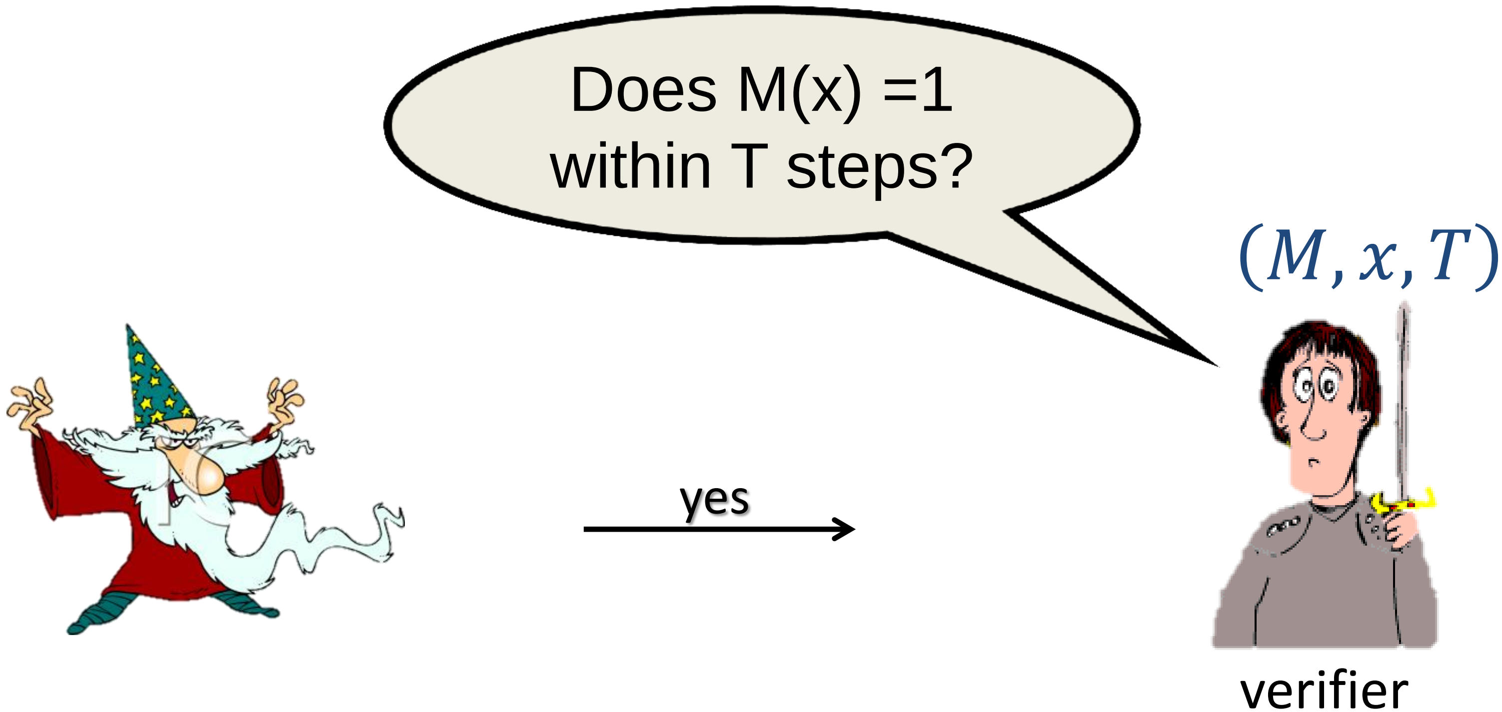

Verify by running M(x) for T steps.

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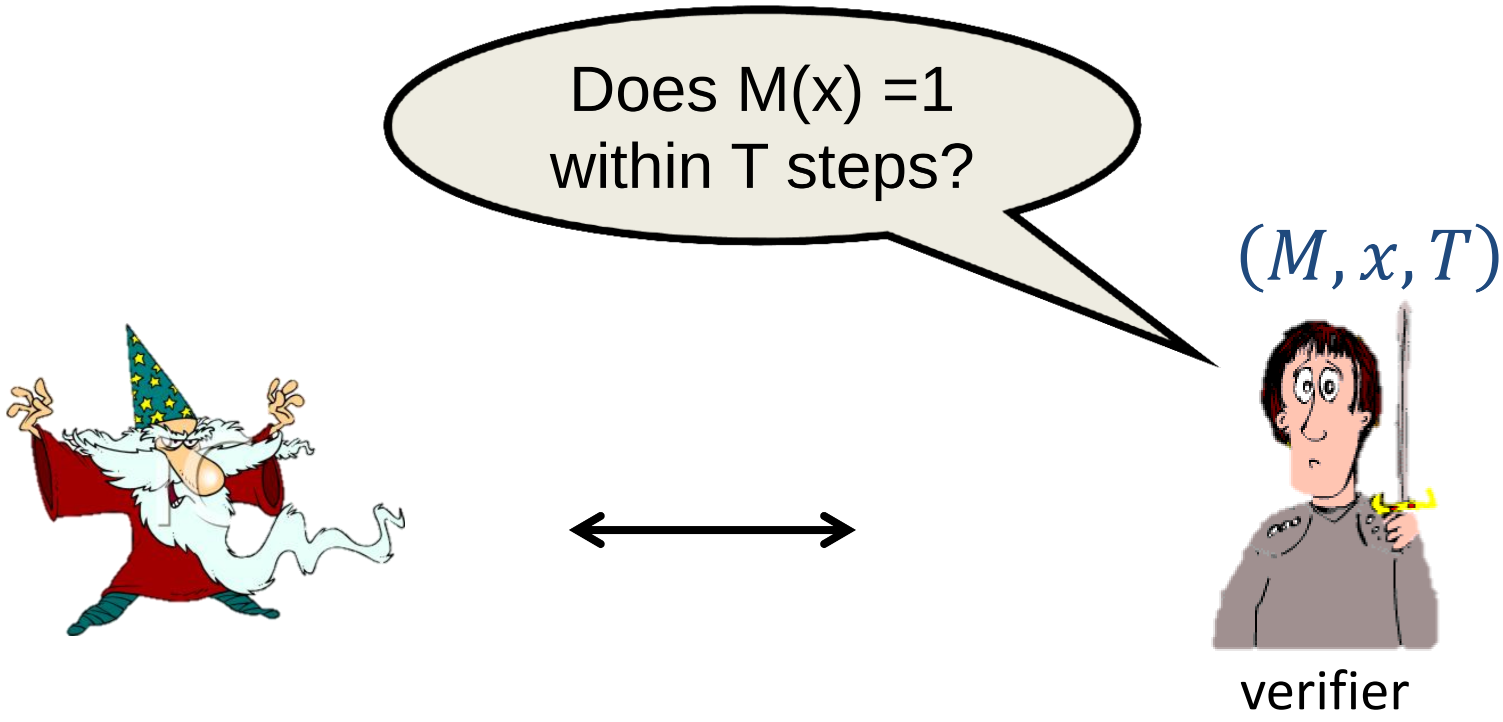

Can we do better?

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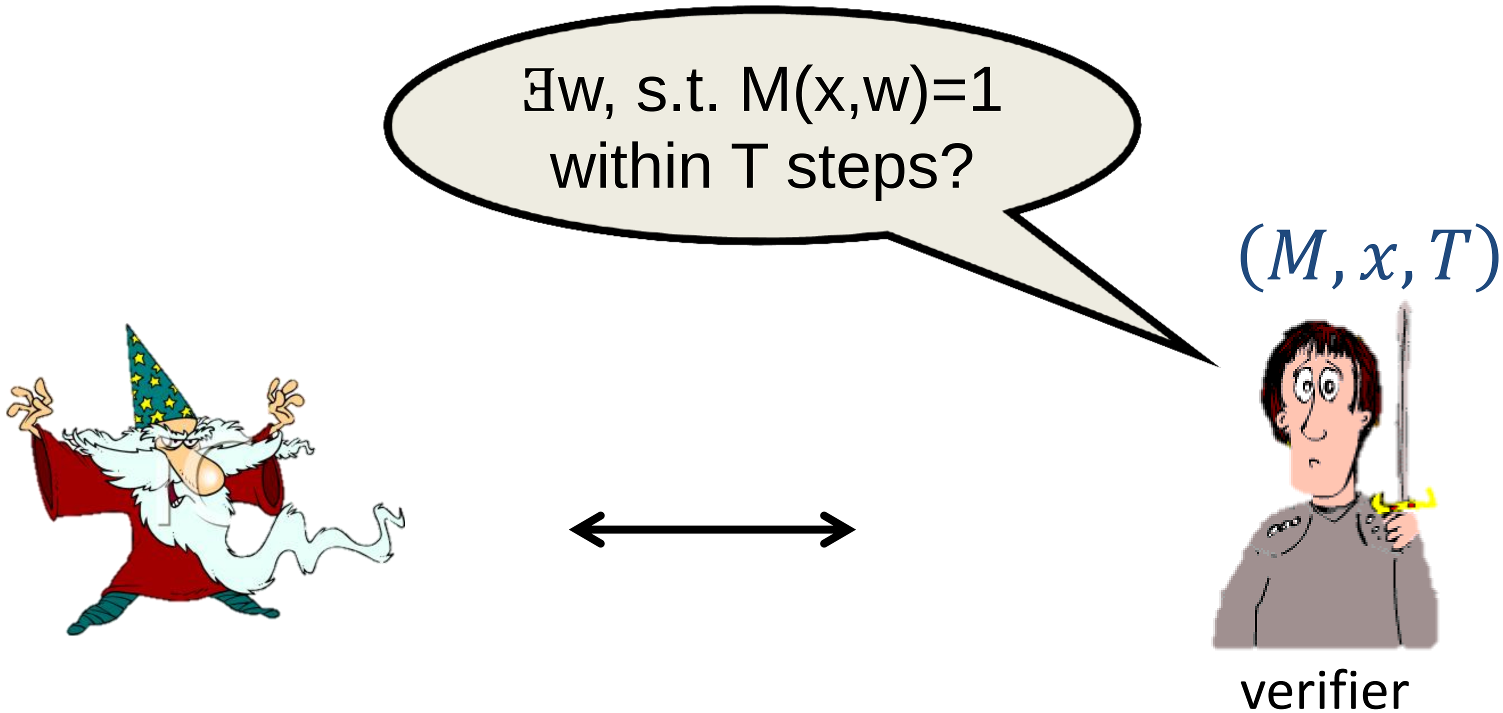
(with prover input – “NP version”)



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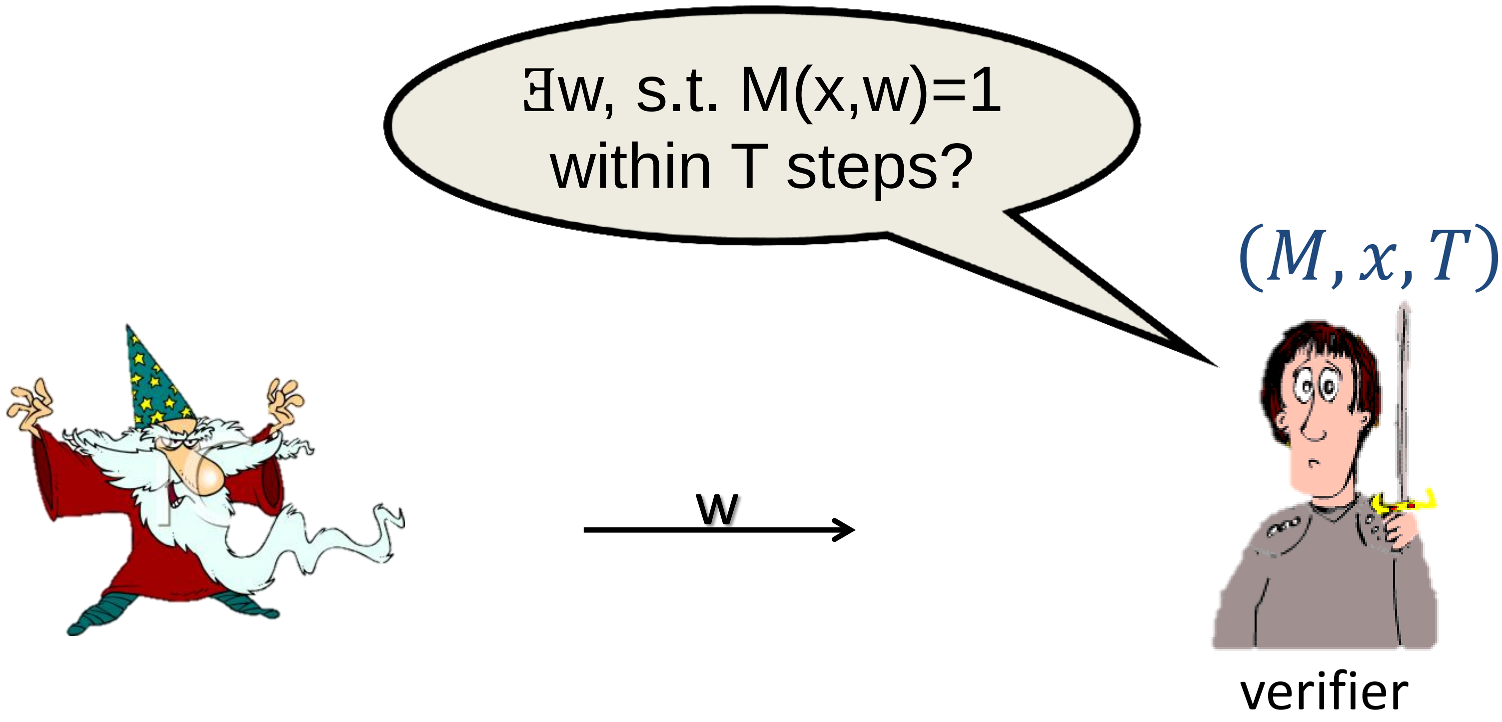

Verify by running M(x,w) for T steps.

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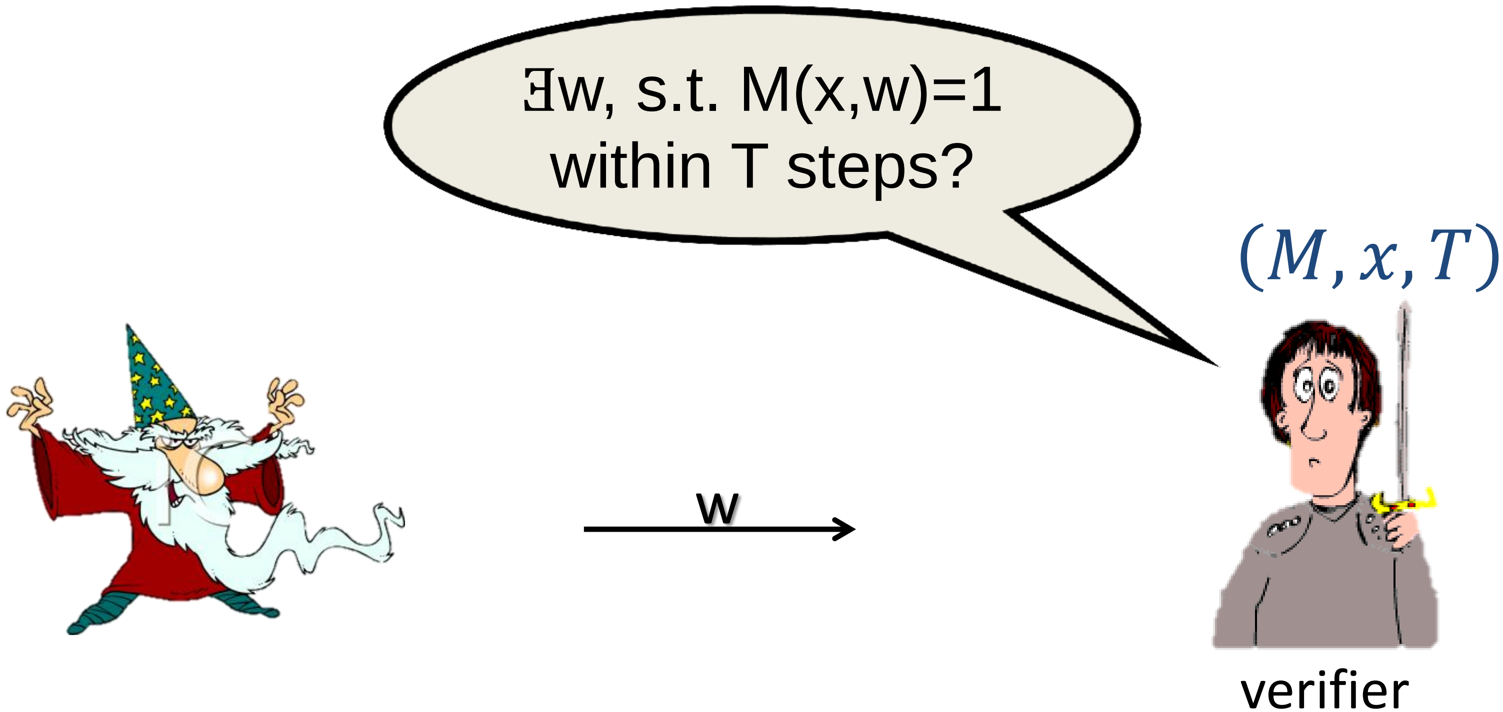


Can we do better?

Succinct Proofs with incomplete input
(“ for NP ”)

possibly long

$(M, x, T), w$

$\exists w$ s.t. $M(x, w) = 1$

in $\leq T$ steps?

↔

(M, x, T)

poly($|x|, k$)

universal poly, e.g.

$|x| \cdot k$

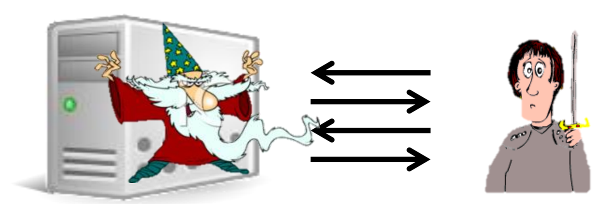
independent of T!

security parameter

Succinct Proofs with incomplete input
(“ for NP ”)

- Statistical soundness is unlikely [BHZ87, GH98, GVW02]. Thus we settle for computational soundness.

- However, we require extractability:
  - Natural in real-life applications (databases…)
  - Crucial for this work



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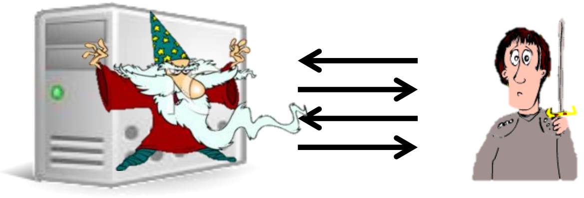
[Kilian 92]: can do 4-message (assuming CRH)



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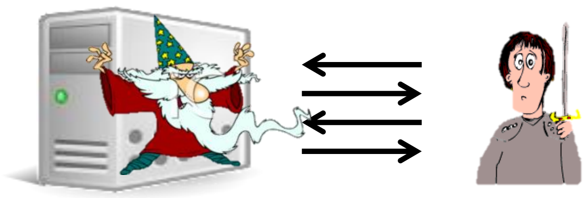
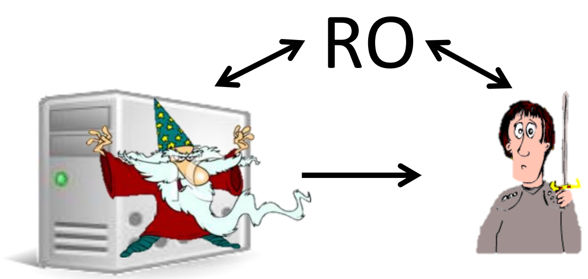


[Micali 94]: one message!
with a random oracle
(aka “CS proofs”)



Non-interactive in the plain model?

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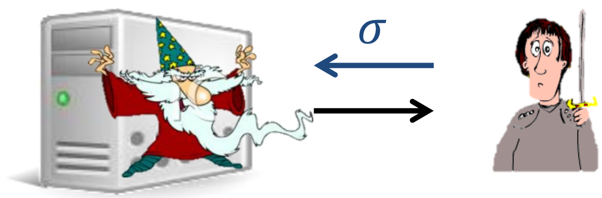
Totally non-interactive protocols
(against non-uniform provers
for “hard enough languages”)
Are unlikely [BHZ87, GH98, GVW02].

With a verifier initial message (reference string)?



reference string σ
sent before statements

Succinct Non-Interactive Argument of Knowledge (SNARK):

A protocol (P,V) such that:

- V sends an initial message σ to P
- Repeat: - P sends (M,x,T), π to V
  - V(M,x,T, π, σ)=acc/rej

Succinct Non-Interactive Argument of Knowledge (SNARK):

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Completeness: If ∃w s.t. M(x,w)=1 within T steps, then V accepts.

Extractability: ∀ pt P' ∃ pt E, such that when (P',V) accepts (M,x,t, π), E outputs w s.t. M(x,w)=1 within T steps (except w.p. negl(k)).

Designated verifier SNARKs

Same as (publicly verifier) SNARKs except:

- V keeps secret state τ associated with σ .
- V uses τ in each verification.

Disadvantages:

- Vulnerable to leakage on verifier (even the verifier's decision)
- Proofs are no longer transferrable or publicly verifiable ("publishable").
- Harder to compose (later on)

Can we construct SNARKs?

No SNARK can be proven secure via “black-box reduction to an efficiently falsifiable assumption”

[Gentry-Wichs11].

- even for designated verifier SNARKs
- even if we only require plain soundness (without knowledge extraction)

Can we construct SNARKs?

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- even if we only require plain soundness (without knowledge extraction)

What can we do?

- Option 1: Use non BB reductions
- Option 2: Use other assumptions

SNARKs from "non--falsifiable assumptions"

- Replace the RO in [Micali94] with a "sufficiently complicated" hash function and assume security.

Disadvantages: Implementation specific, doesn't teach us much…

- Based on "extractable collision resistant hash functions" [Bitansky Canetti Chiesa Tromer 11 , Goldwasser Lin Rubinstein 11, Damgard Faust Hazay 11]

Disadvantage: Only designated verifier.

PV SNARKs with long reference string ("with pre-processing")

In the initial stage, V "works hard":

generates (σ,τ) where:

- τ is poly(k)
- σ is poly(T,k)

In proof stage, V is still succinct - only uses τ.

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In proof stage, V is still succinct - only uses τ.

Note: τ is public!

Can realize based on a Knowledge-of-exponent assumption in bilinear groups

[Groth10, Lipmaa12, Gennaro-Gentry-Parno-Raykova12]

Another advantage of [G10,L12,GGPR12]
(Following [Ishai-Kushilevitz-Ostrovsky07])

Very different techniques – alternative to PCPs

Potentially better efficiency (for prover).

Prover efficiency is important !
(e.g. cloud computing)

Another advantage of [G10,L12,GGPR12]
(Following [Ishai-Kushilevitz-Ostrovsky07])

Very different techniques – alternative to PCPs

Potentially better efficiency (for prover).

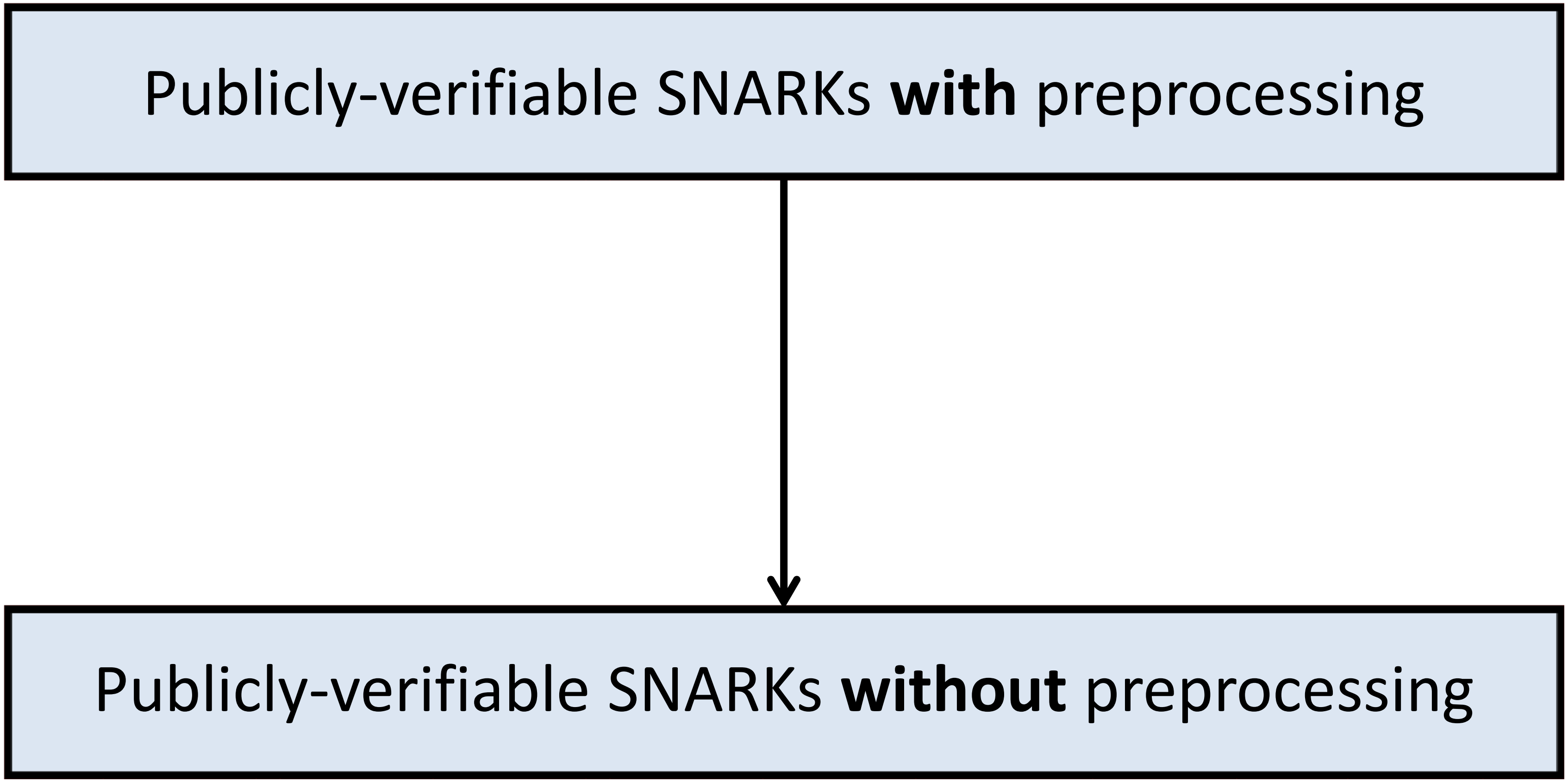
But…

For computations with time T , space S

Prover needs T poly(k) ***space!***

Would like to preserve time and space individually.

First Main Result



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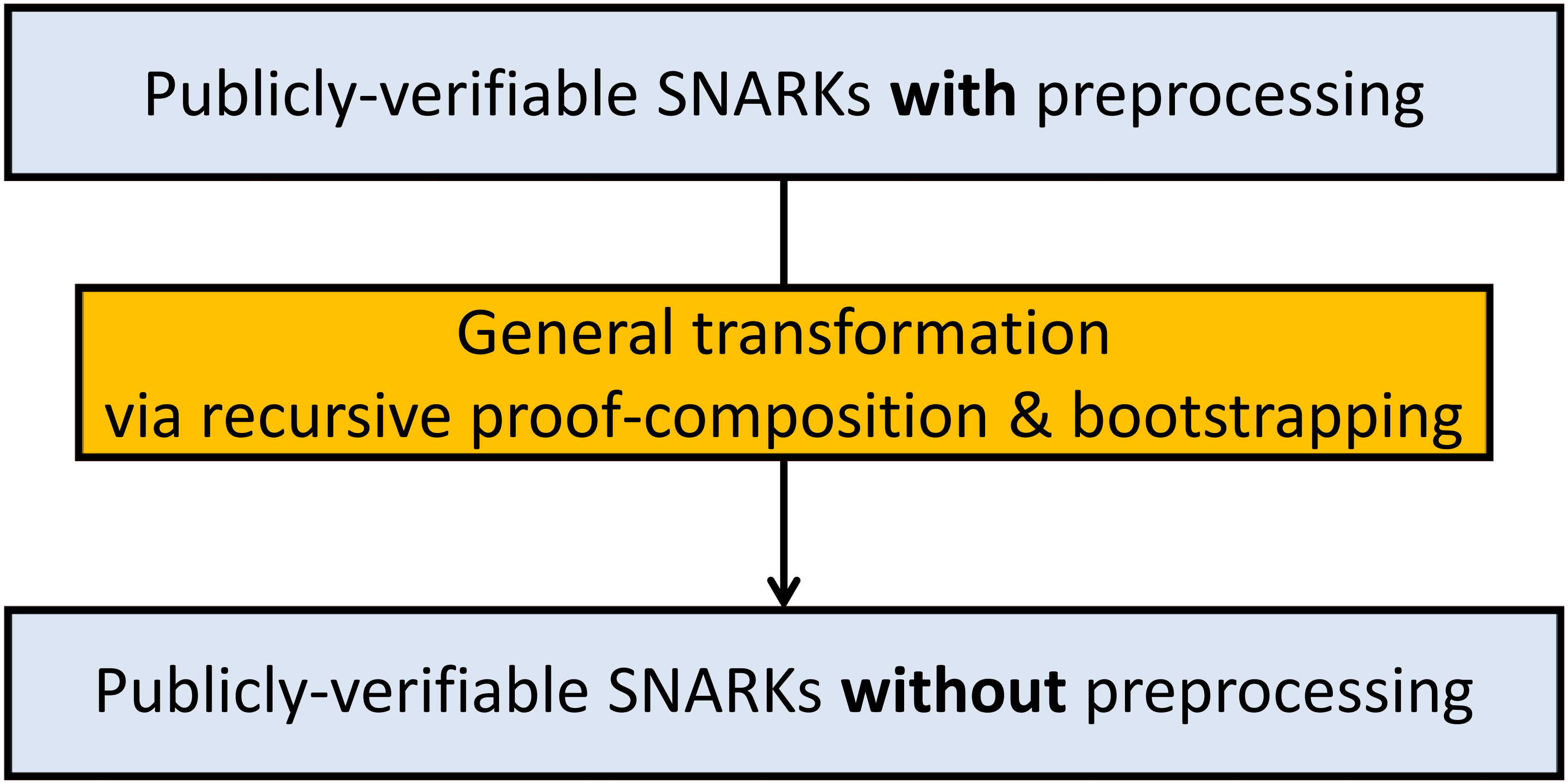

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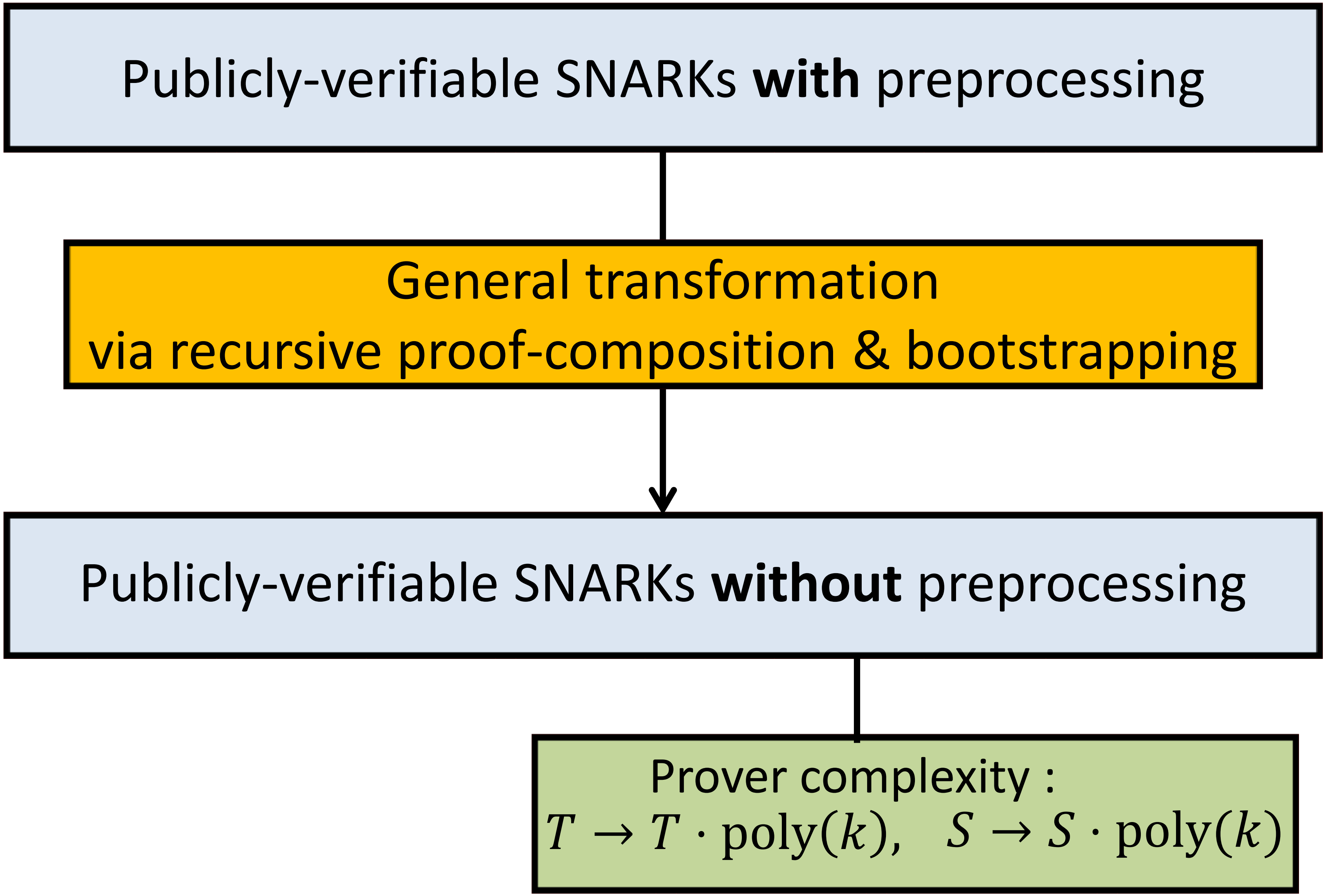

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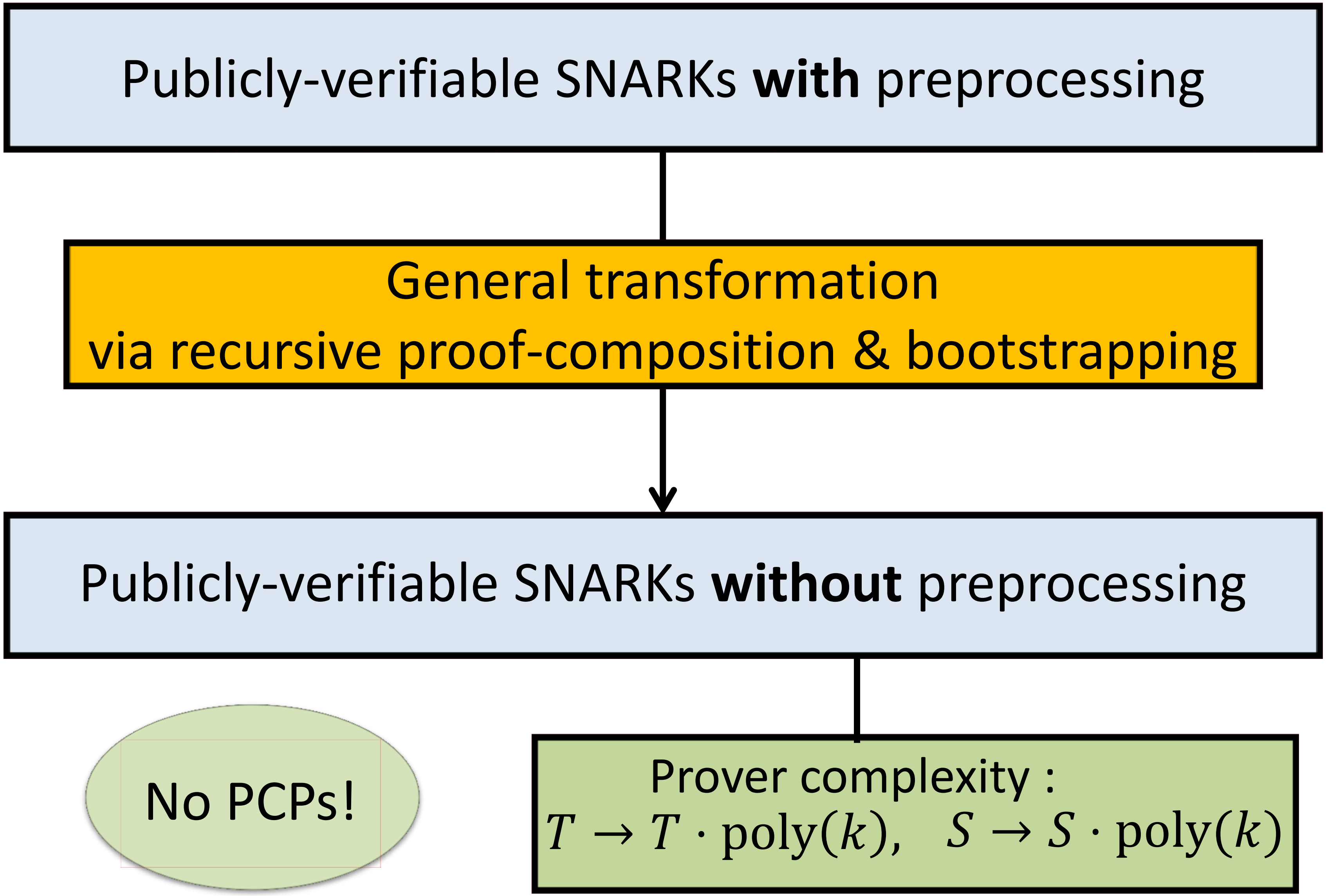

Corollaries

Assuming KEA in a bilinear group, there exist

fully succinct publicly-verifiable SNARKs .

Any SNARK can be transformed into a SNARK where:

- Prover time is $T \cdot poly(k)$

- Prover space is $S \cdot poly(k)$

(T,S are time and space of original M)

The Core Idea:
Bootstrapping a SNARK

Only need to be able to prove correctness of (many) small computations.

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Only need to be able to prove correctness of (many) small computations.

How small?

as small as SNARK verification (and a bit more)

- ➔ The preprocessing becomes cheap (poly(k))
- ➔ Prover overhead becomes poly(k) (both in time and in space)

Part I

How to Bootstrap a SNARK:
a Bare-Bones Description

Part II

Using the Proof Carrying Data
(PCD) abstraction

Part I:
Bare-Bones Description

Incremental Computation [Valiant08]
a possibly useful idea

Compile a computation $M(x, w)$ to a new one that after each step spits a **short** proof of its correctness **so far**

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Compile a computation $\boldsymbol{M(x,w)}$ to a new one that after each step spits a **short** proof of its correctness **so far**

but… (implicitly) assumes fully-succinct SNARKs

Incremental Computation [Valiant08]
a possibly useful idea

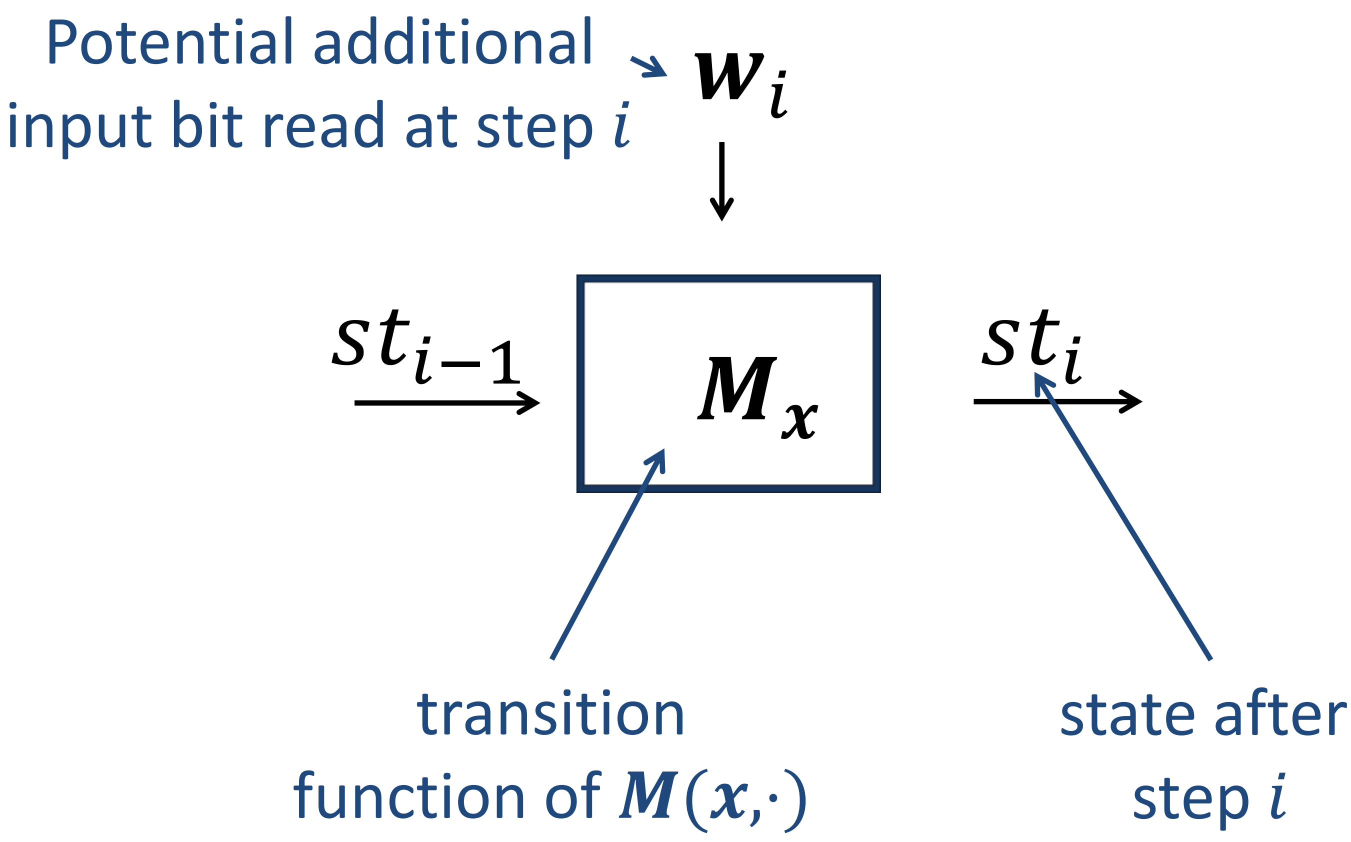
Still uses SNARKs in a non-trivial way:
proofs only involve "small" computations:
proportional to the space S used by $\boldsymbol{M}$.

Can use preprocessing SNARKs, where
preprocessing is as cheap as S ….

Problems:
In general, S may be as large as T
Need to carefully aggregate proofs by composition

Incremental Computation More Concretely

Split a T-step computation $\boldsymbol{M}(\boldsymbol{x}, \boldsymbol{w})$ to T single-step computations



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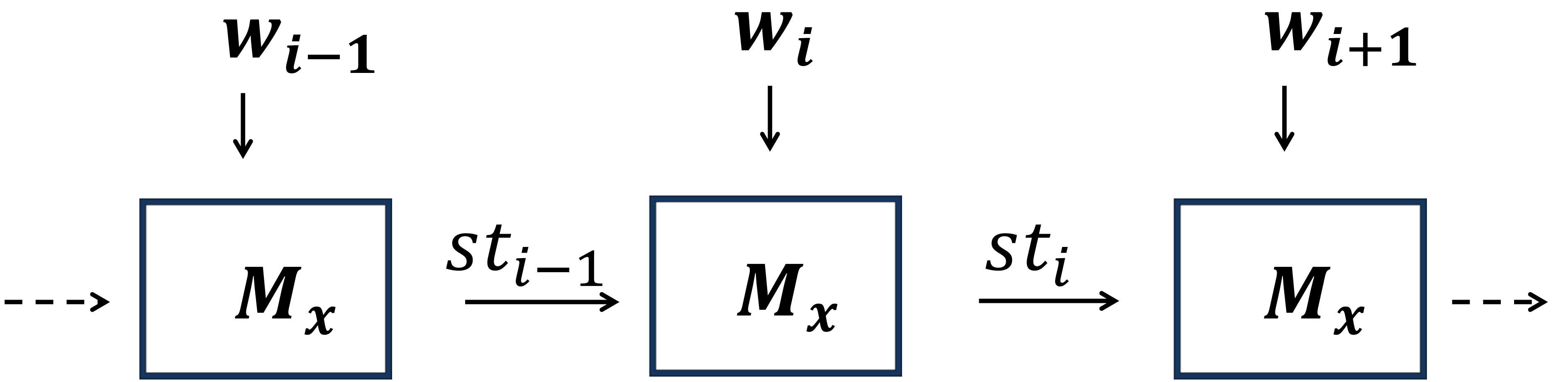
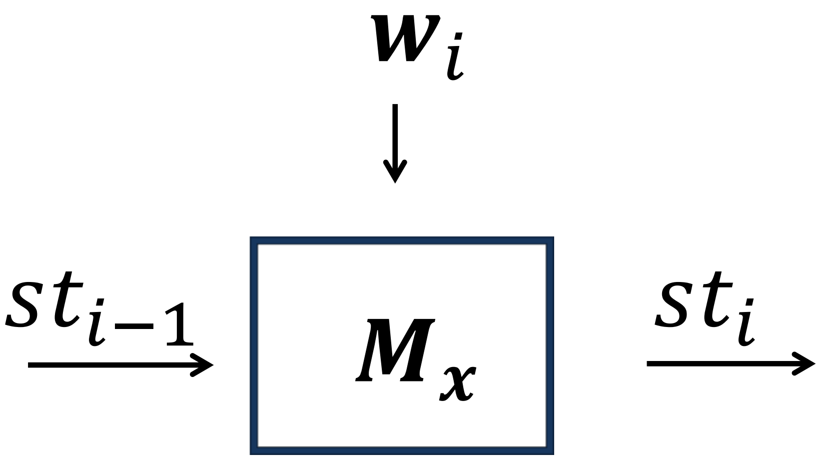
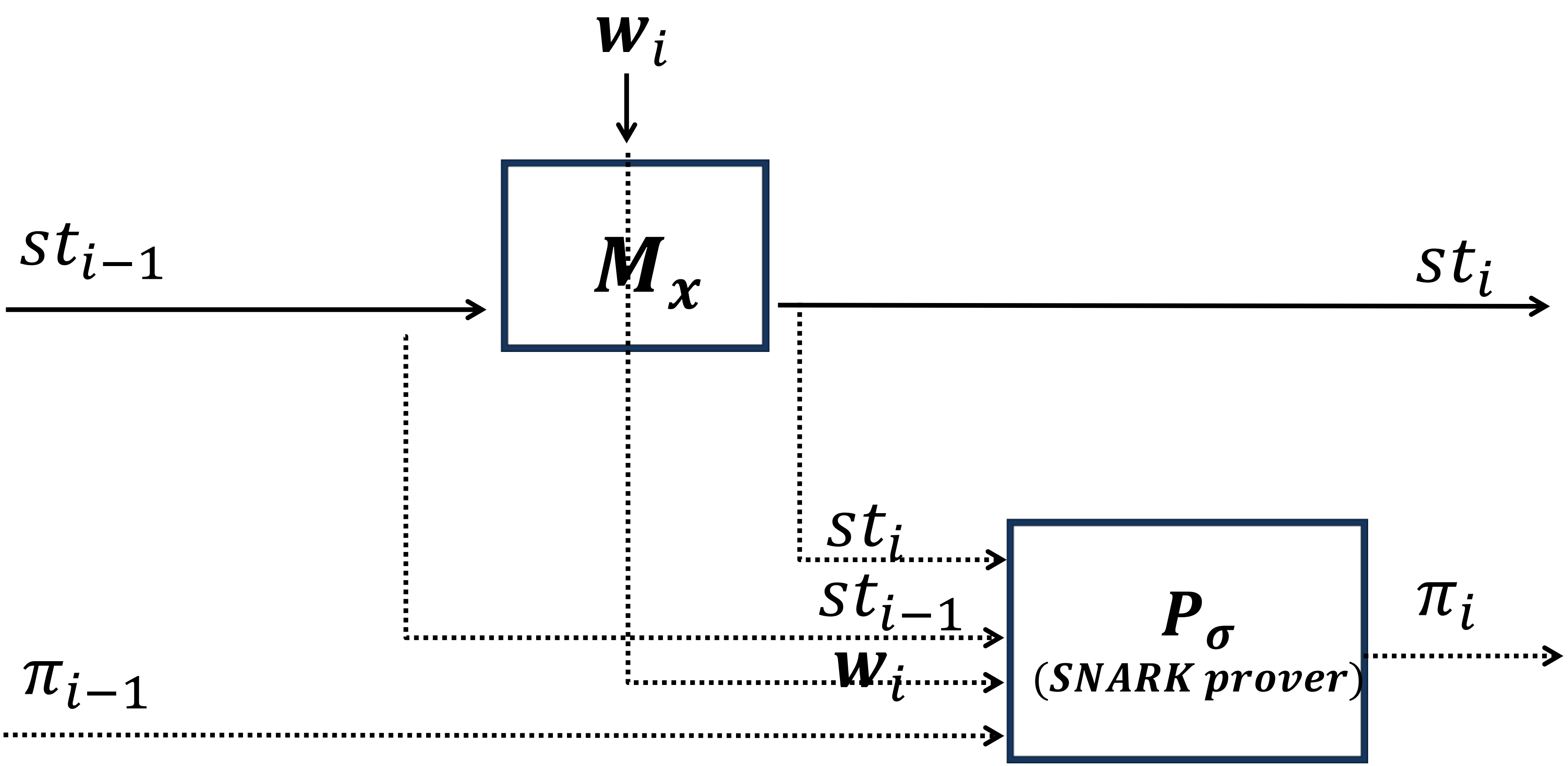




Compose short proof for current step with short proof for previous steps:

1. performed step i correctly
2. verified a proof π_{i-1} for correctness of steps $1 \ldots i-1$

Augment computation $\boldsymbol{M(x,w)}$ with consistency proofs



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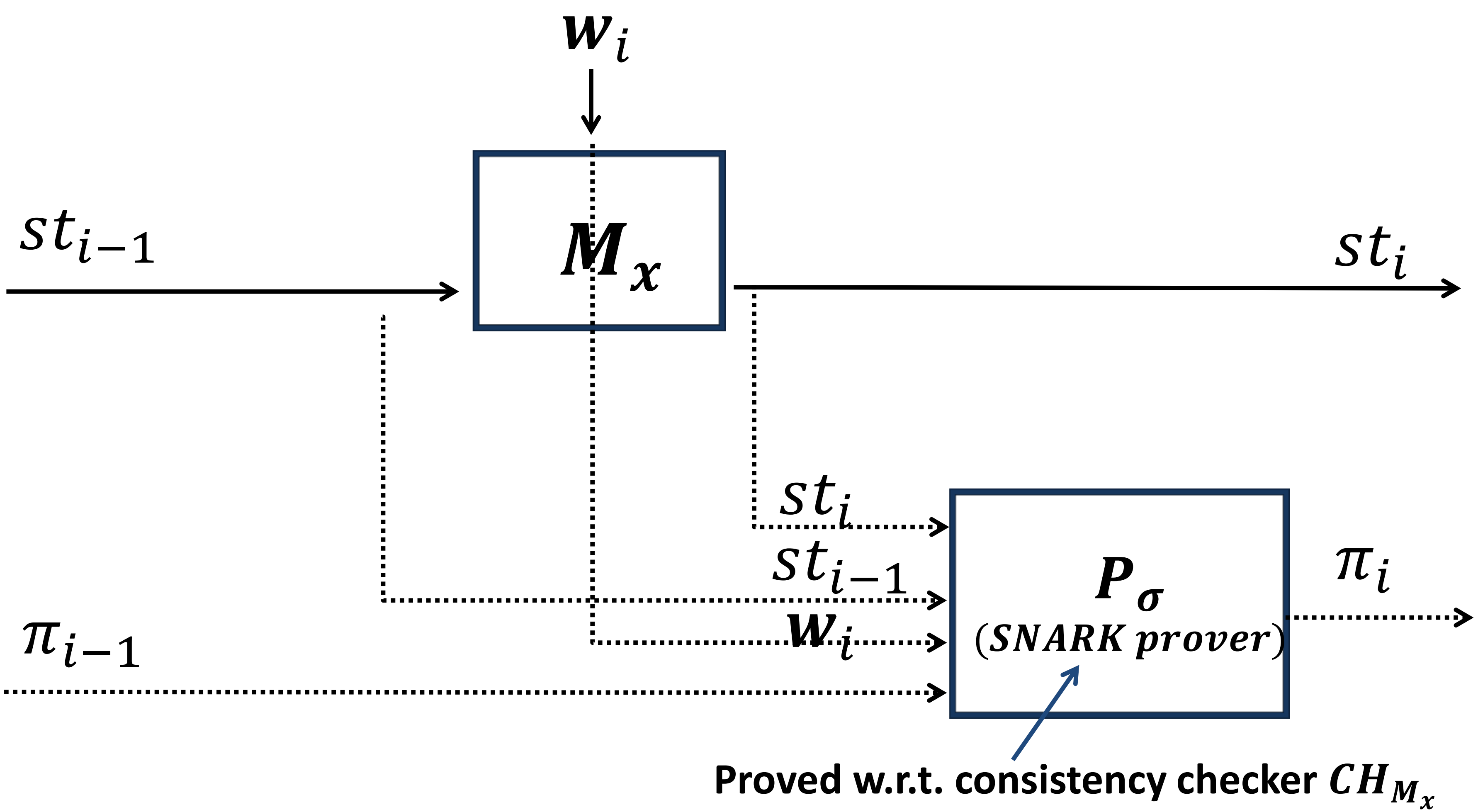
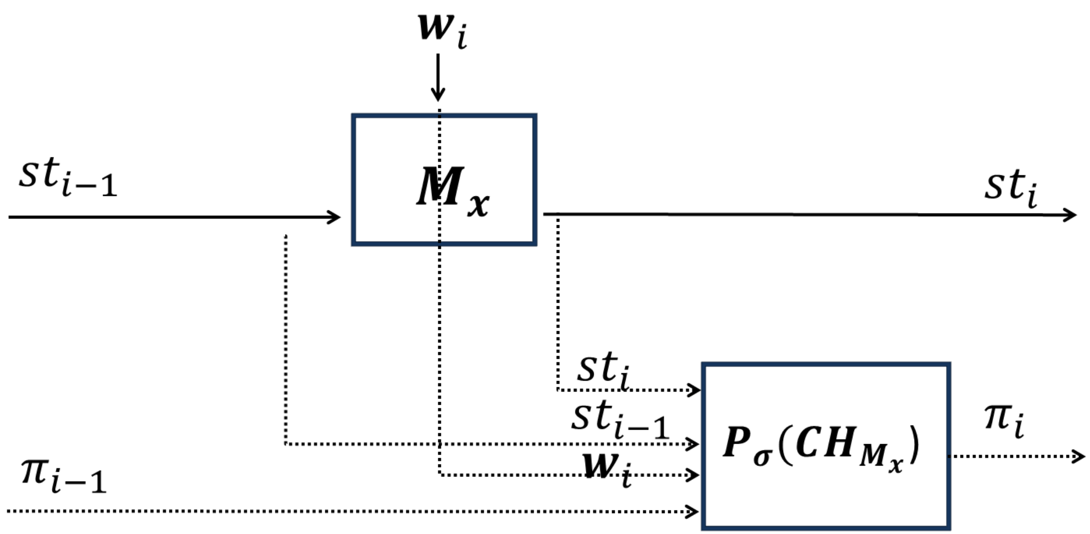
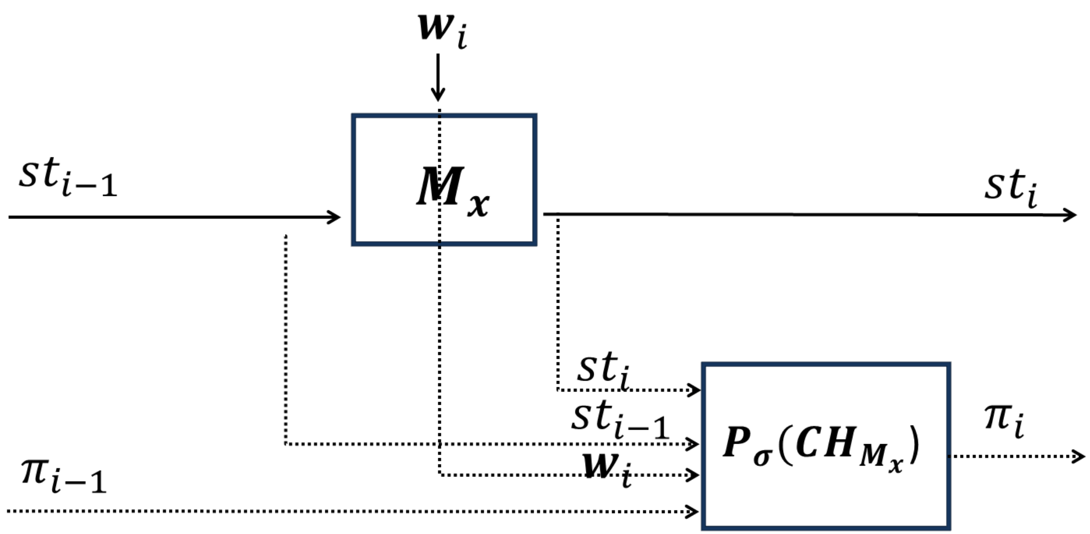




Recursive Consistency Checker $\boldsymbol{CH_{M_x}}$

Input: st_i witness: $(st_{i-1}, \pi_{i-1}, \boldsymbol{w_i})$



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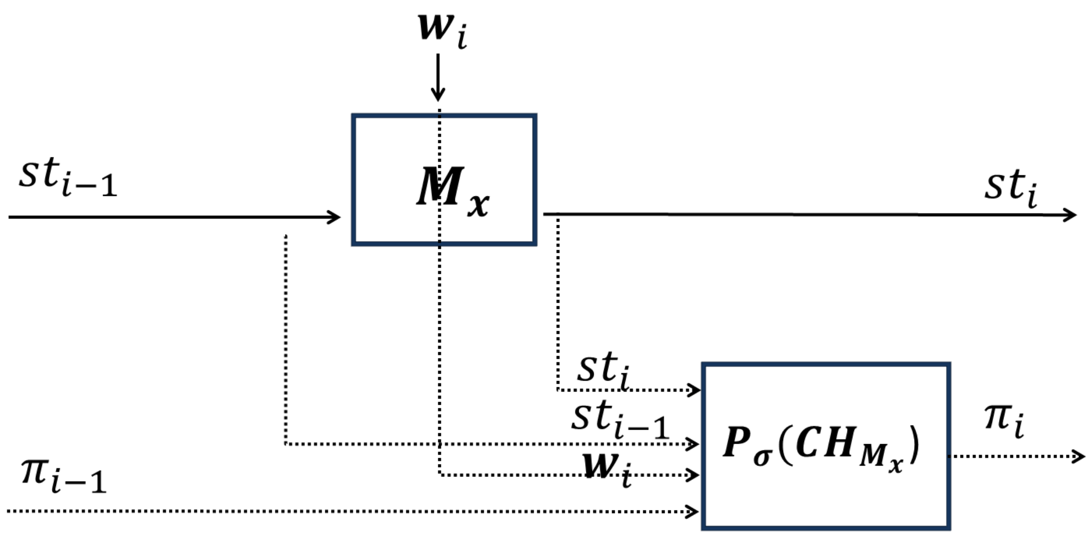
If $i = 0$ and $st_0 = initial\ state,$ accept.

else check:

$\boldsymbol{M_x}(st_{i-1}; \boldsymbol{w_i}) = st_i$

$V_\tau(\boldsymbol{CH_{M_x}}, st_{i-1}, \pi_{i-1})$=acc



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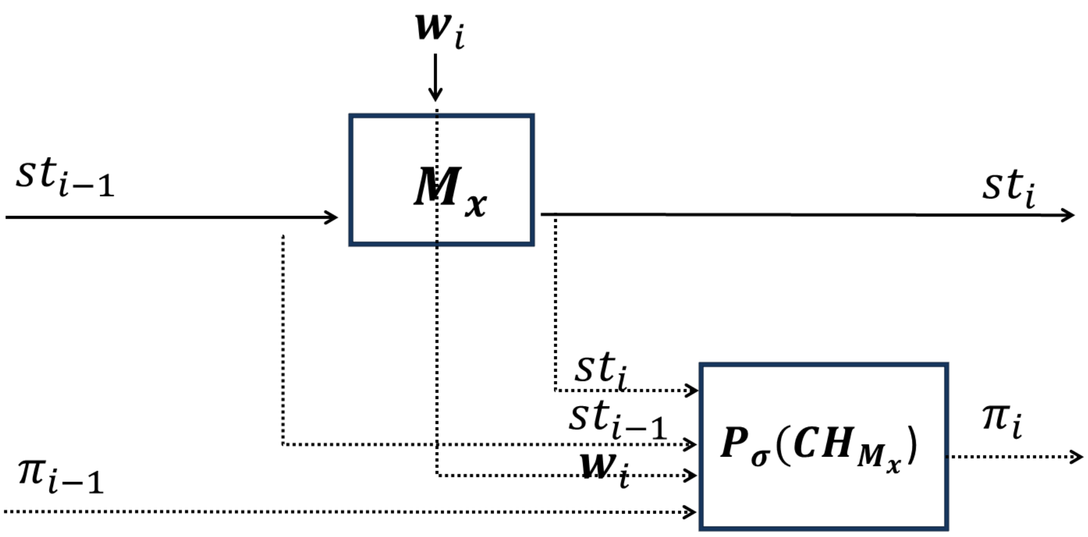
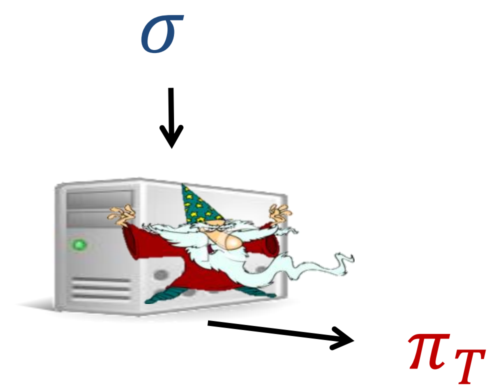
need recursion

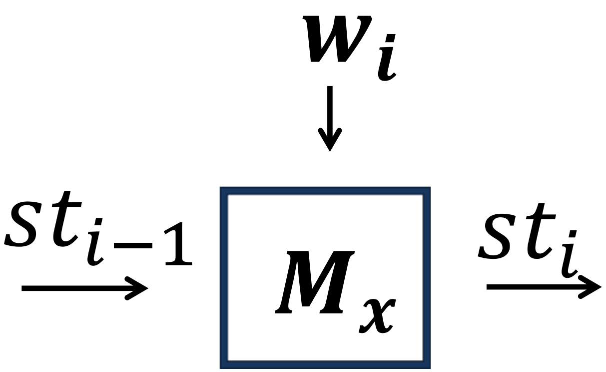


Is the resulting proof sound?

$$V_\tau(\boldsymbol{CH}_{\boldsymbol{M_x}}; st_T; \pi_T) = 1$$

$$st_T = \text{“accept”}$$





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V_τ accepts π_{i-1} for statement “ $\boldsymbol{CH}_{\boldsymbol{M_x}}$ accepts st_{i-1}

$$\exists(\pi_{T-1}, st_{T-1}, \boldsymbol{w_T}):$$
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$$V_\tau(\boldsymbol{CH_{M_x}}; st_{T-1}; \pi_{T-1}) = 1$$

$\longleftarrow$

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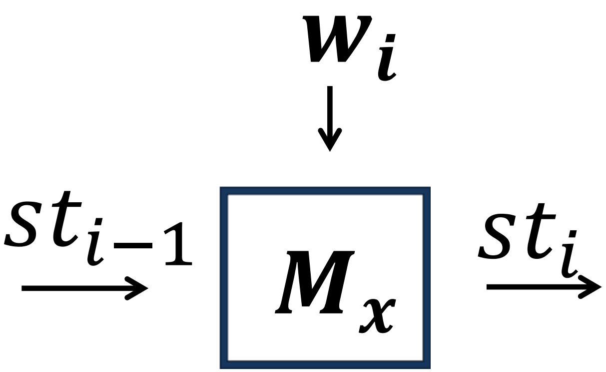

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$\downarrow$

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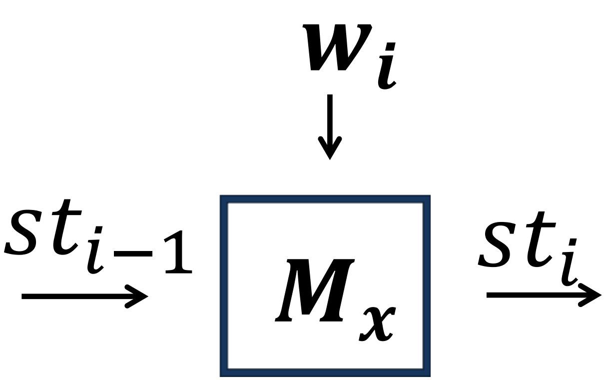

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↓

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- - - →

$$\exists(\pi_0, st_0, \boldsymbol{w_1}):$$
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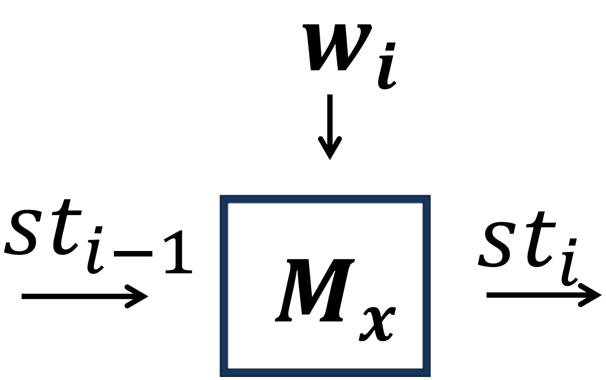

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➔ **Computational** soundness isn't enough

➔ Need knowledge extraction

➔ Need to apply the extraction recursively.

The extraction guarantee of SNARKs

$\forall$ prover P^*

ref string → σ

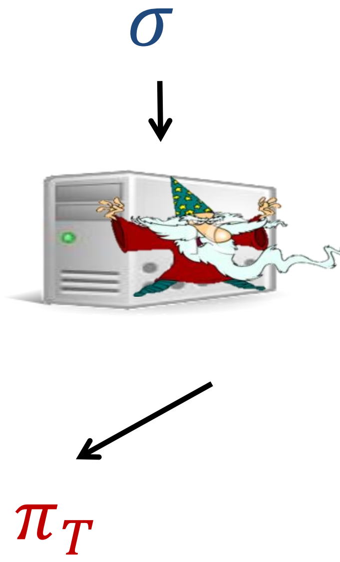
st_i, π_i that V_τ accepts

$\exists$ extractor E_{P^*}

σ

$wit = st_{i-1}, \pi_{i-1}, \boldsymbol{w_i}$

s.t. $\boldsymbol{CH_{M_x}(st_i, wit) = 1}$


σ
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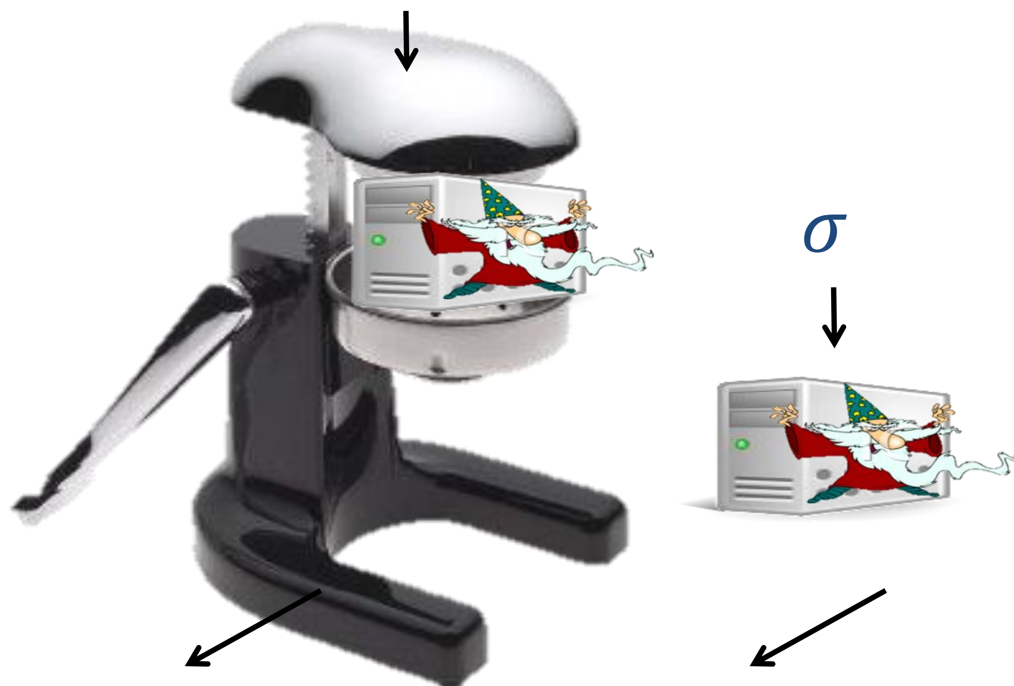
σ σ



$(\pi_{T-1}, st_{T-1}, \boldsymbol{w}_{\boldsymbol{T}})$ π_T

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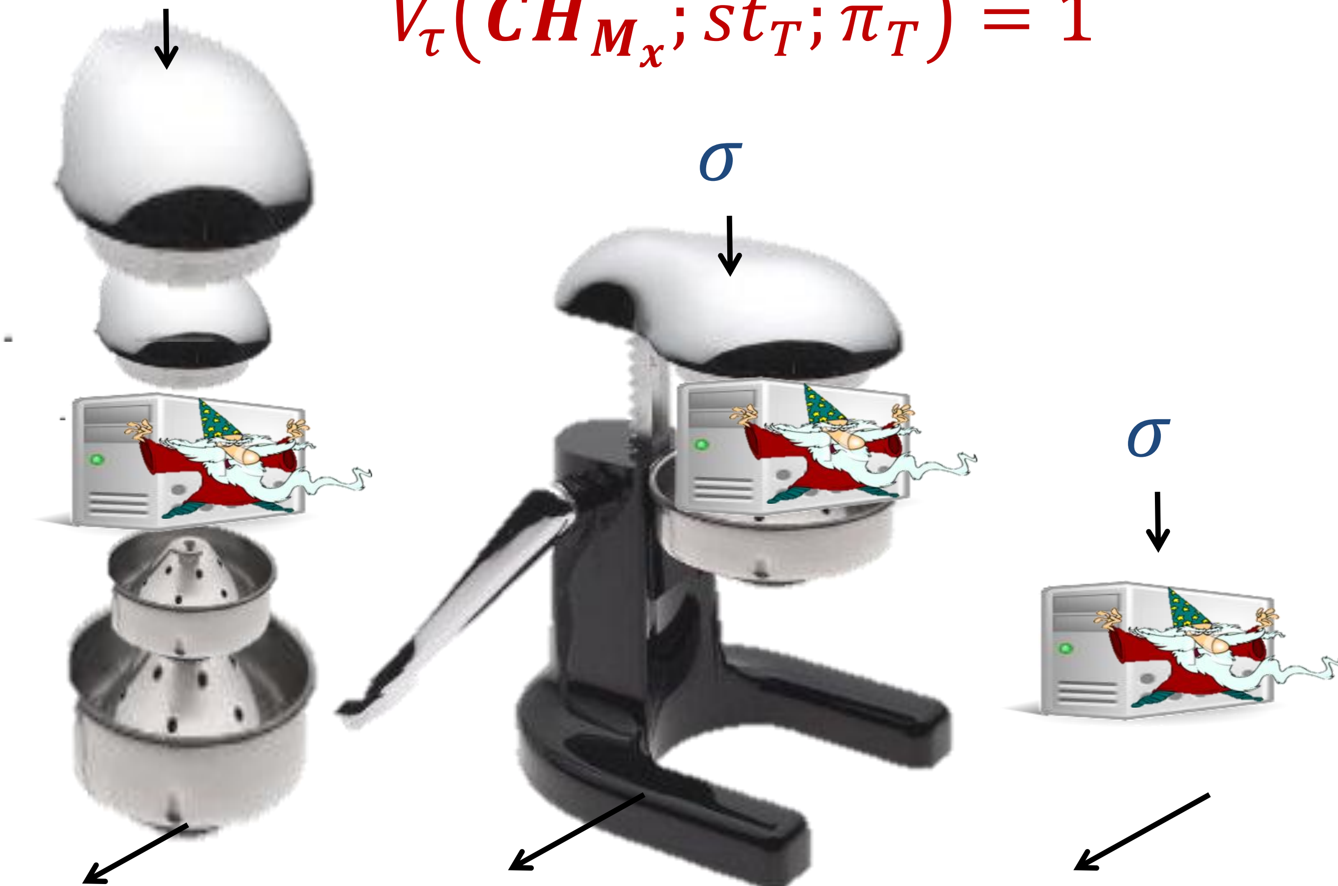

σ σ σ

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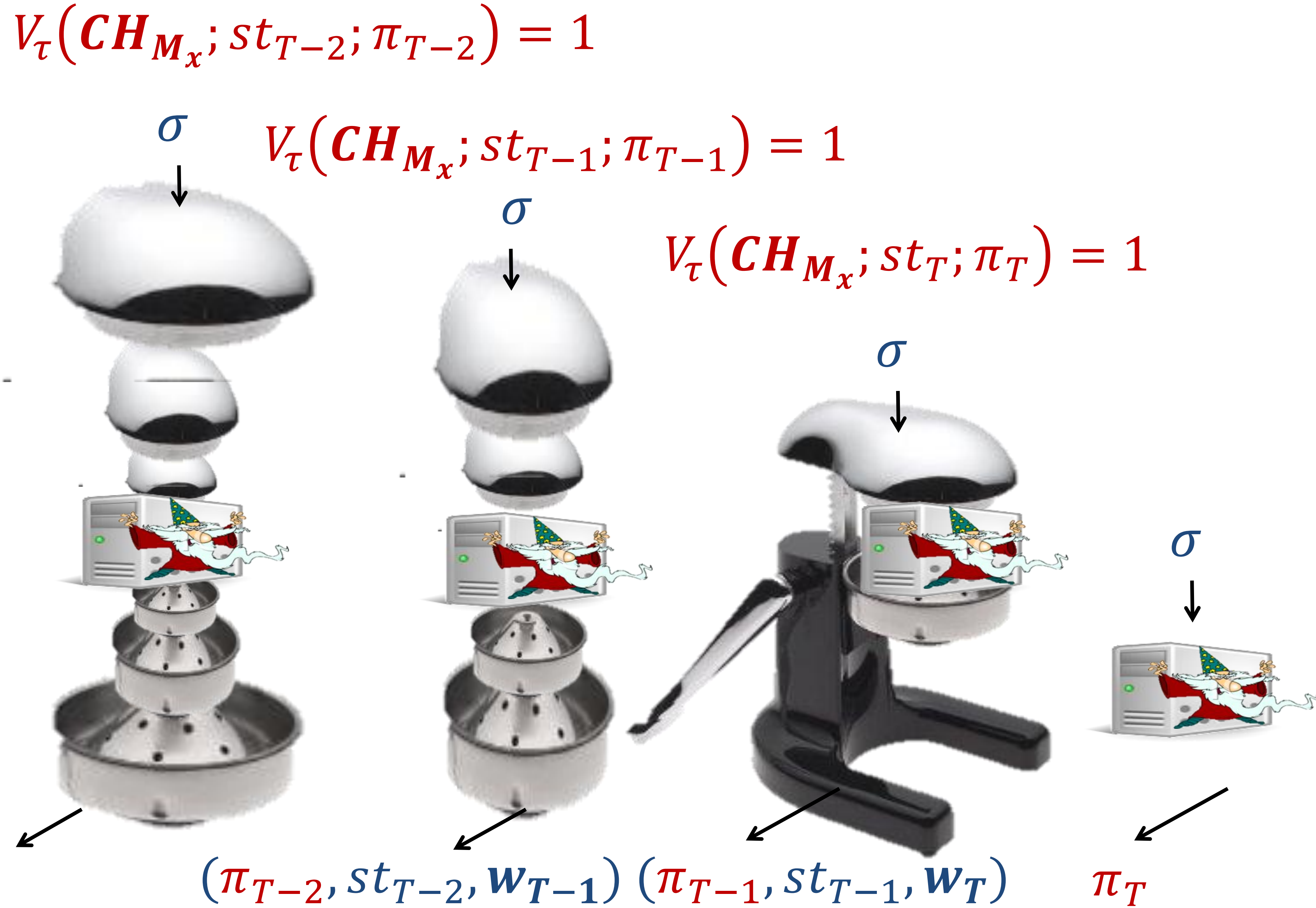

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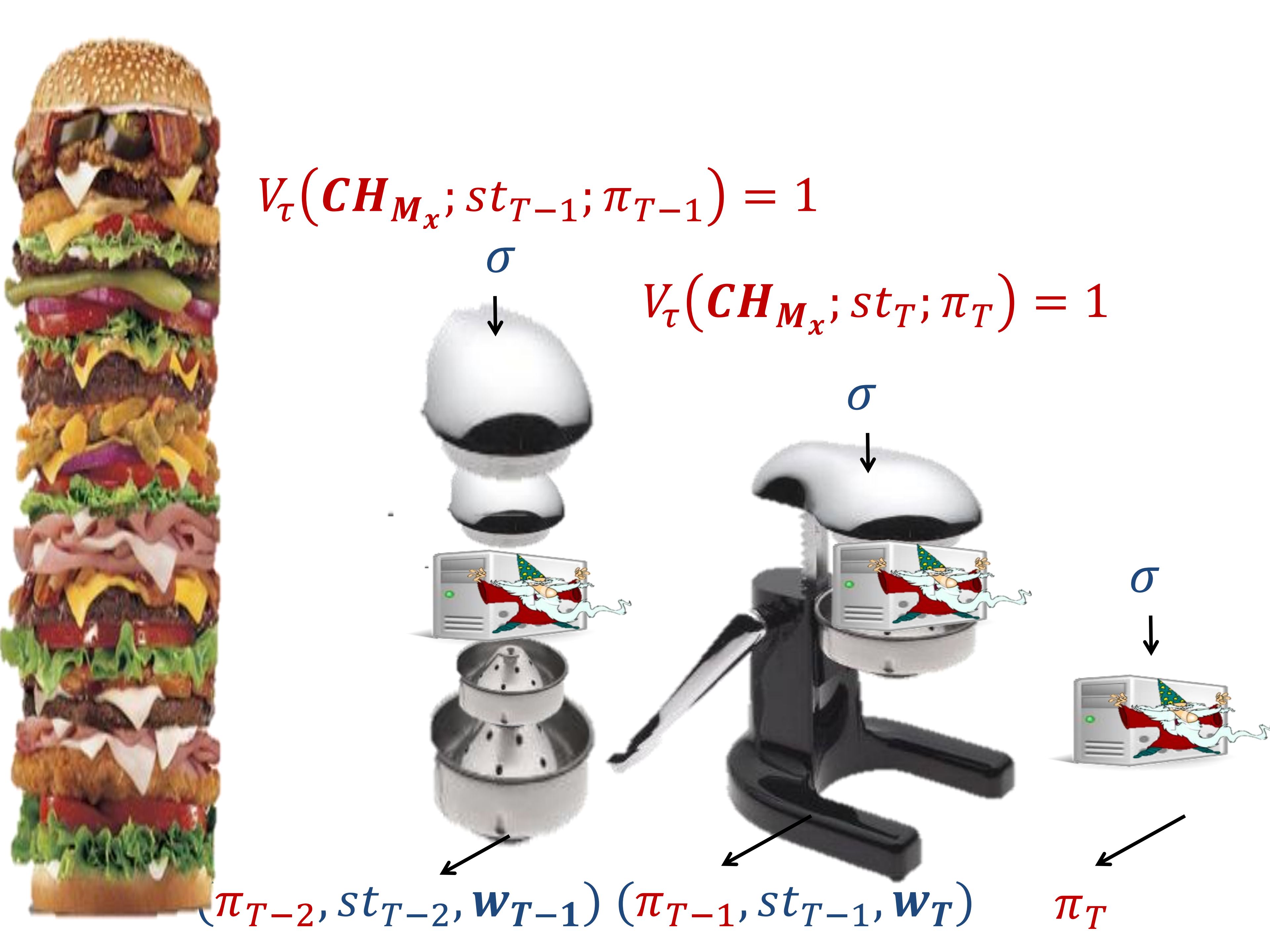
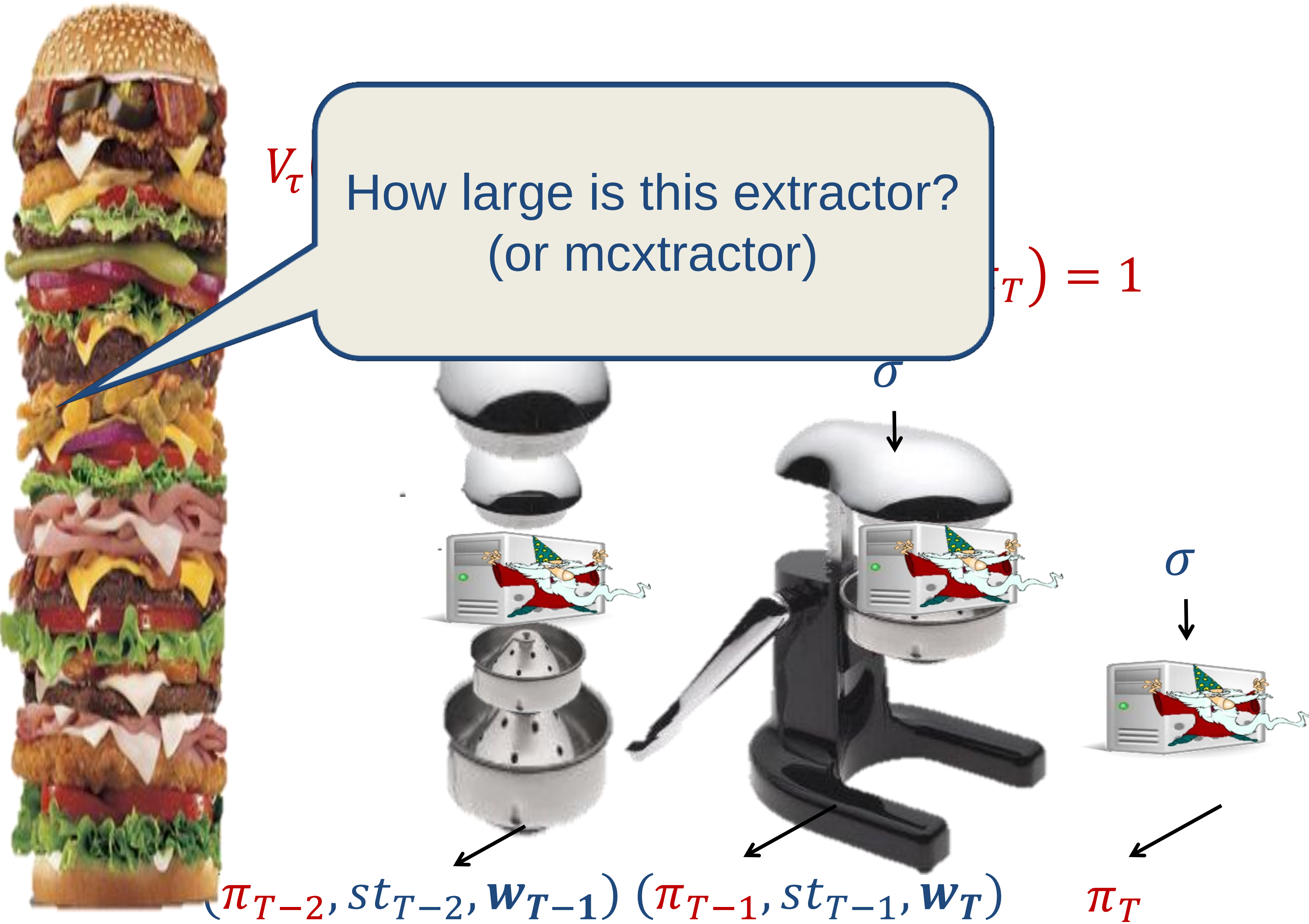
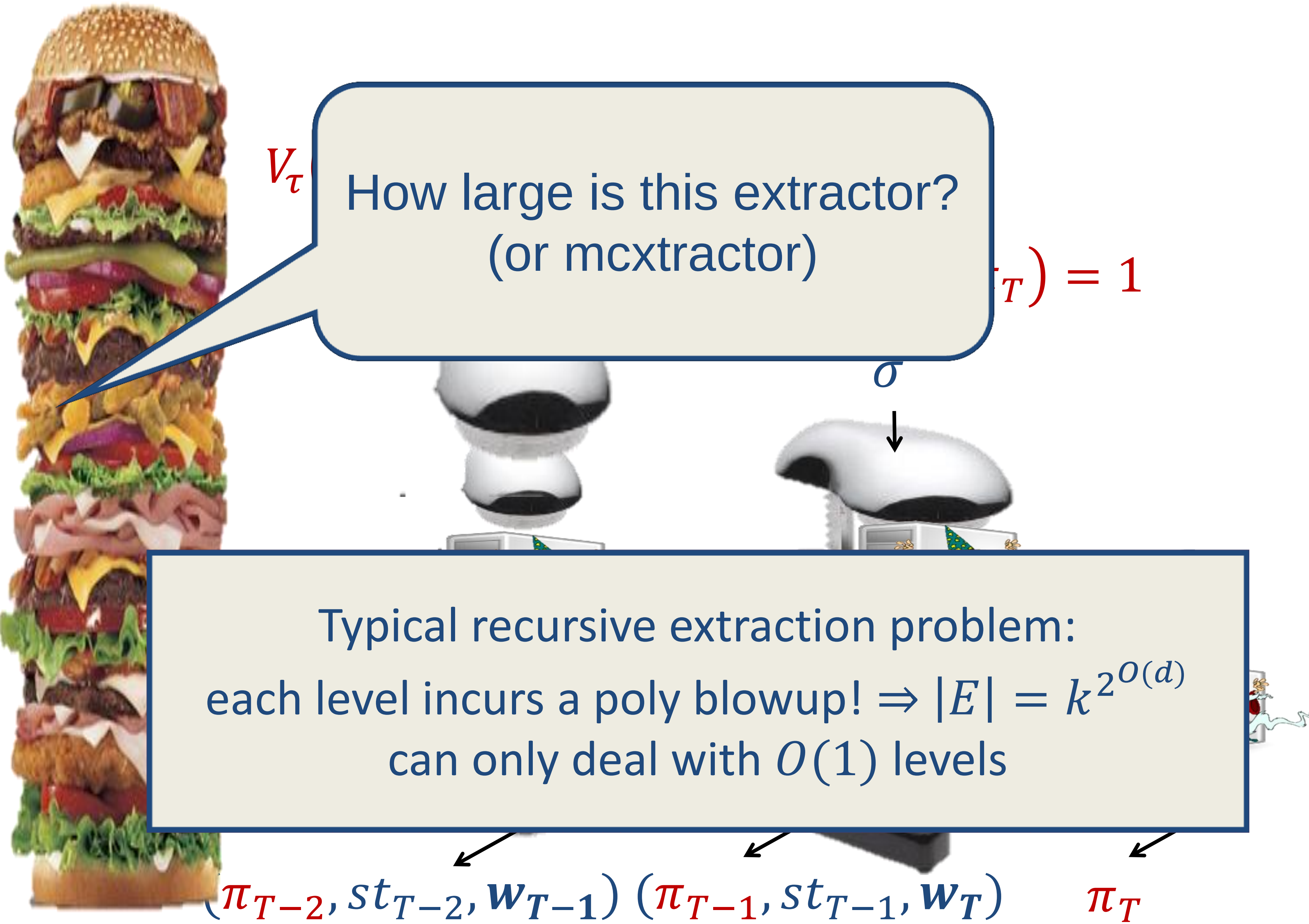
π_T


$V_\tau(\boldsymbol{CH}_{\boldsymbol{M_x}}; st_{T-1}; \pi_{T-1}) = 1$
σ
$V_\tau(\boldsymbol{CH}_{\boldsymbol{M_x}}; st_T; \pi_T) = 1$
σ
σ
$(\pi_{T-2}, st_{T-2}, \boldsymbol{w}_{\boldsymbol{T-1}})$
$(\pi_{T-1}, st_{T-1}, \boldsymbol{w}_{\boldsymbol{T}})$
π_T


How large is this extractor?
(or mcxtractor)
V_τ
$) = 1$
σ
σ
$(\pi_{T-2}, st_{T-2}, \boldsymbol{w_{T-1}})$ $(\pi_{T-1}, st_{T-1}, \boldsymbol{w_T})$ π_T

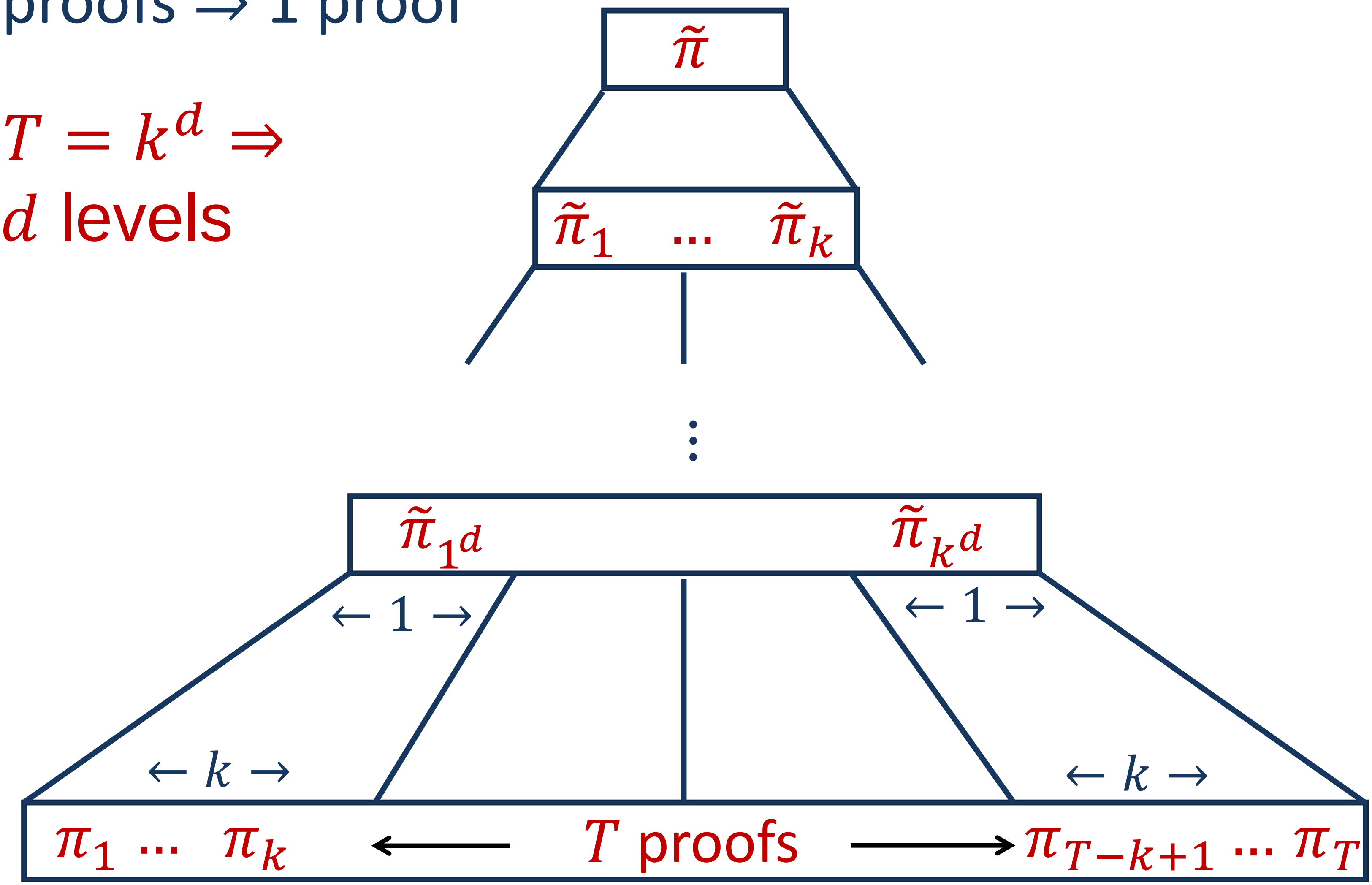


How large is this extractor?
(or mcxtractor)
$= 1$
σ
Typical recursive extraction problem:
each level incurs a poly blowup! $\Rightarrow |E| = k^{2^{O(d)}}$
can only deal with $O(1)$ levels
$(\pi_{T-2}, st_{T-2}, \mathbf{w}_{T-1})$ $(\pi_{T-1}, st_{T-1}, \mathbf{w}_T)$ π_T

A solution: aggregate proofs in a wide tree

k proofs $\Rightarrow$ 1 proof

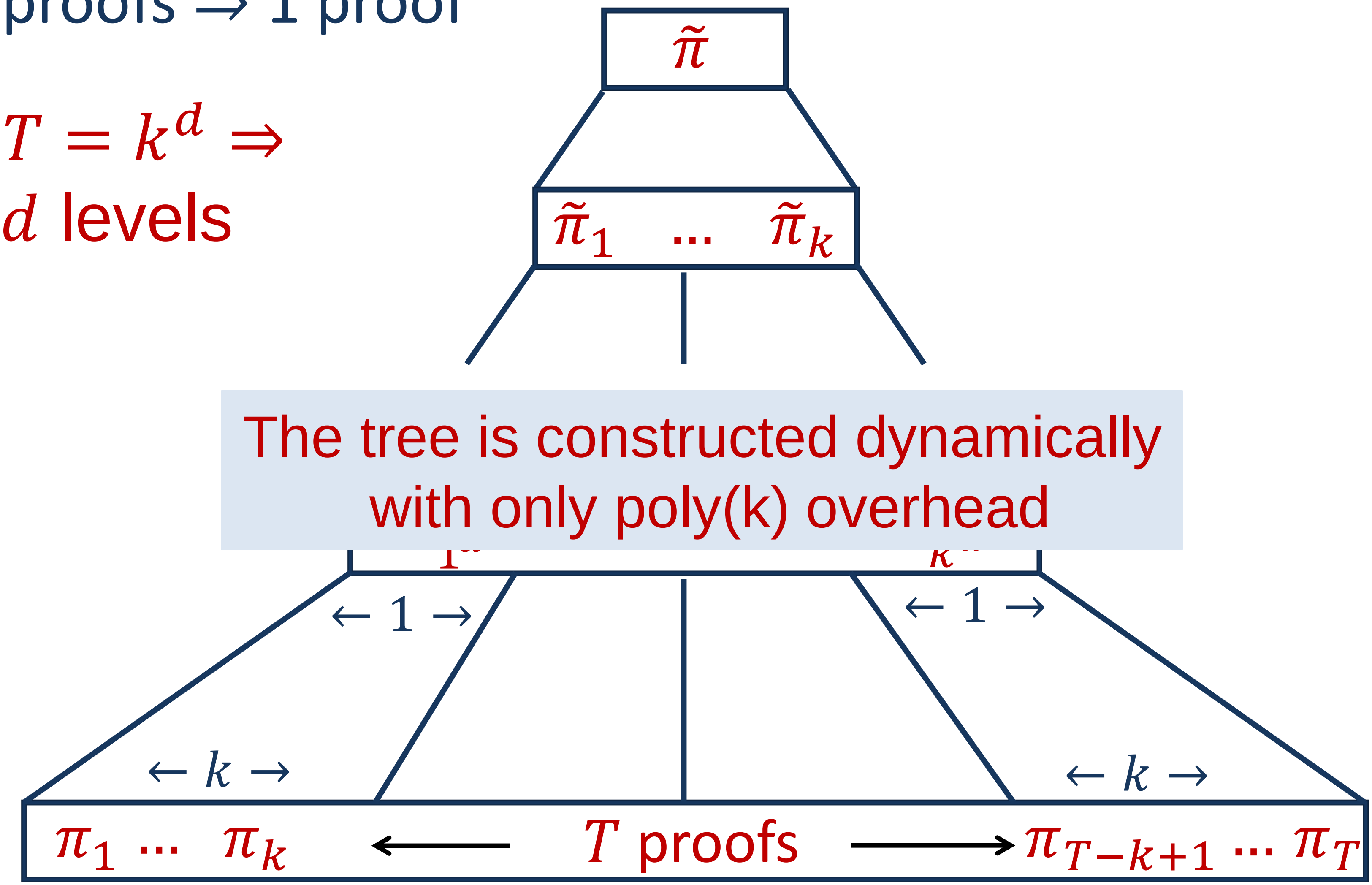
If $T = k^d \Rightarrow$
d levels

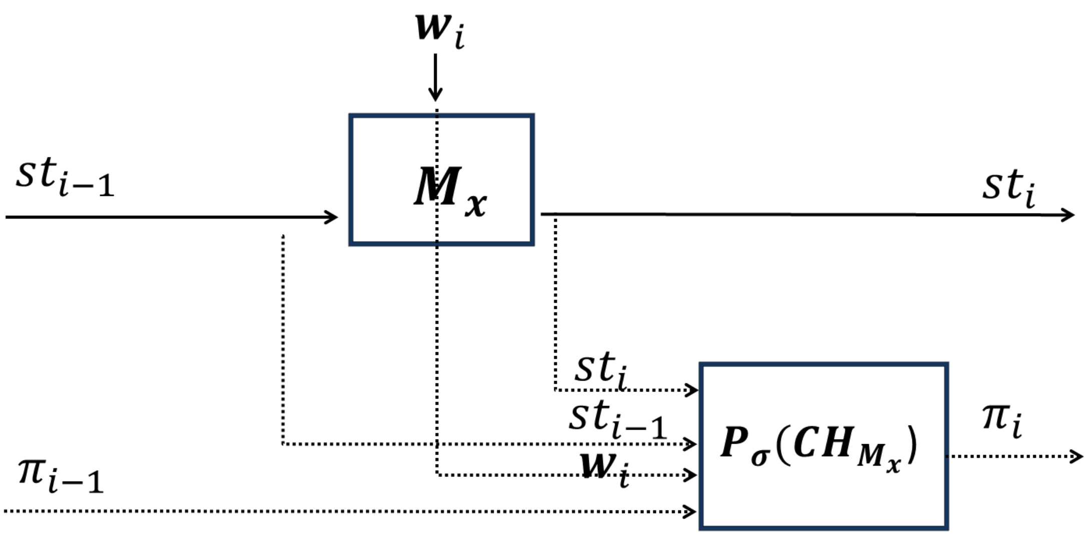


A solution: aggregate proofs in a wide tree

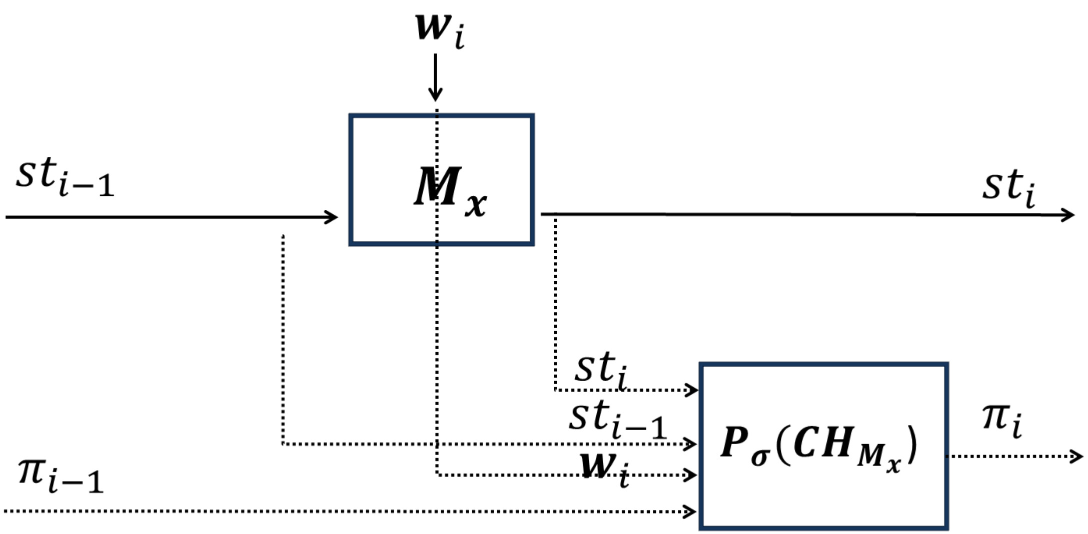
k proofs ⇒ 1 proof

If $T = k^d$ ⇒ d levels

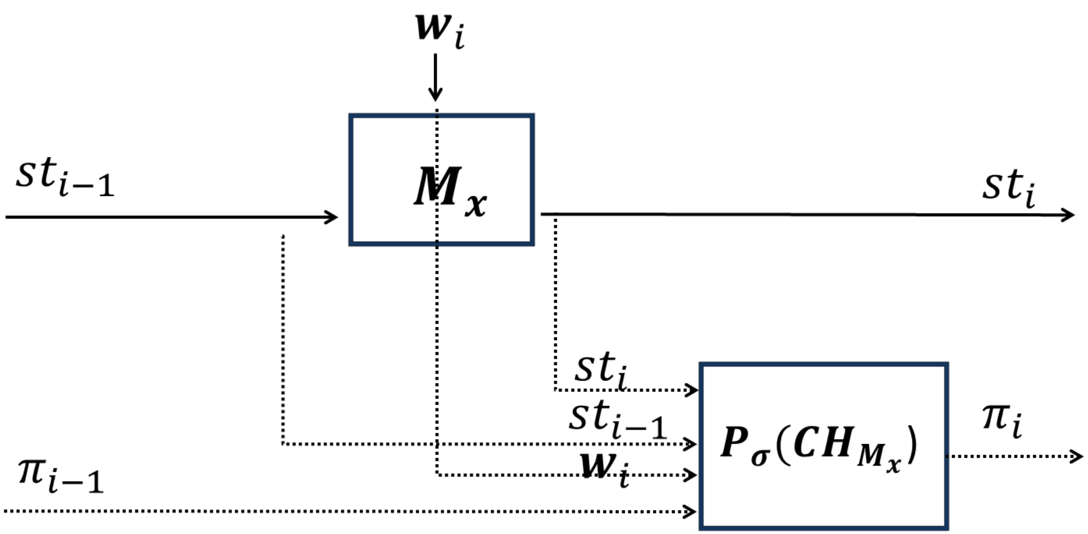




Is the resulting proof sound?

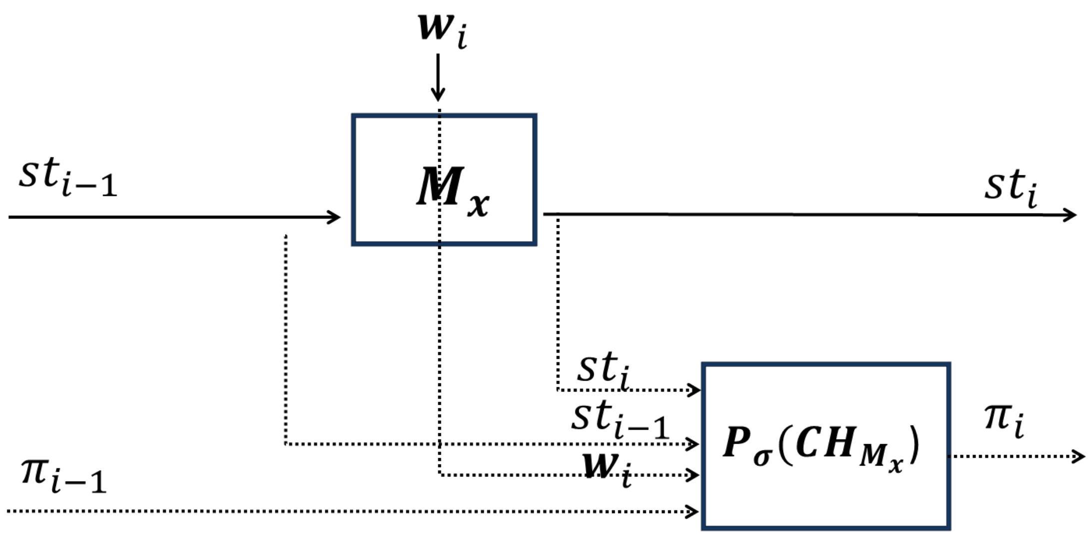


So Far: Preprocessing cost is proportional to single-step computation.



So Far: Preprocessing cost is proportional to single-step computation.

But how large is a single-step computation?



So Far: Preprocessing cost is proportional to single-step computation.

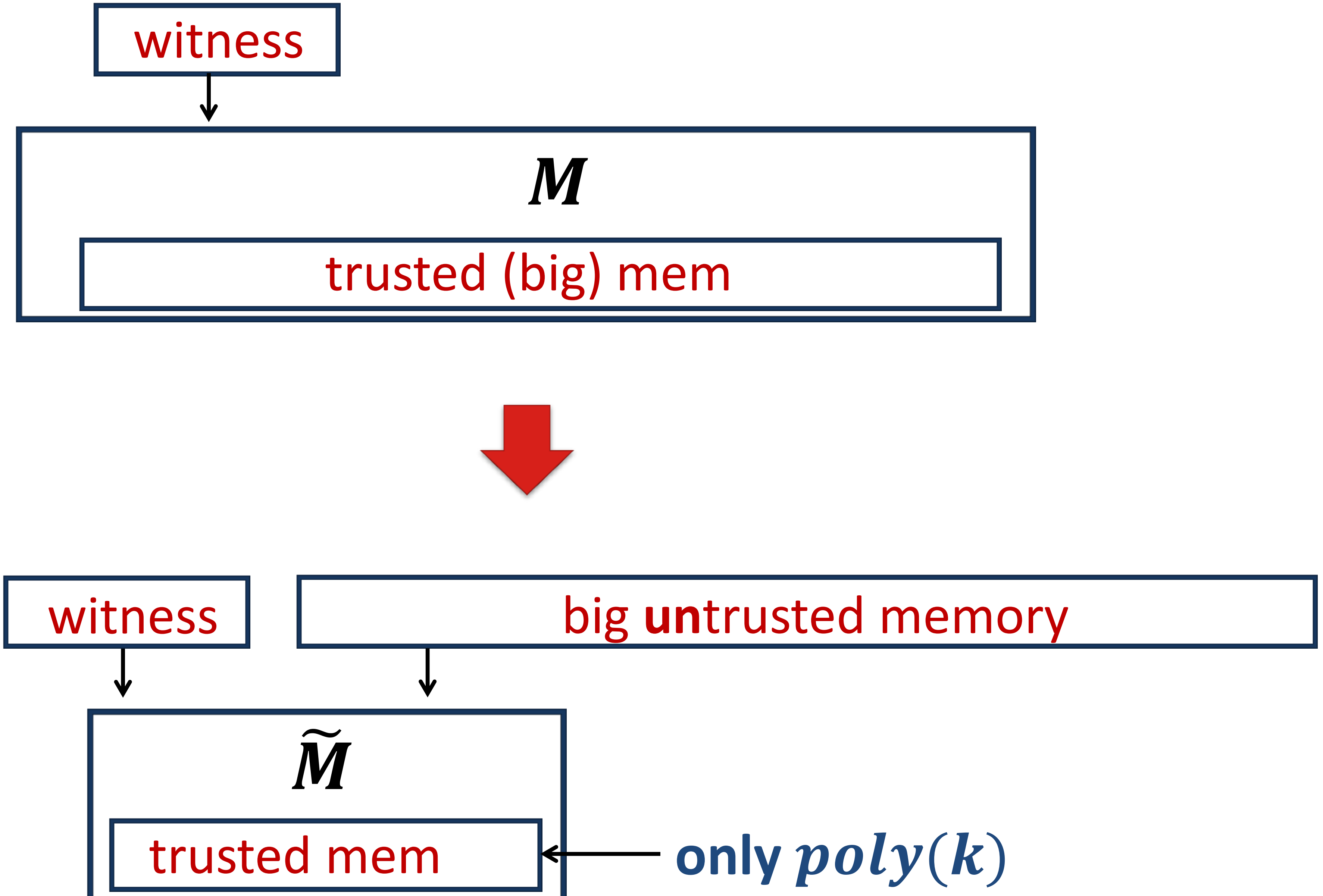
But how large is a single-step computation?

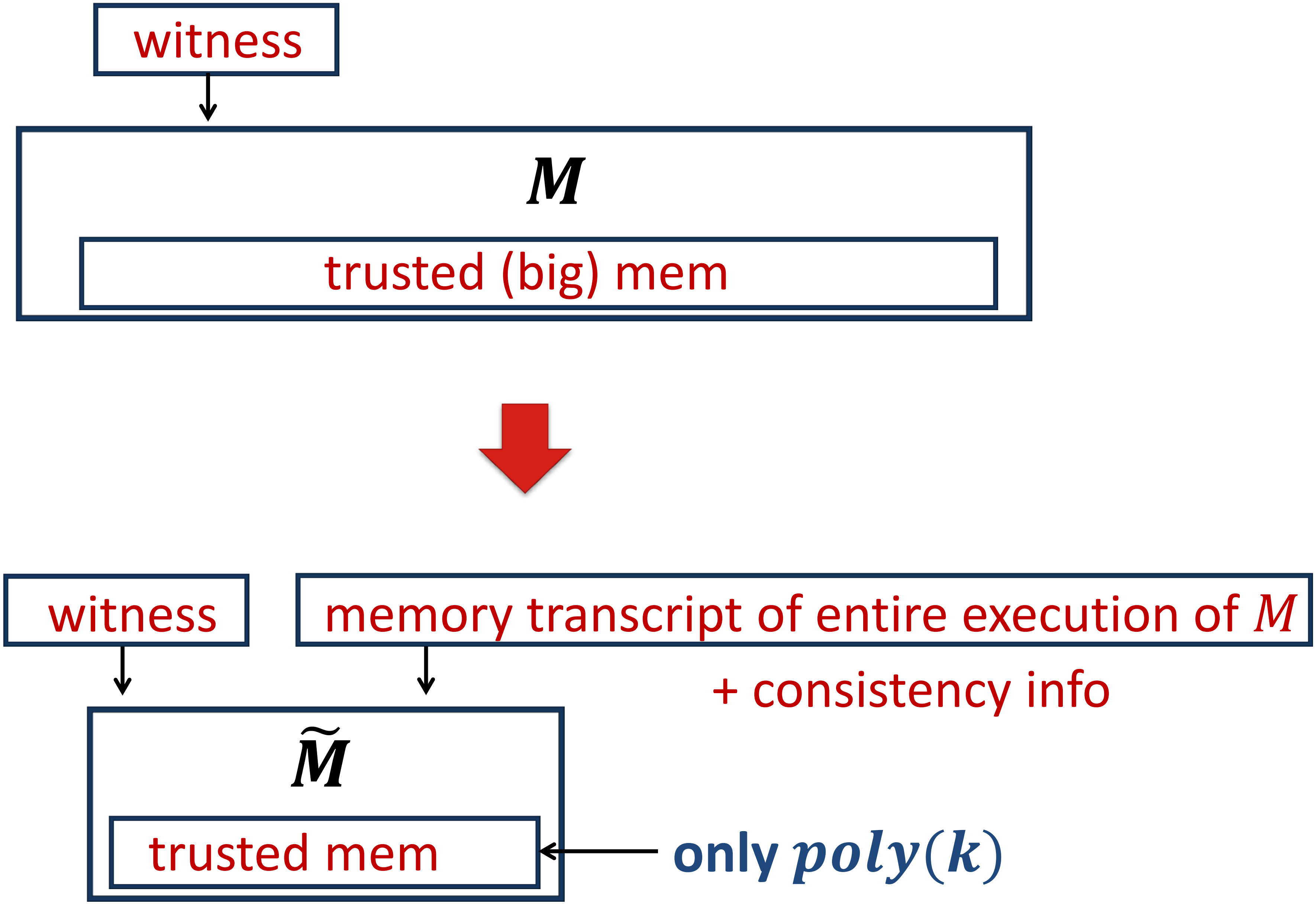
➔Bounded only by S, which can be as large as T…

➔Preprocessing stage can still be poly(T)…

Idea:
Move from machines with large memory to machines with:

- “small” trusted memory
- “big” untrusted memory


witness
M
trusted (big) mem
witness
big **un**trusted memory
$\widetilde{M}$
trusted mem
only $poly(k)$


witness
M
trusted (big) mem
witness
memory transcript of entire execution of M
+ consistency info
M̃
trusted mem
only poly(k)

A computational reduction using CRH

[Blum Evans Gemmell Kannan Naor 94, Ben-Sasson Chiesa Genkin Tromer 12]

$\boldsymbol{M} \xrightarrow{\;h\;} \widetilde{\boldsymbol{M}}_h$

$\boldsymbol{M}(\boldsymbol{x}, \boldsymbol{w})$ accepts **Or** h-collisions can be (eff.) extracted from mem $\Longleftarrow$ $\widetilde{\boldsymbol{M}}_h(\boldsymbol{x}, \boldsymbol{w}, mem)$ accepts

A computational reduction using CRH

[Blum Evans Gemmell Kannan Naor 94, Ben-Sasson Chiesa Genkin Tromer 12]

h

$\boldsymbol{M}$ → $\widetilde{\boldsymbol{M}}_h$

$\boldsymbol{M}(\boldsymbol{x}, \boldsymbol{w})$ accepts ← $\widetilde{\boldsymbol{M}}_h(\boldsymbol{x}, \boldsymbol{w}, mem)$ accepts

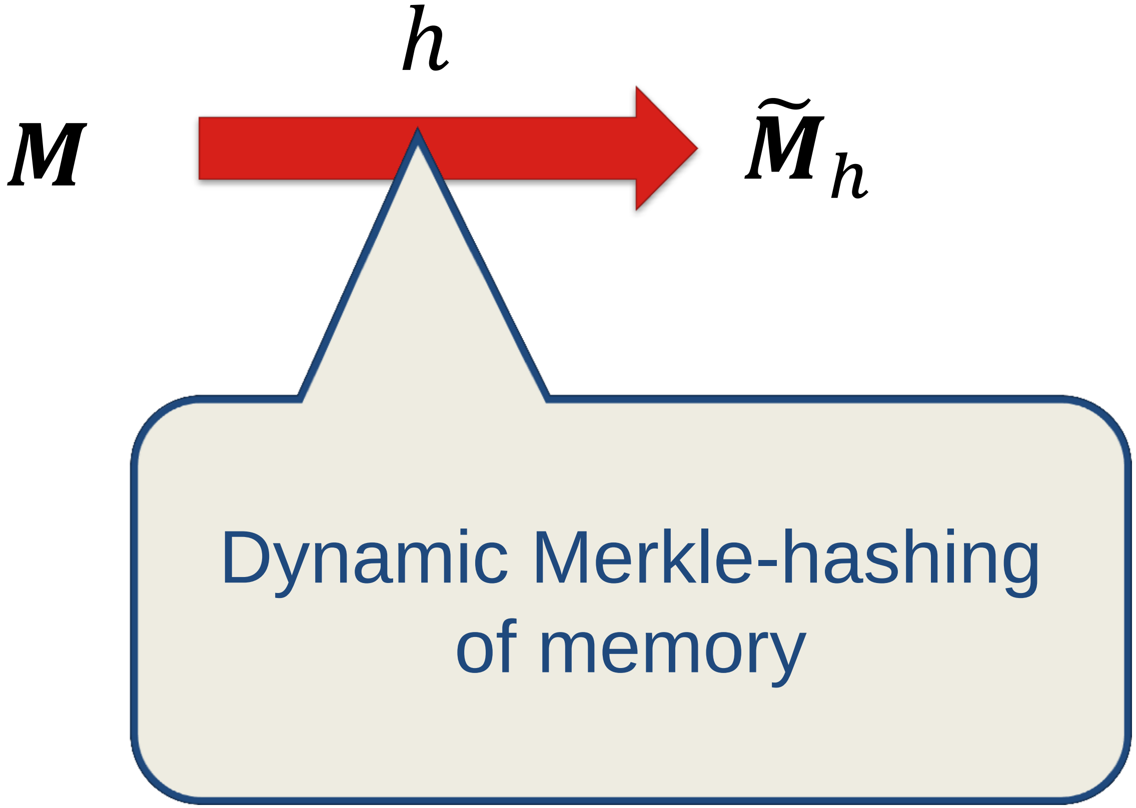
Or

h-collisions can be (eff.) extracted from mem

→ **$\exists mem$ not enough need knowledge**

A computational reduction using CRH

[Blum Evans Gemmell Kannan Naor 94, Ben-Sasson Chiesa Genkin Tromer 12]



$\widetilde{M}_h$ runs in time $T_M \cdot \text{poly}(k)$, space $\text{poly}(k)$ and *mem* computed from $(\boldsymbol{x}, \boldsymbol{w})$ in time $T_M \cdot \text{poly}(k)$ & space $S_M \cdot \text{poly}(k)$

➔ A single-step computation is now of size $\boldsymbol{poly_h(k)}$

(subsequent steps can be computed dynamically preserving time and space of original computation)

what's left?
…SNARK verification

Input: st_i witness: $(\pi_{i-1}, st_{i-1}, \boldsymbol{w_i})$

If st_i is initial state of $\widetilde{\boldsymbol{M}}_{\boldsymbol{x}}$ accept.

else check:

$\widetilde{\boldsymbol{M}}_{\boldsymbol{x}}(st_{i-1}; \boldsymbol{w_i}) = st_i$

V_τ accepts π_{i-1} for statement $\boldsymbol{CH}_{\widetilde{\boldsymbol{M}}_{\boldsymbol{x}}}, st_{i-1}$

only $\mathrm{poly}_V(k)$,

independently of preprocessing limit

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only $\text{poly}_V(k)$,

independently of preprocessing limit

⇒ budget only for $\boldsymbol{poly_V(k)}$+$\boldsymbol{poly_h(k)}$

Bye Bye
Long Preprocessing…

Part I:

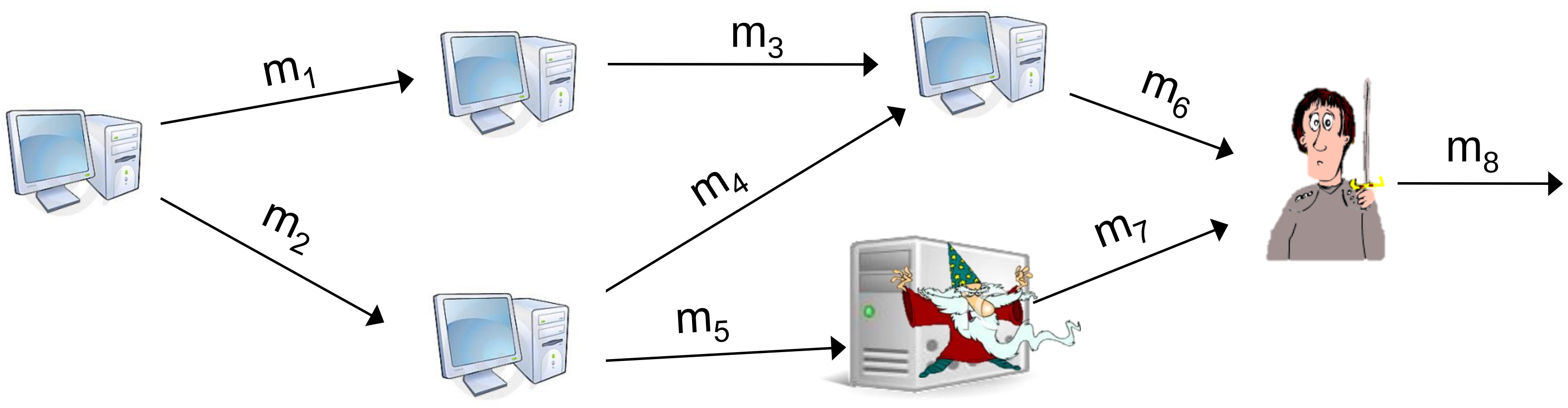
How to Bootstrap a SNARK
in Public

Part II:

Part I (again) and Beyond
with Proof Carrying Data

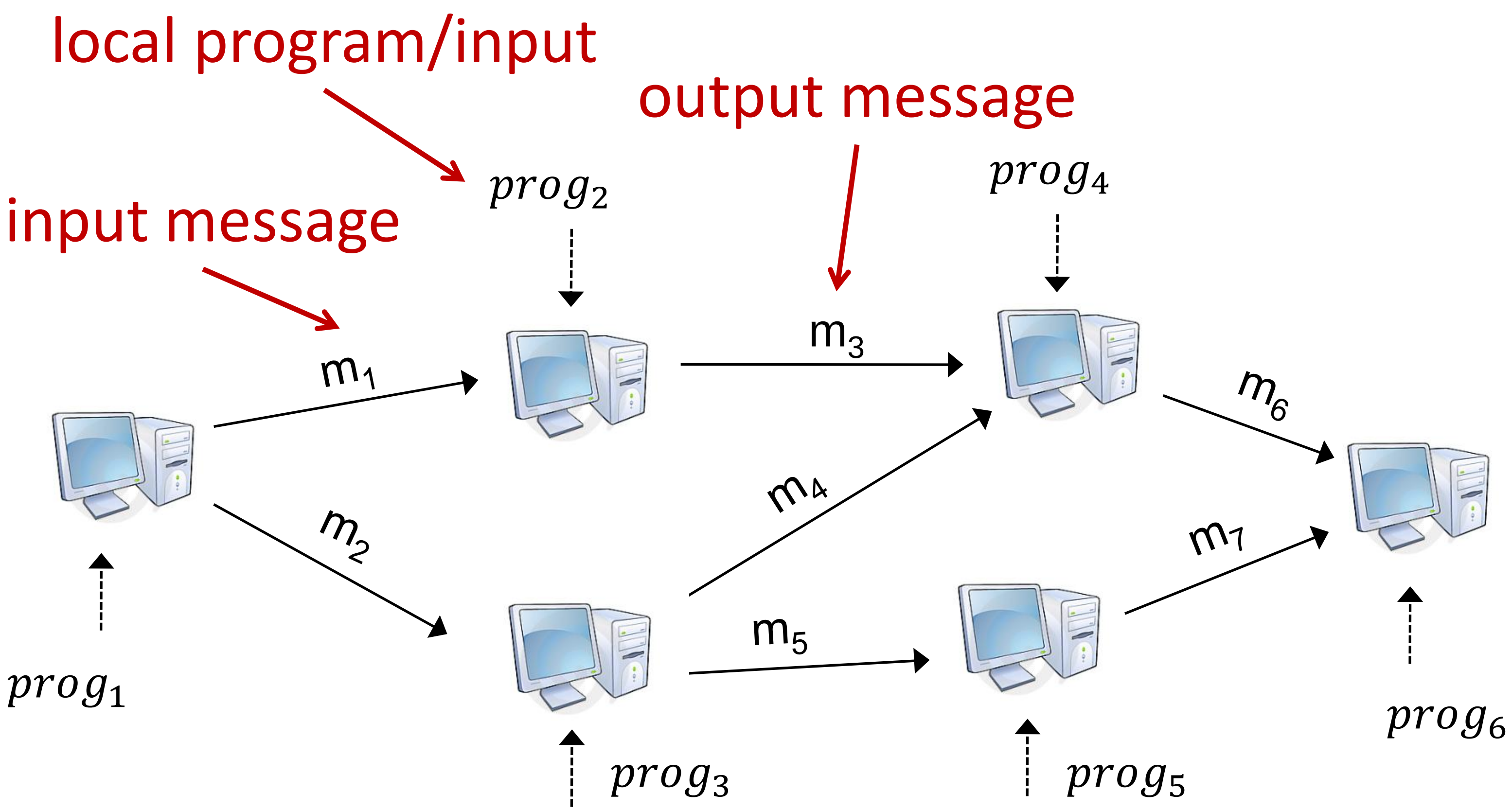
In SNARKs: one prover and one verifier

But sometimes in life…



Computations involve many parties
each party has its own:
role, capabilities, friends, enemies,…

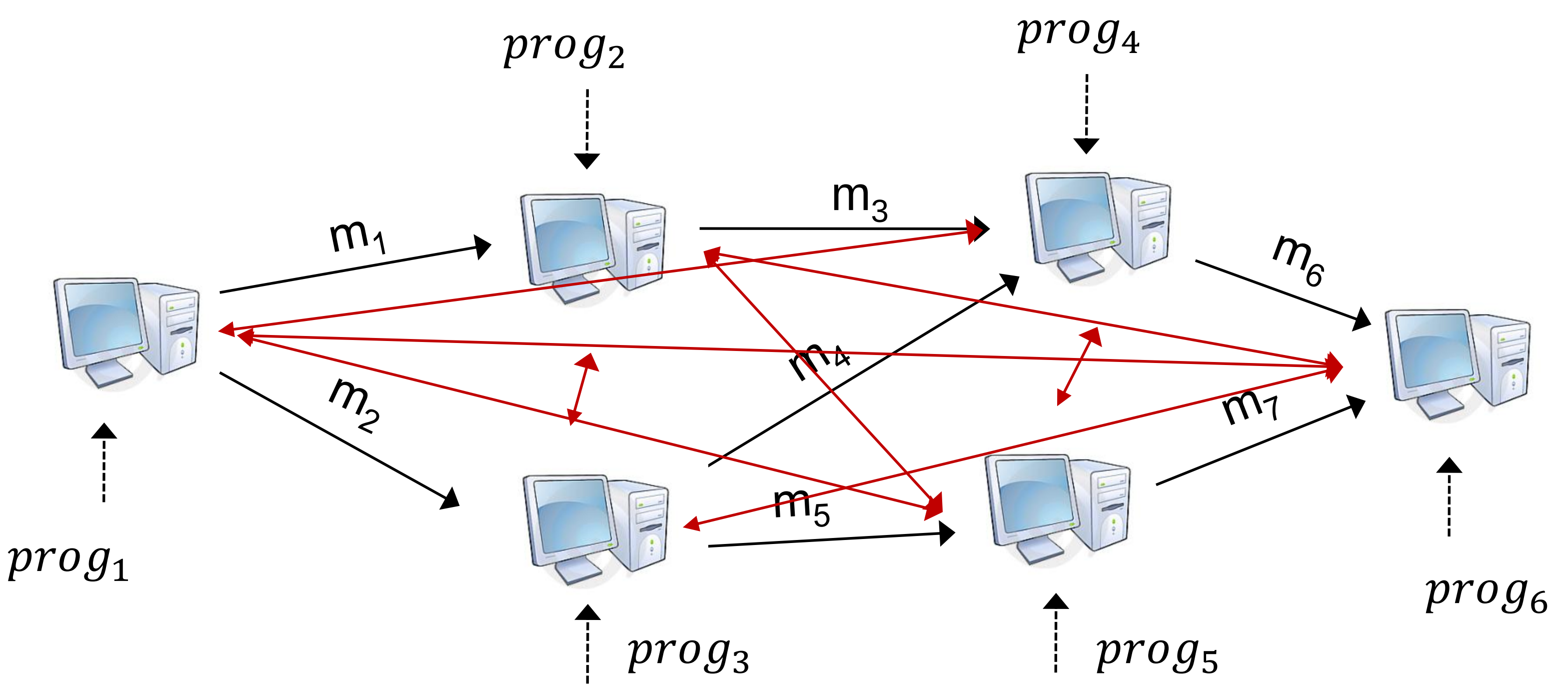
How can we enforce general correctness properties of distributed computations?



Use MPC?

enforce **any** property of **all** the inputs/outputs of all parties

but: large overhead: all parties must communicate with each other (necessary, e.g. Byzantine agreement)

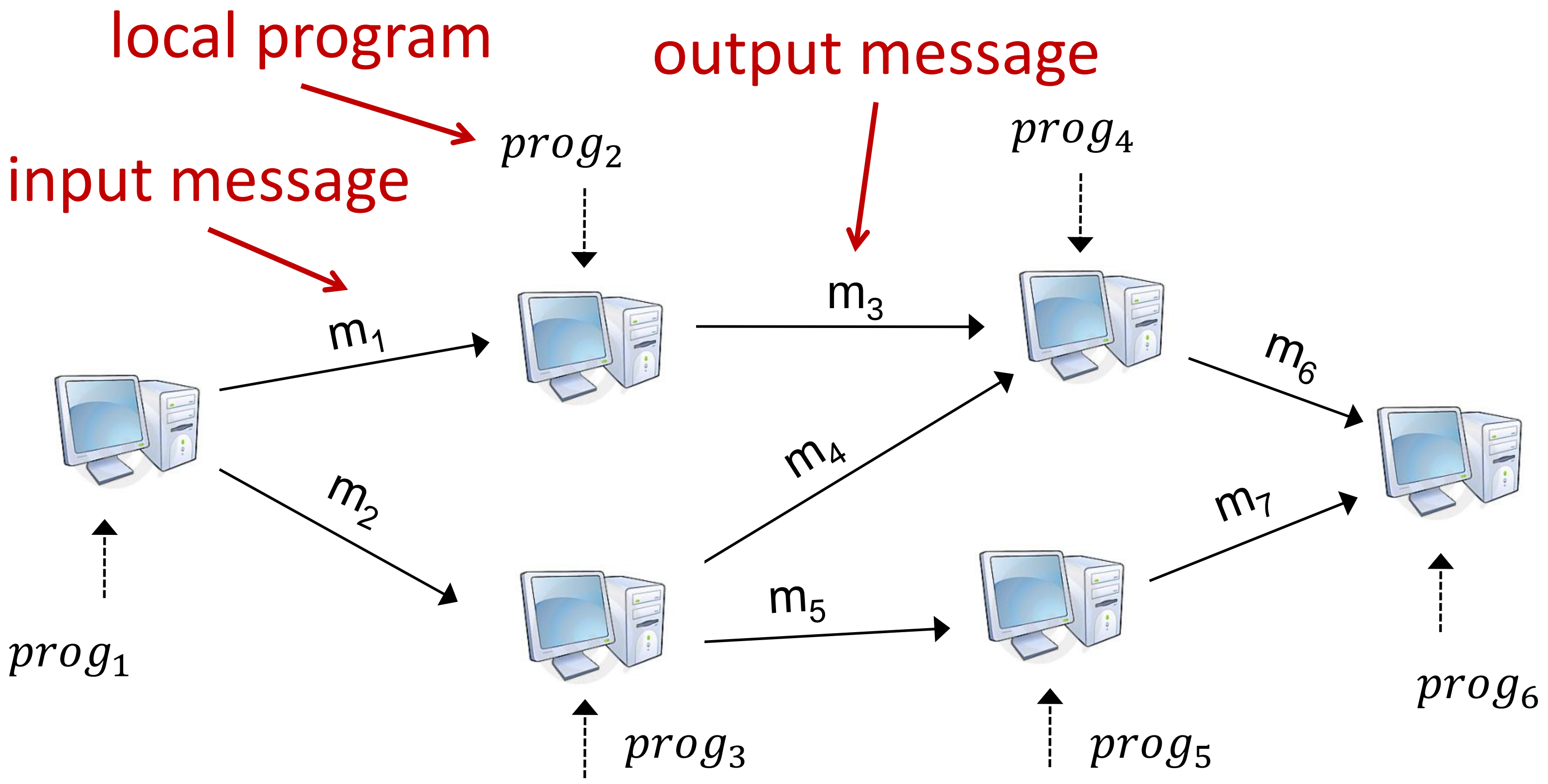


A relaxed question:
how to enforce **local** properties?

Local property = property of the view of a single node

Example: ensure that the program executed at every node was signed by system admin

if property holds **everywhere** → global meaning



Proof Carrying Data (PCD)
[Chiesa Tromer 10]

<u>Goal</u>:

Guarantee “local properties” **while respecting the original computation**:

- preserve communication graph
- minimal computational overhead

The original computation

- Can be viewed as a DAG evolving over time
- nodes have input and output messages
  + a local program (with embedded inputs).

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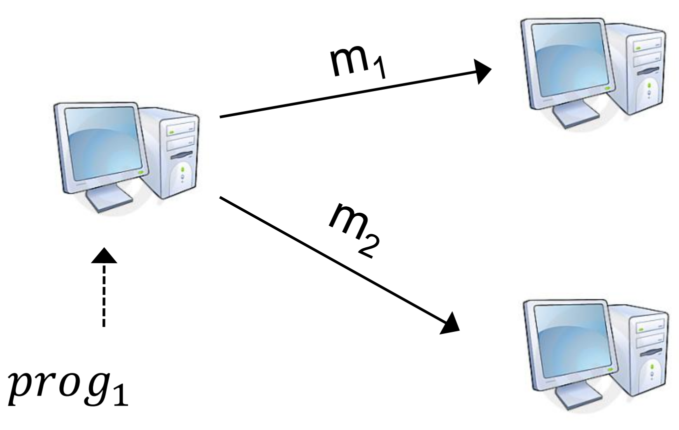

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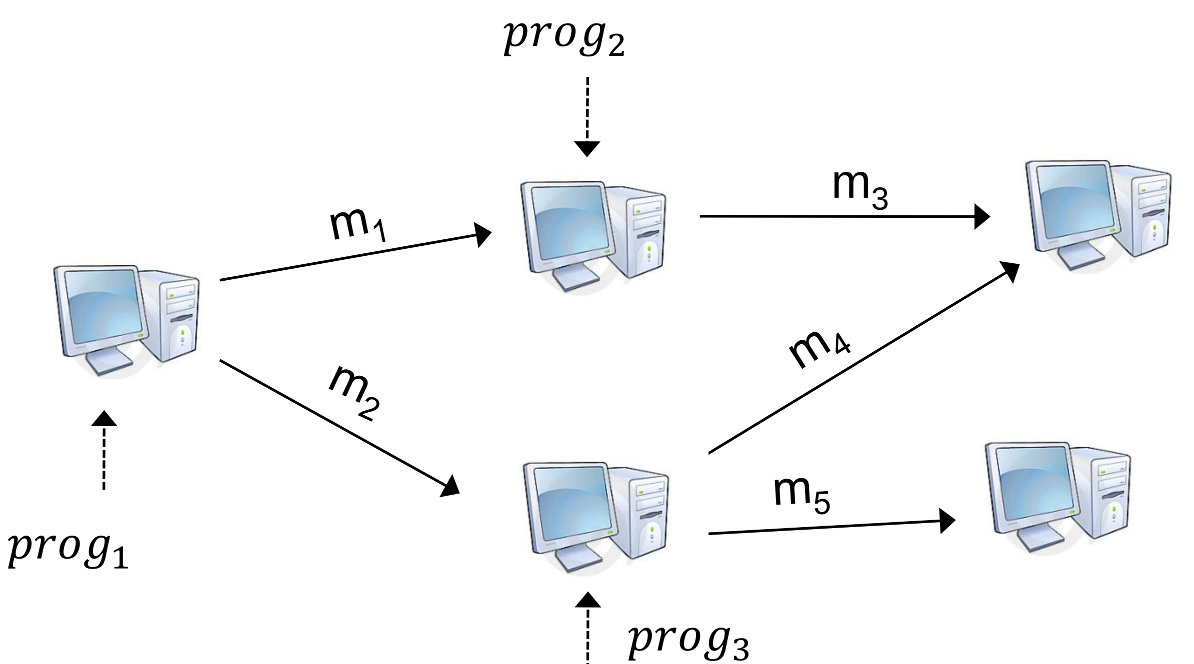

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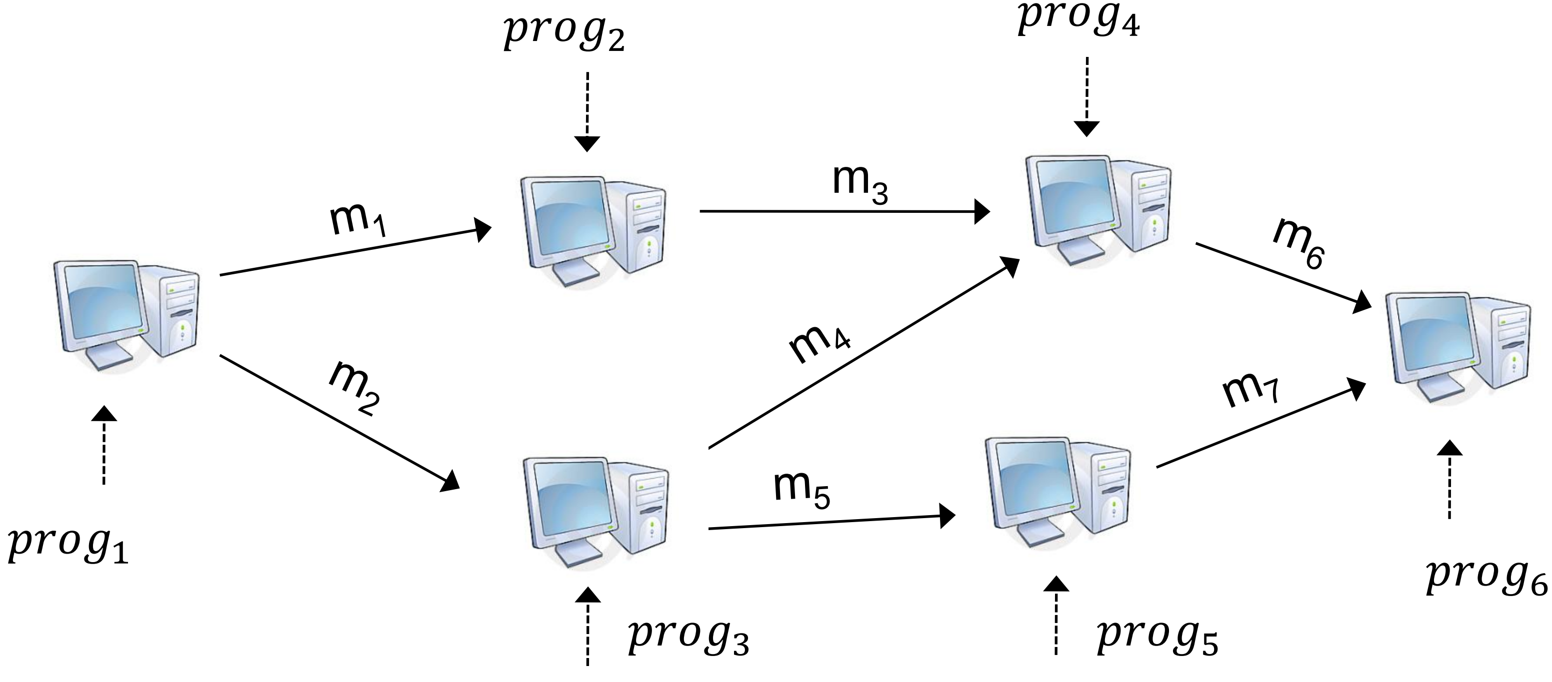
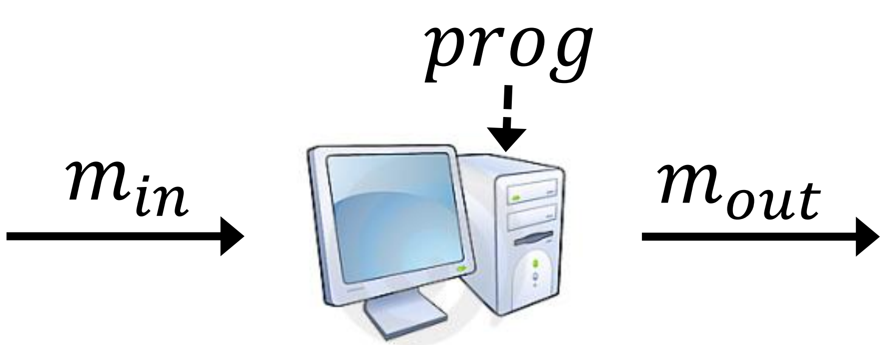


Local properties as $\boldsymbol{C}$-compliance

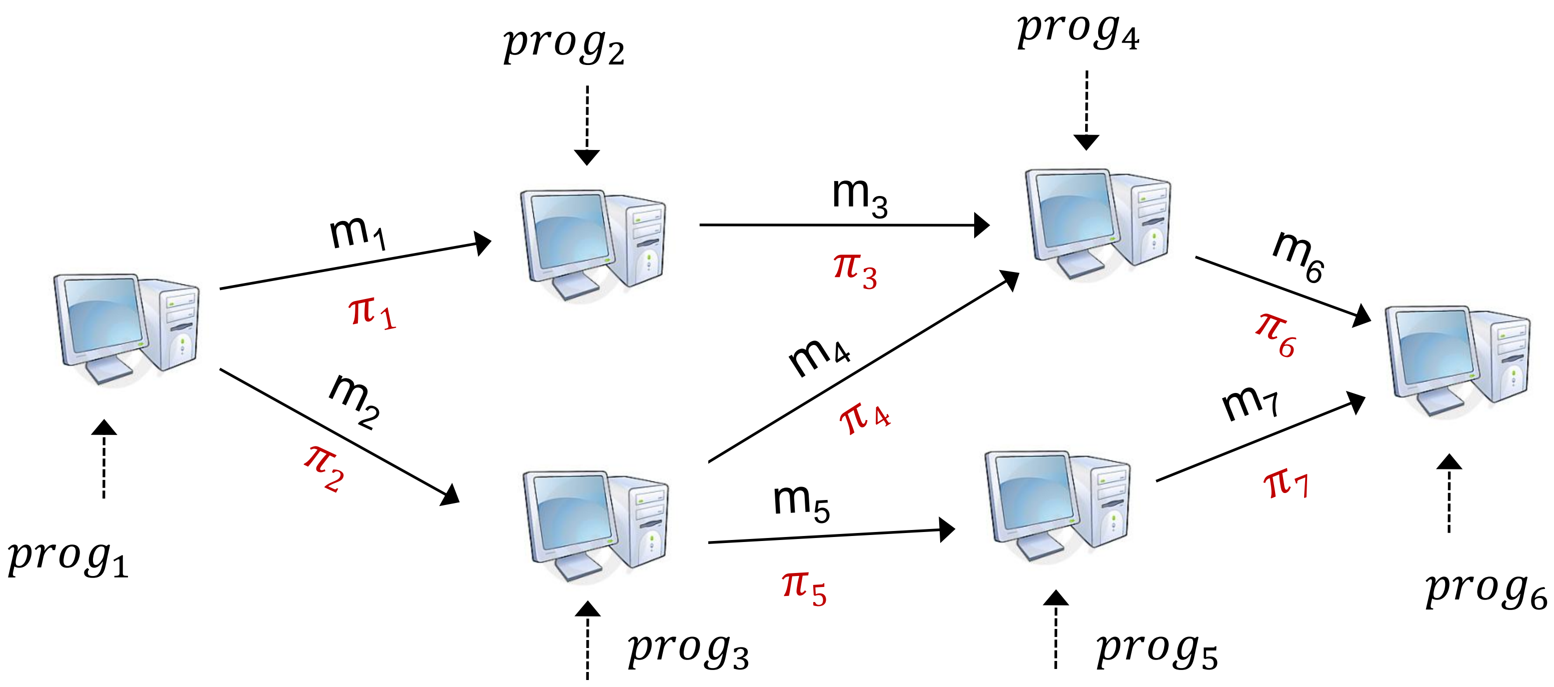
$\boldsymbol{C}(prog, m_{in}, m_{out})$ is a predicate specifying a local property, e.g.:

- $\boldsymbol{C}_{adm}$: "$prog = (M, s)$ where s is an admin signature on M and $M(m_{in}) = m_{out}$"
- $\boldsymbol{C}_{\boldsymbol{JVM}}$: "$prog$ is a JAVA program and $JVM(prog, m_{in}) = m_{out}$"
- $\boldsymbol{C}_{M_x}$: "$prog = \boldsymbol{w_i}, m_{in} = st_{i-1}$, $m_{out} = st_i$ and $\boldsymbol{M_x}(st_{i-1}, \boldsymbol{w_i}) = st_i$ "



A PCD system

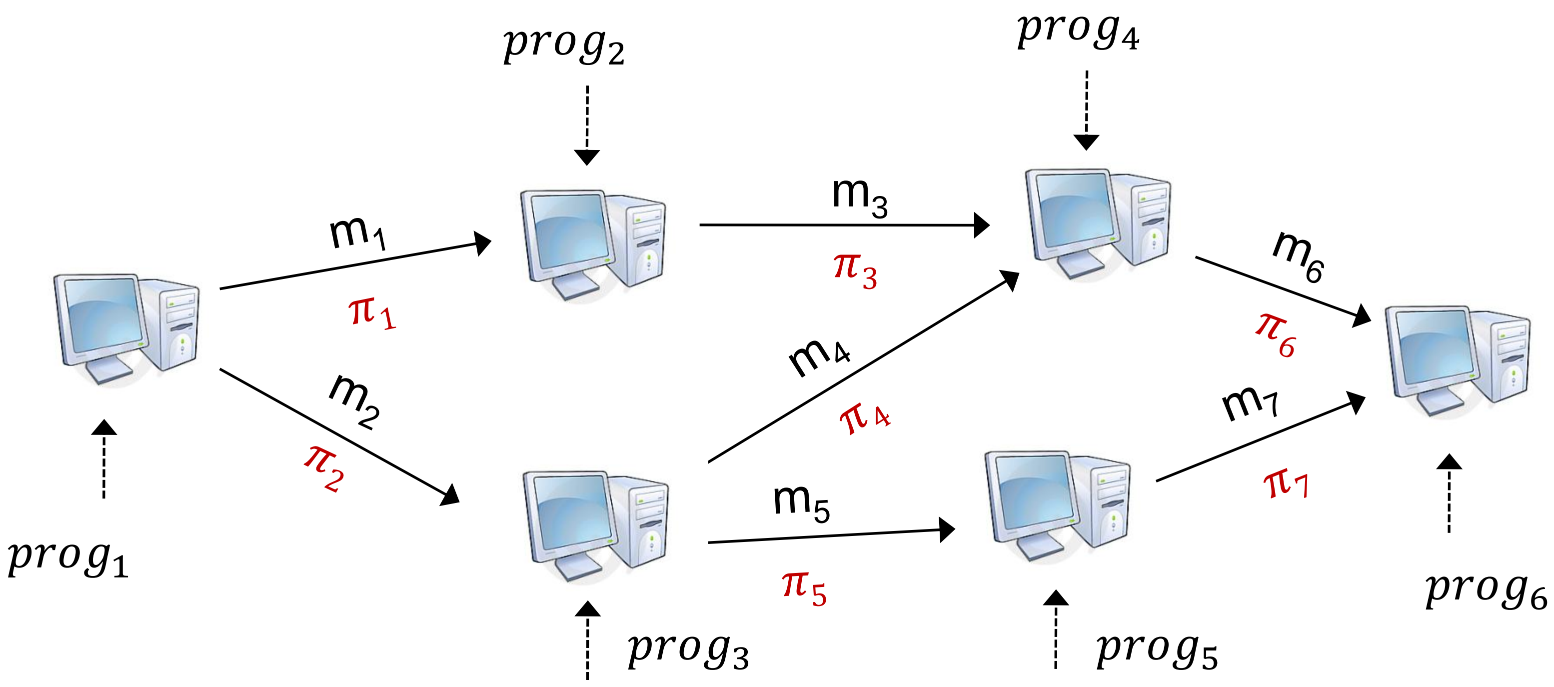
- compile on-the-fly original computation
- (short) proofs are appended to messages



A PCD system

- compile on-the-fly original computation
- (short) proofs are appended to messages

Note: not all properties can be verified this way.
Eg, verifying that $m_1 = m_2$ requires additional interaction.



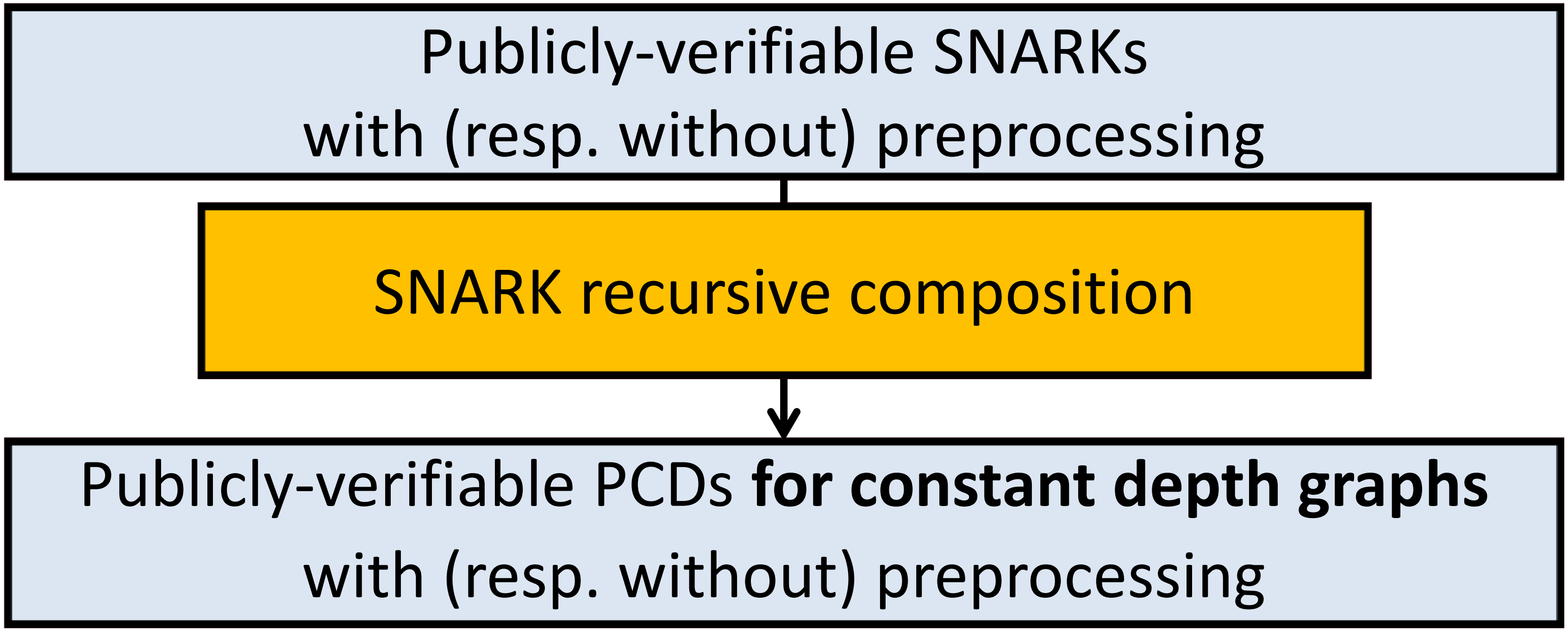
How to construct PCDs?

[CT10]: Using an abstract signature card

How to construct PCDs?

This work: SNARK composition

Results (revisited): General transformations



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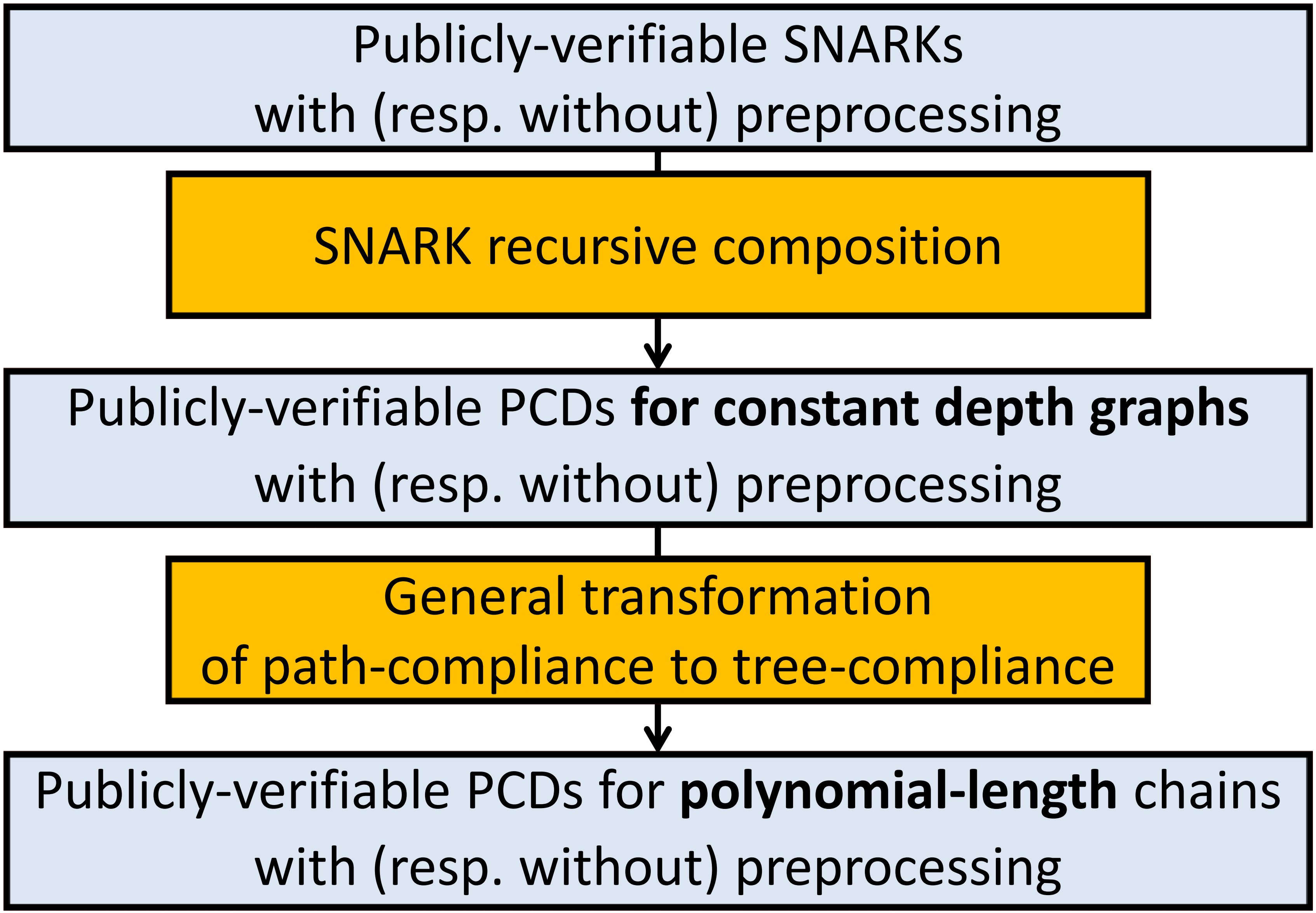
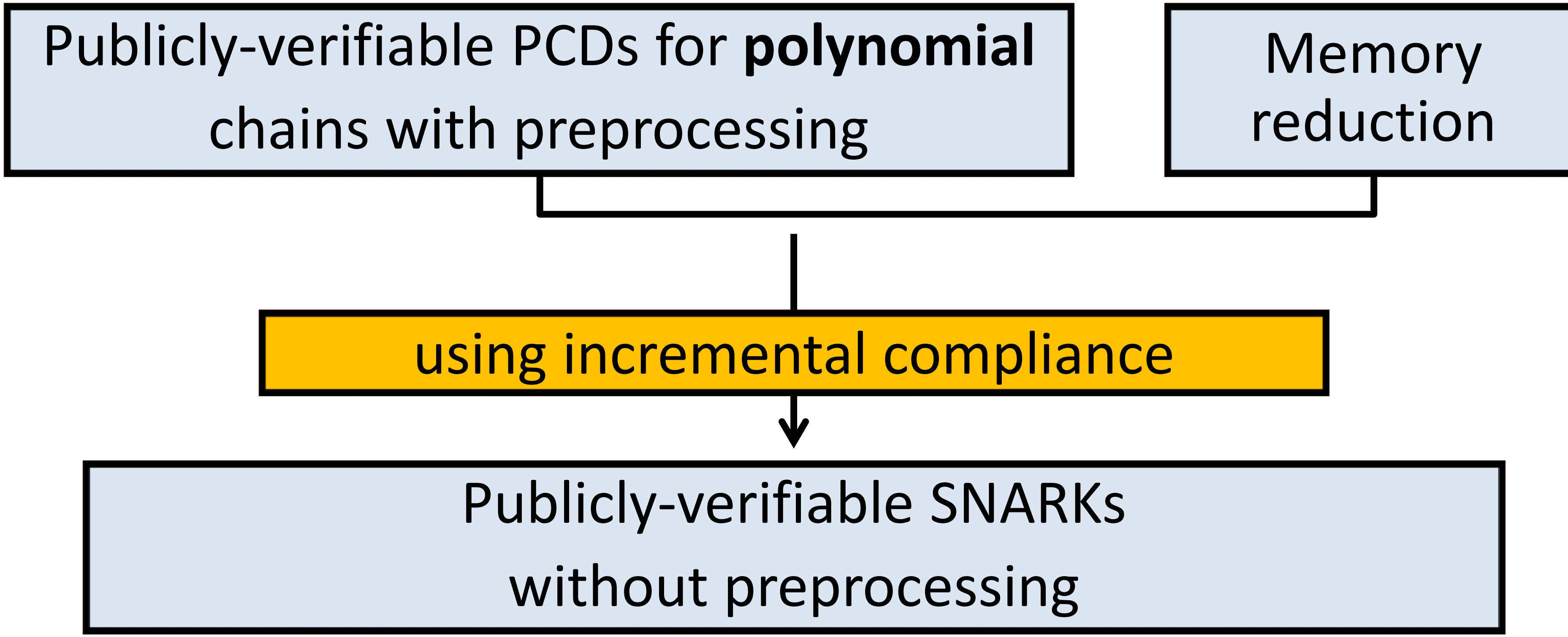


Results (revisited): Eliminating expensive preprocessing



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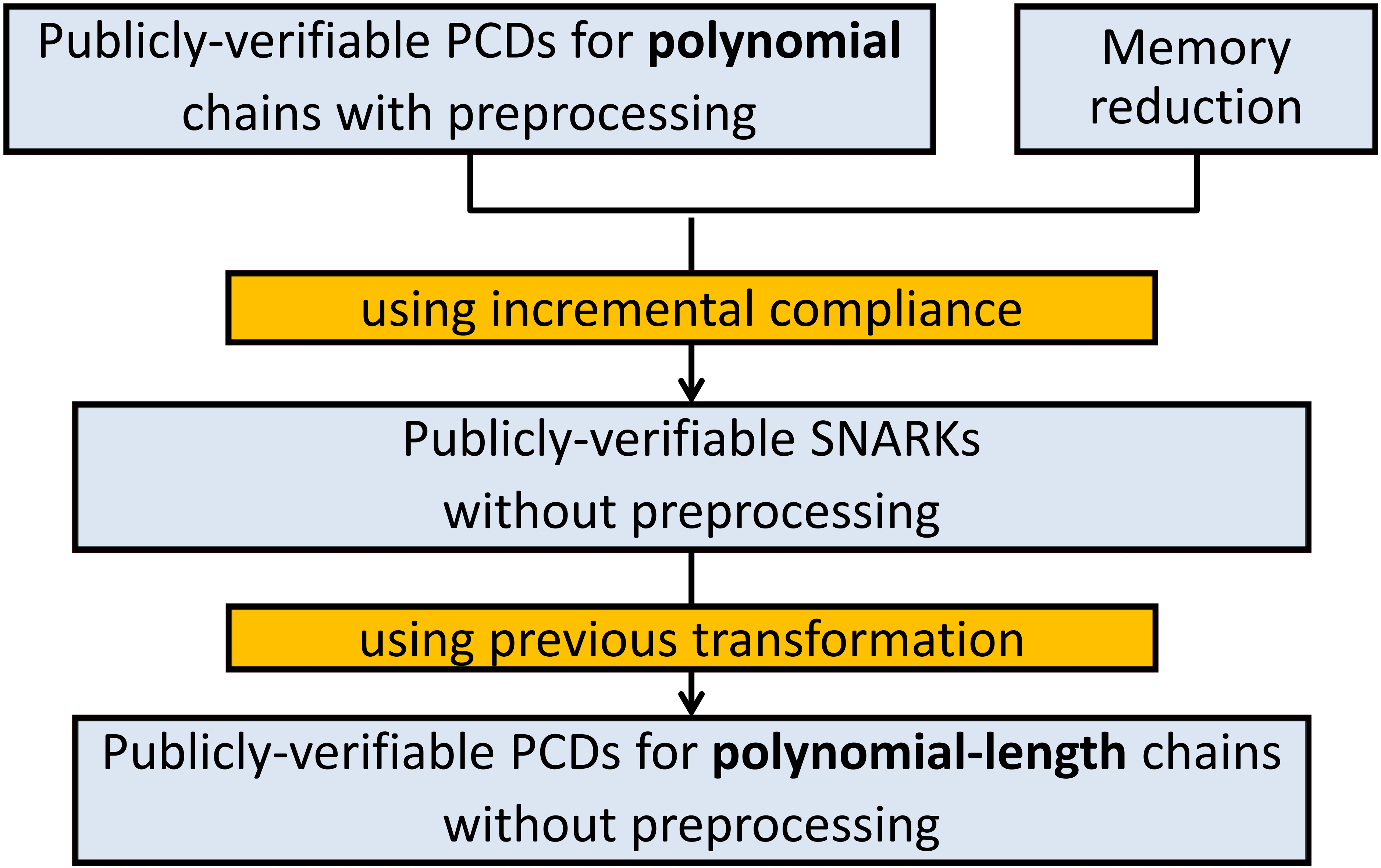

A bonus:
privately-verifiable SNARKs also compose!

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To compose SNARKs we used public-verifiability
proved "I verified a SNARK"

A bonus: privately-verifiable SNARKs also compose!

To compose SNARKs we used public-verifiability
proved "I verified a SNARK"

Looks surprising… but doable (using FHE).

➔ All the PCD results have their privately-verifiable analogs

Question:

which security goals we express using the PCD language?

We've seen some examples
others include: targeted-malleability [BSW11], computing on authenticated Data,…

Other properties?