From Blockchains to Nash

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Chethan Kamath

Krzysztof Pietrzak

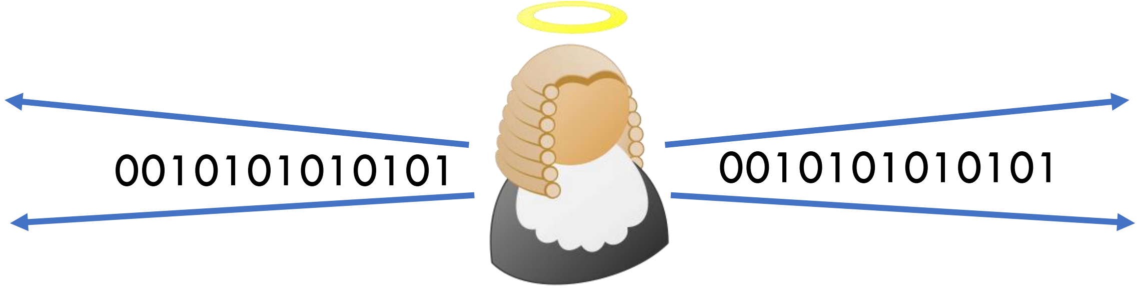
Alon Rosen

Guy Rothblum

Part 1: Blockchains

Verifiable Delay Function(s)

Verifiable Lottery via Randomness Beacon



Randomness Beacon [Rabin'83]

Ideal service that periodically publishes random values that cannot be predicted or manipulated.

Randomness Beacon via Blockchains

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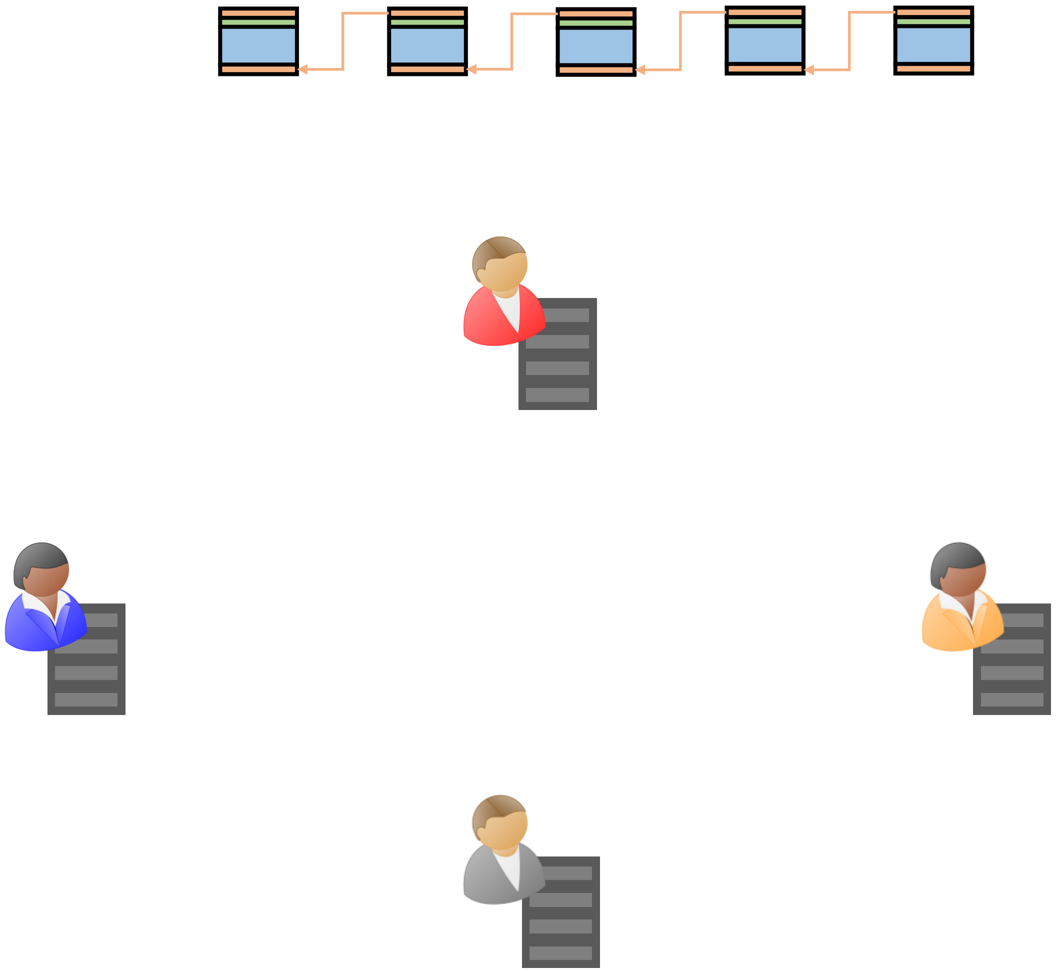

Consider proof of work (PoW) blockchains.

Randomness Beacon via Blockchains

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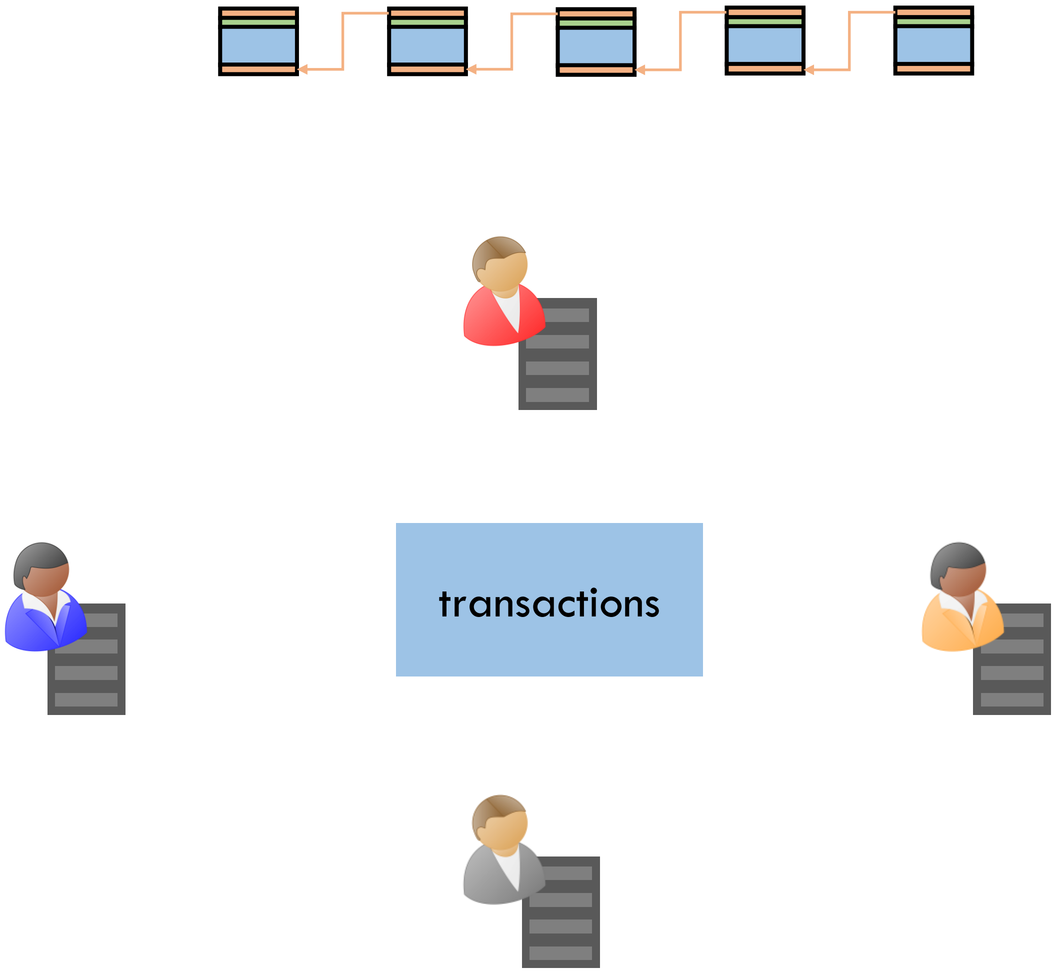

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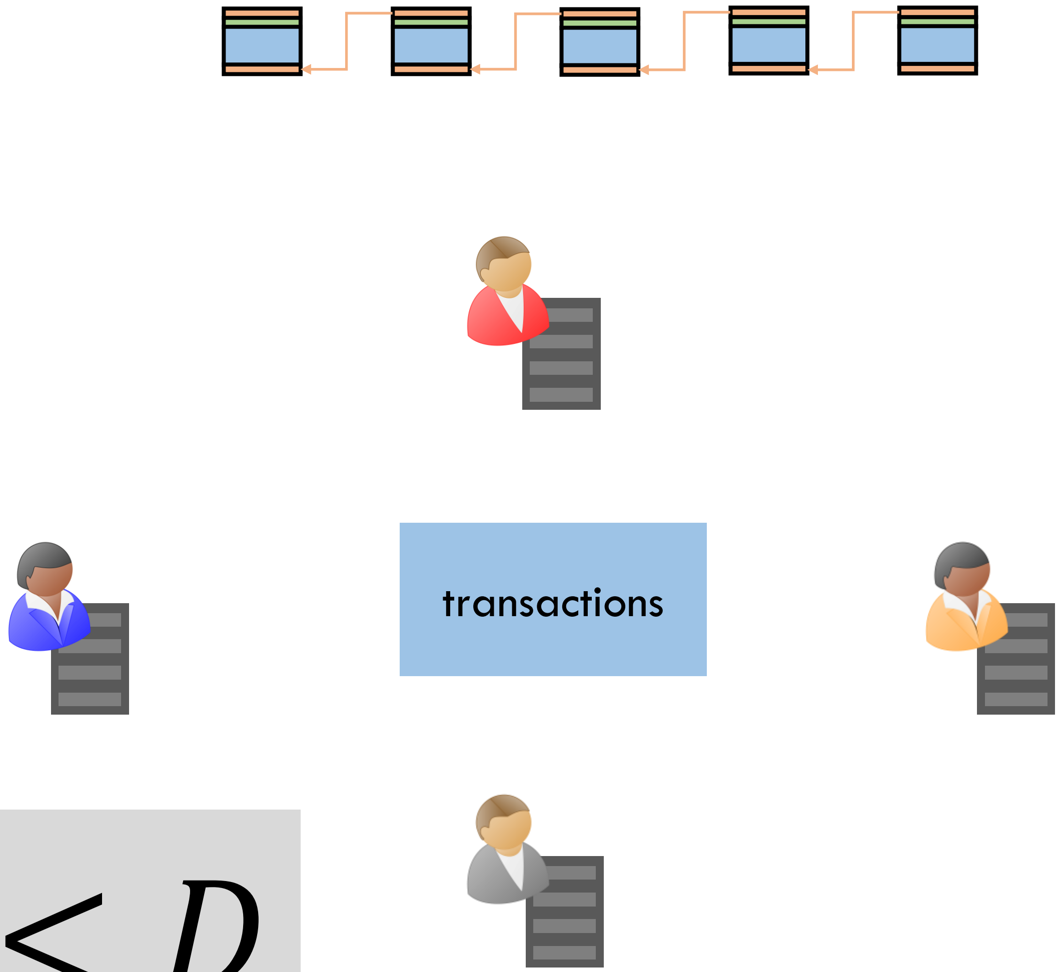

Find

such that $h(\quad) < D$

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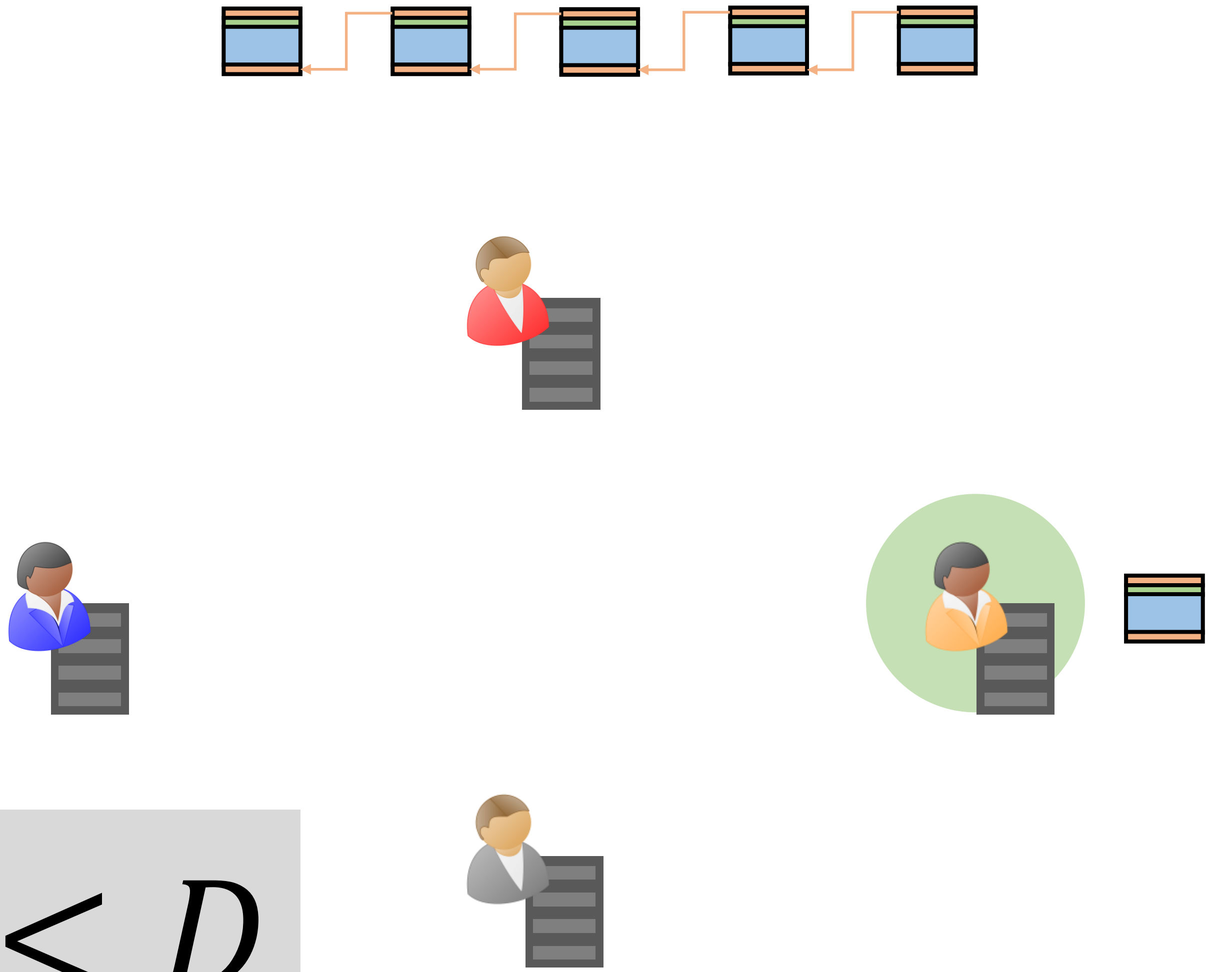

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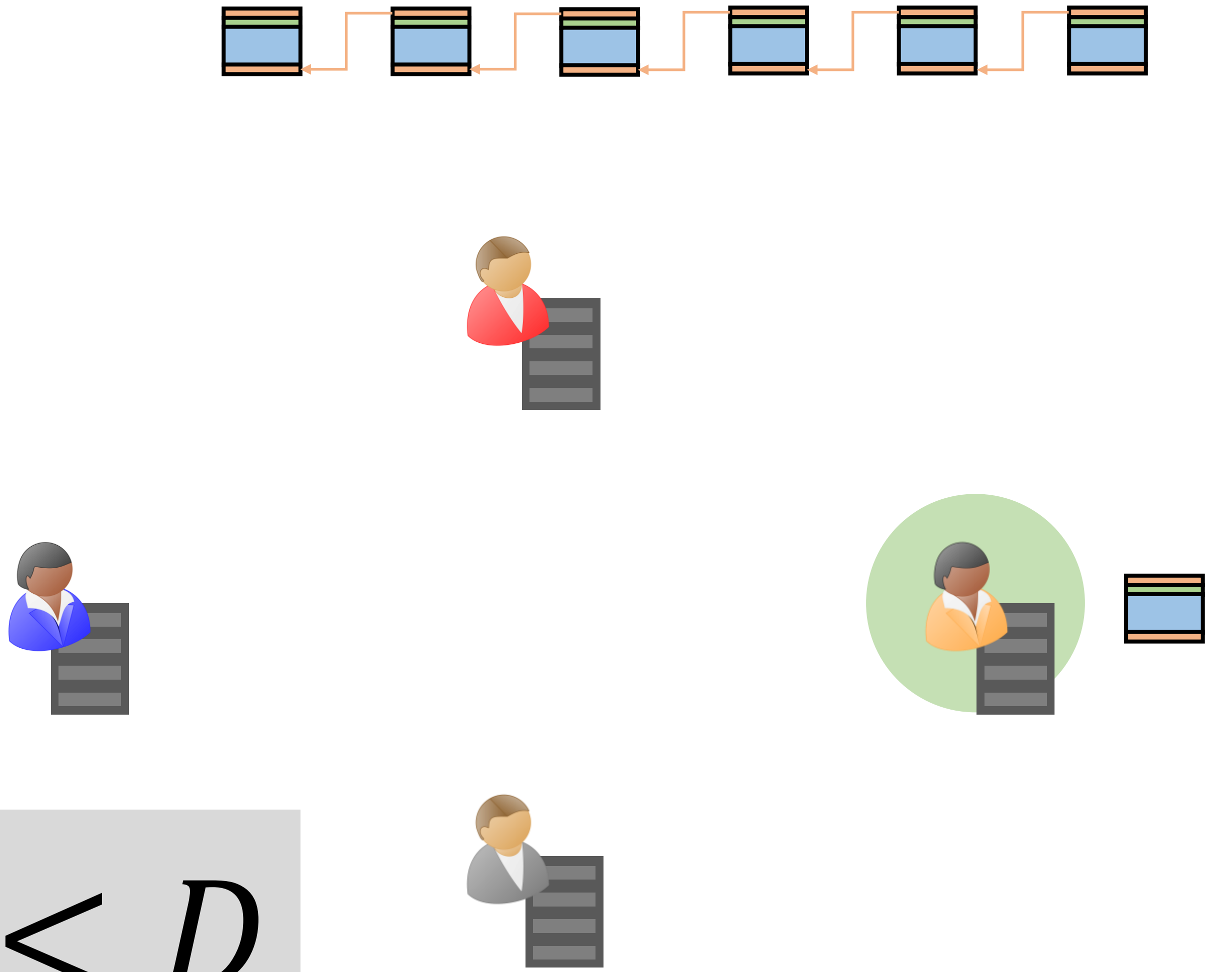

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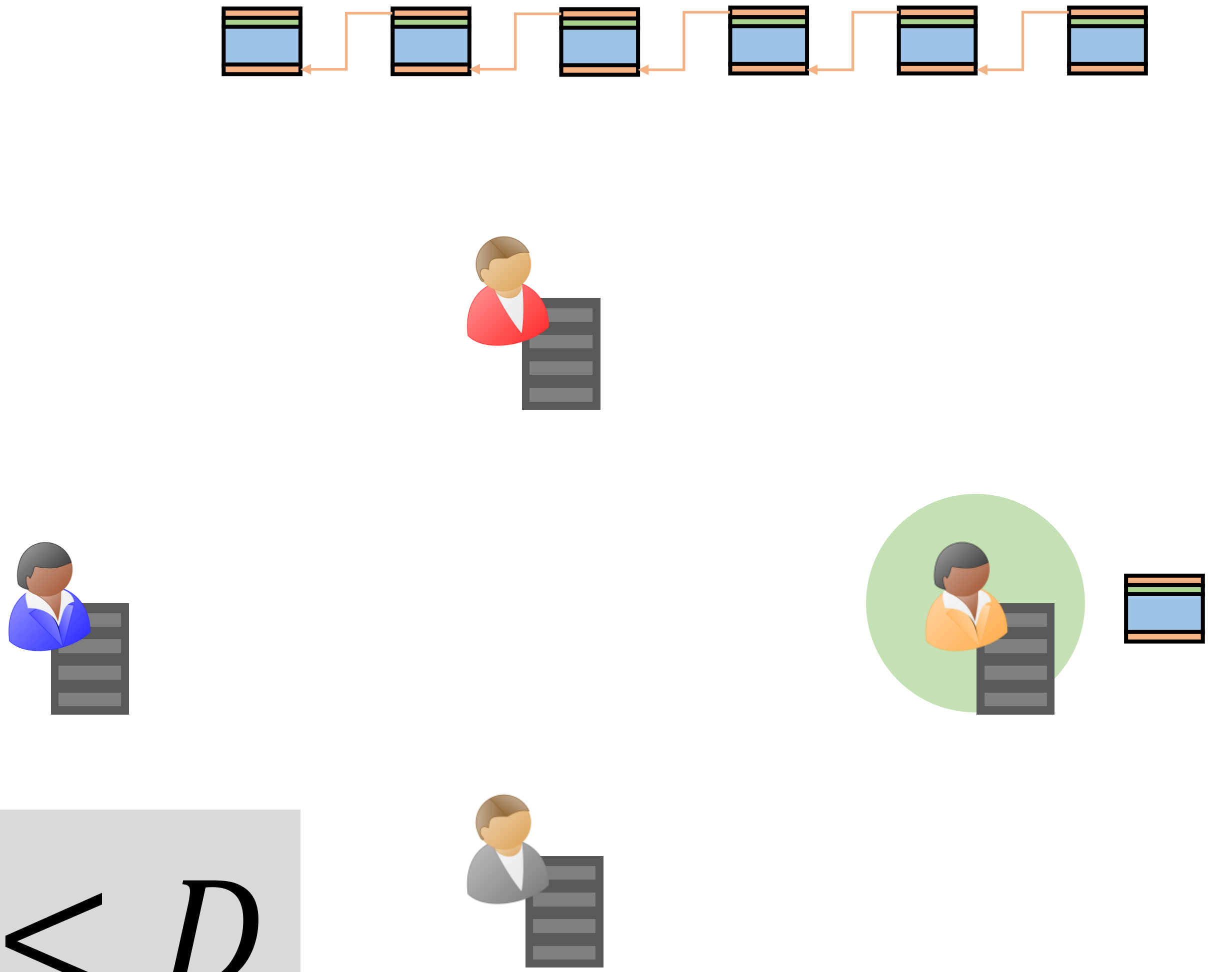

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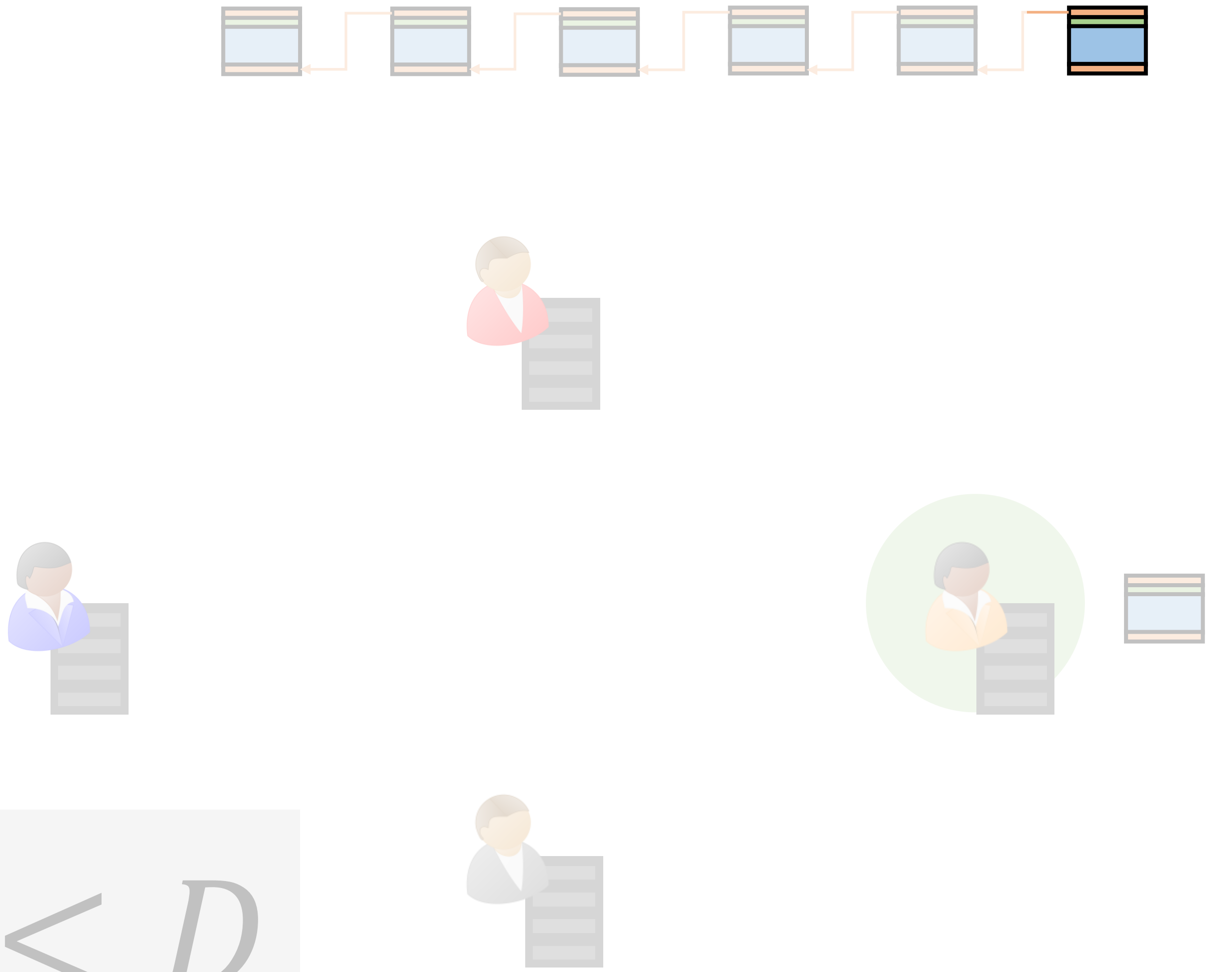

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Randomness Beacon via Blockchains

Extractor( )

Consider proof of work (PoW) blockchains.

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Randomness Beacon via Blockchains

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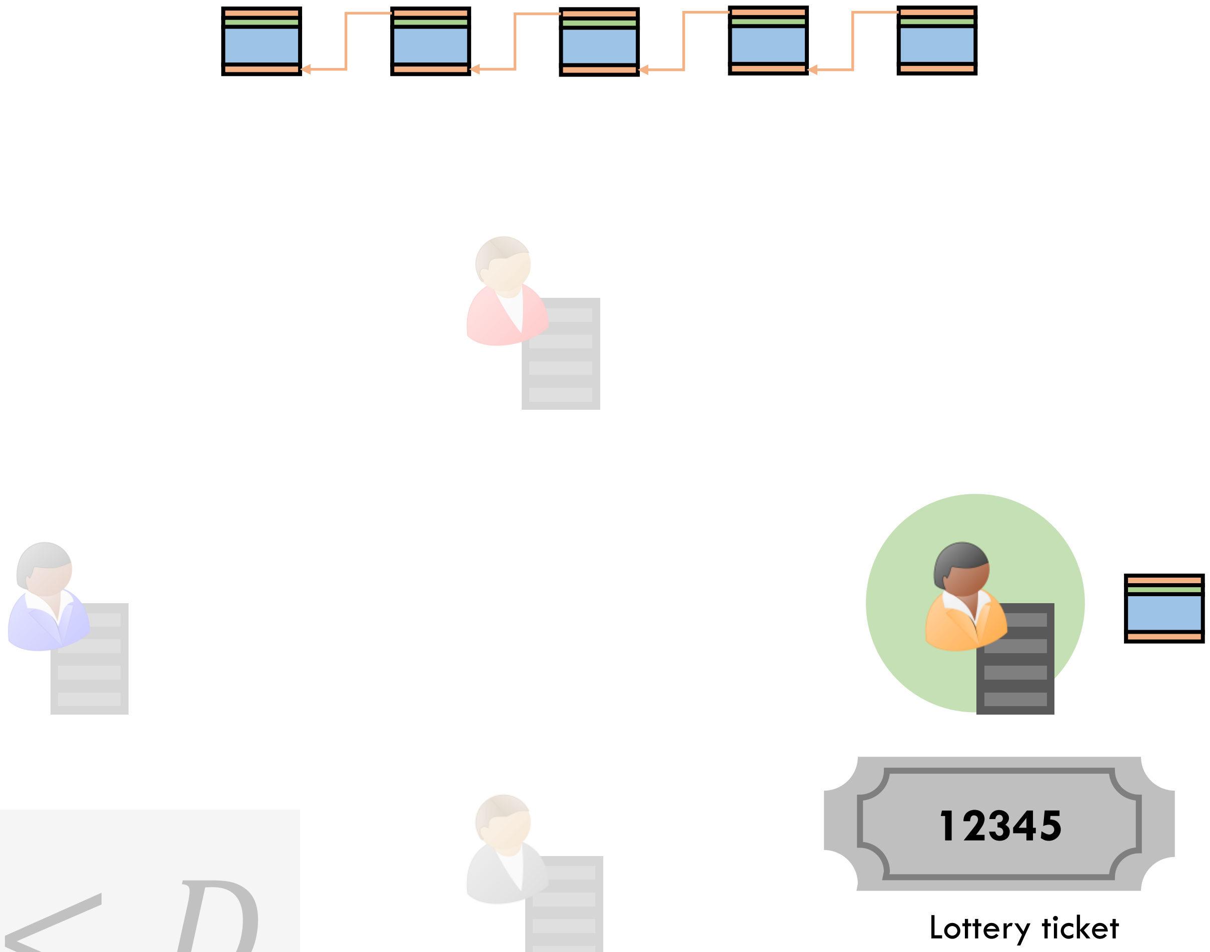

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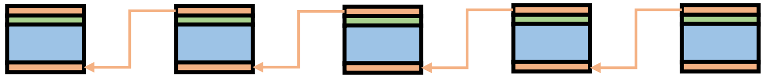

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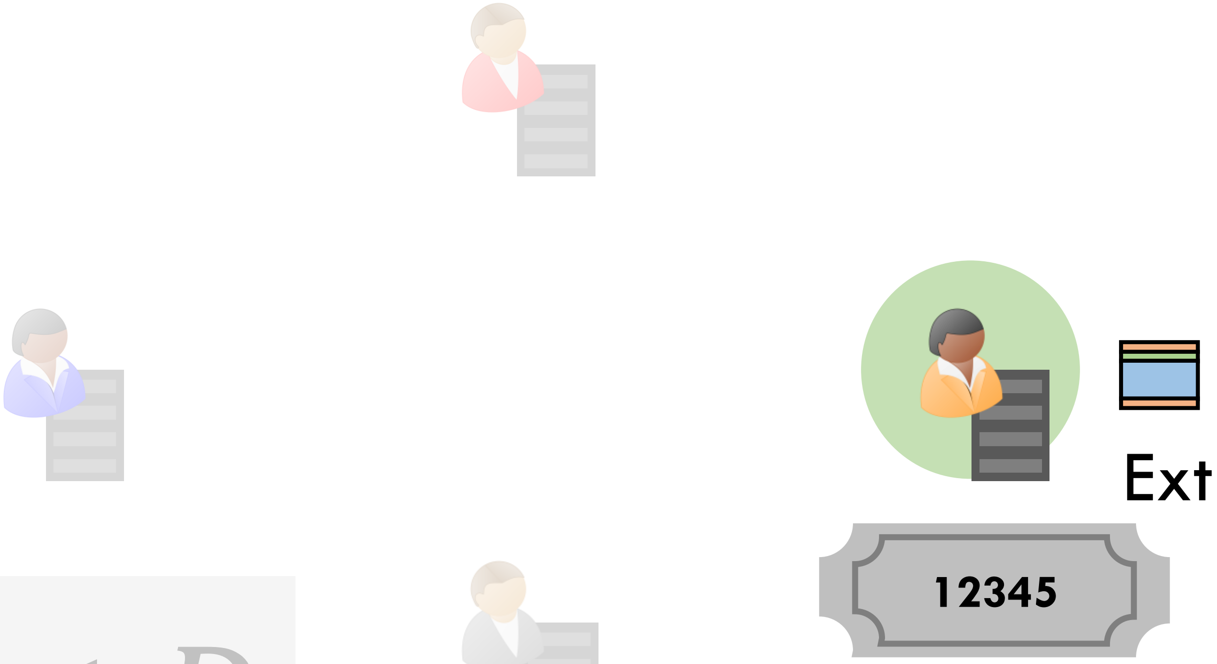

Lottery ticket

Extractor( ) $\stackrel{?}{=}$ 12345

Find

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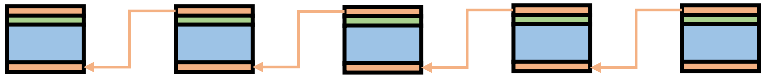
Randomness Beacon via Blockchains



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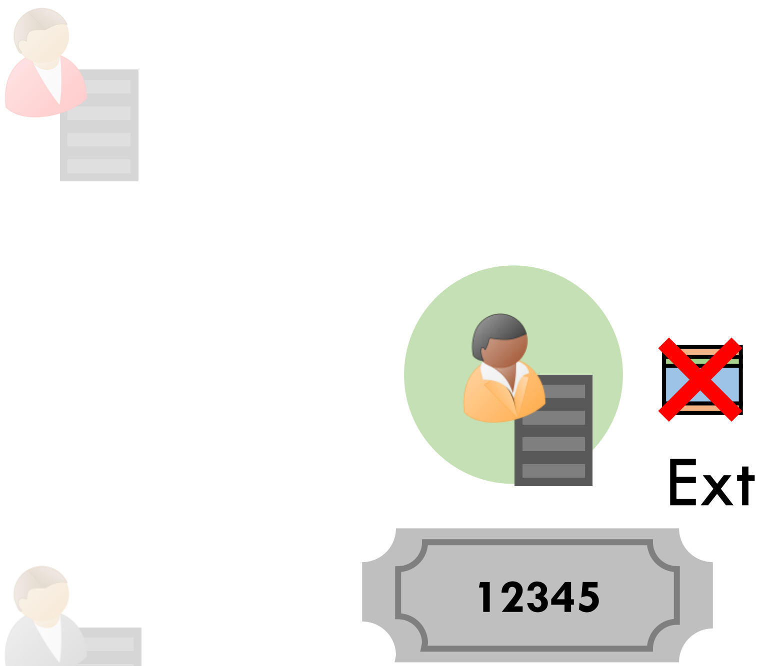

Lottery ticket

1) Blocks produced periodically.
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$$\text{Extractor}(\square) \overset{?}{=} 12345$$

Find such that

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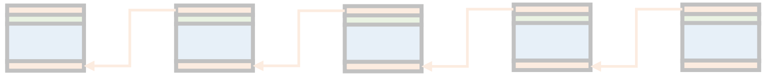
Randomness Beacon via Blockchains



Consider proof of work (PoW) blockchains.

Randomness Beacon [Rabin'83]

Ideal service that periodically publishes random values that cannot be predicted or manipulated.

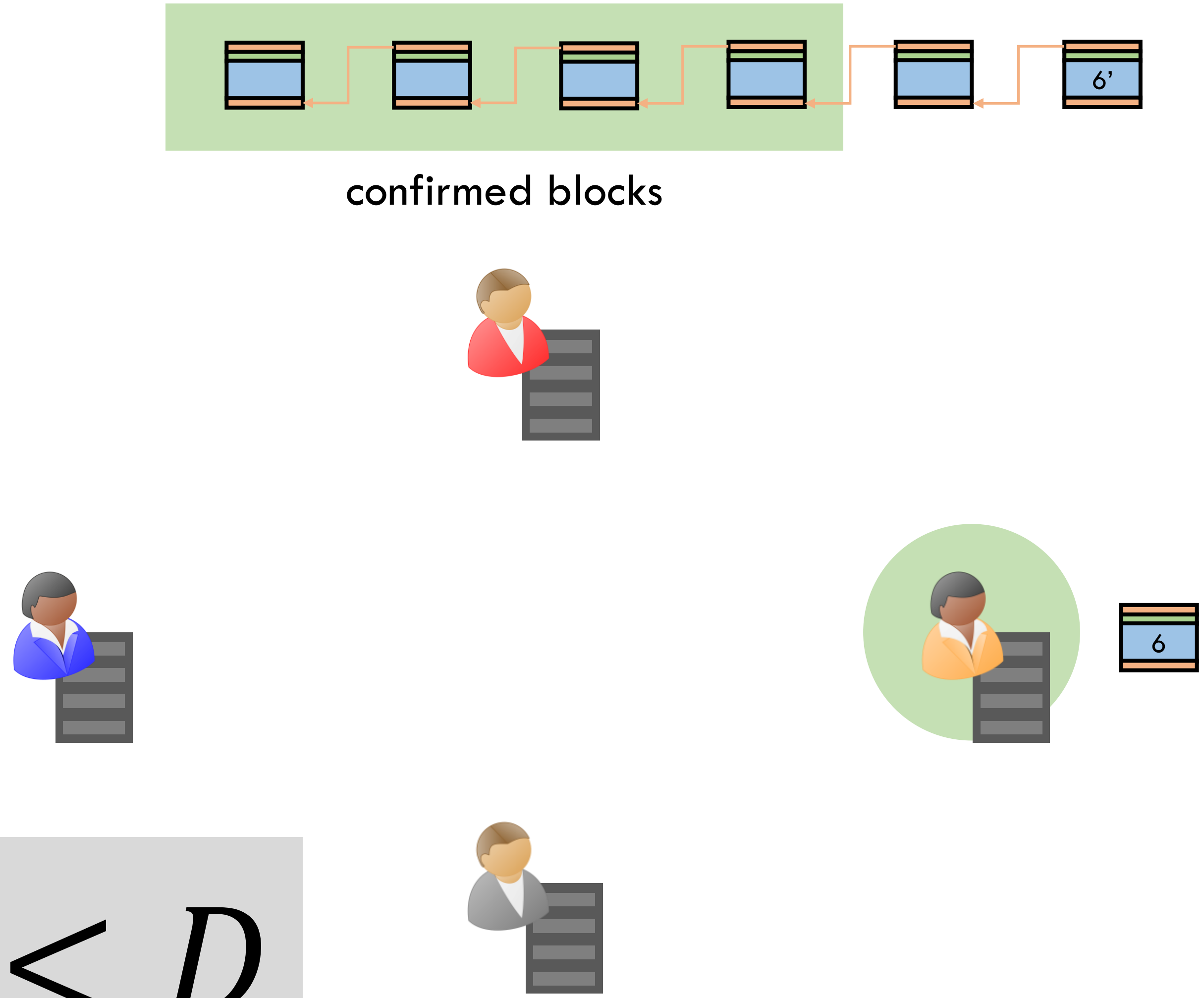
Find such that $h(\cdot) < D$

Extractor( ) $\stackrel{?}{=}$ 12345

12345

Lottery ticket

Randomness Beacon via Blockchains



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Find  such that

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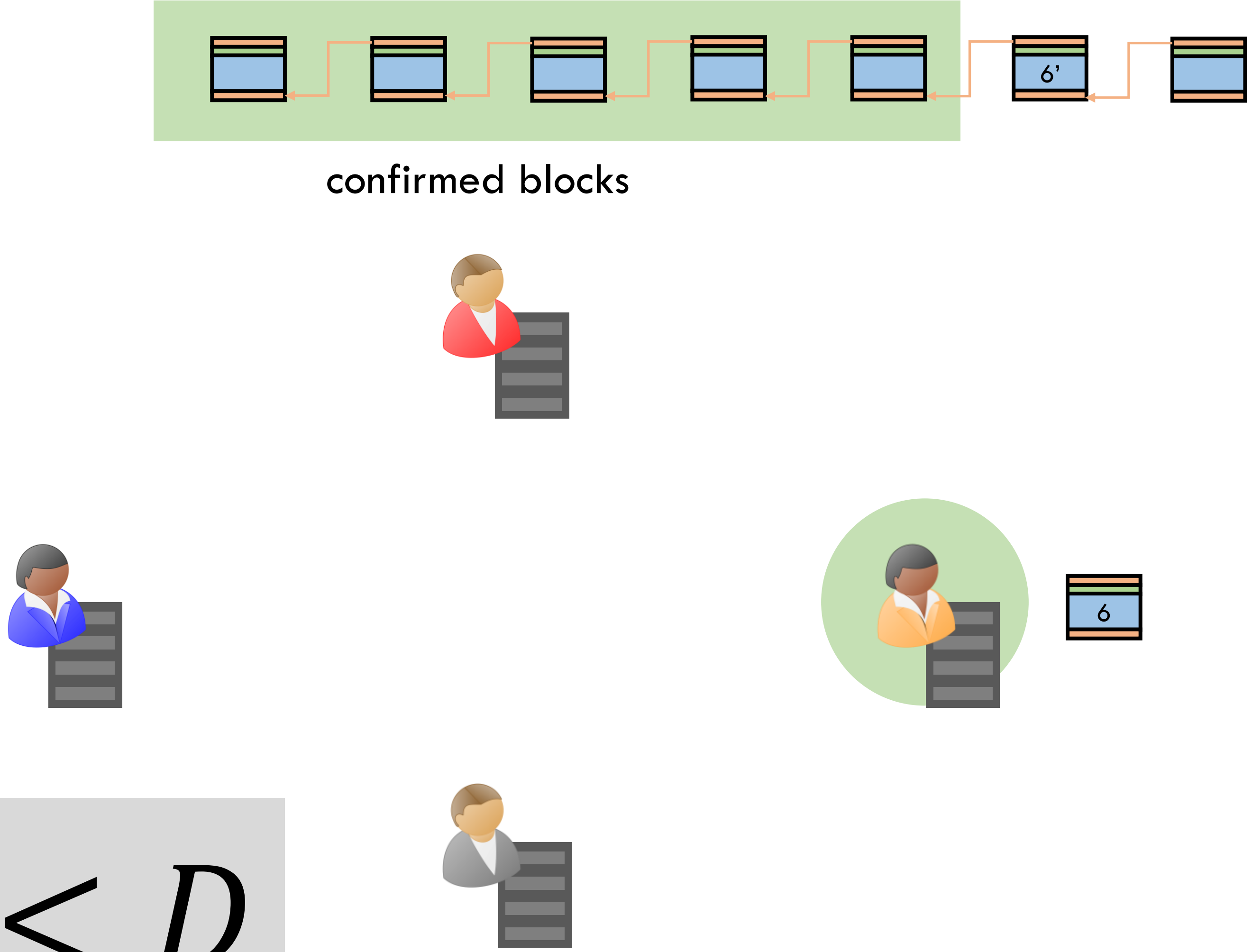

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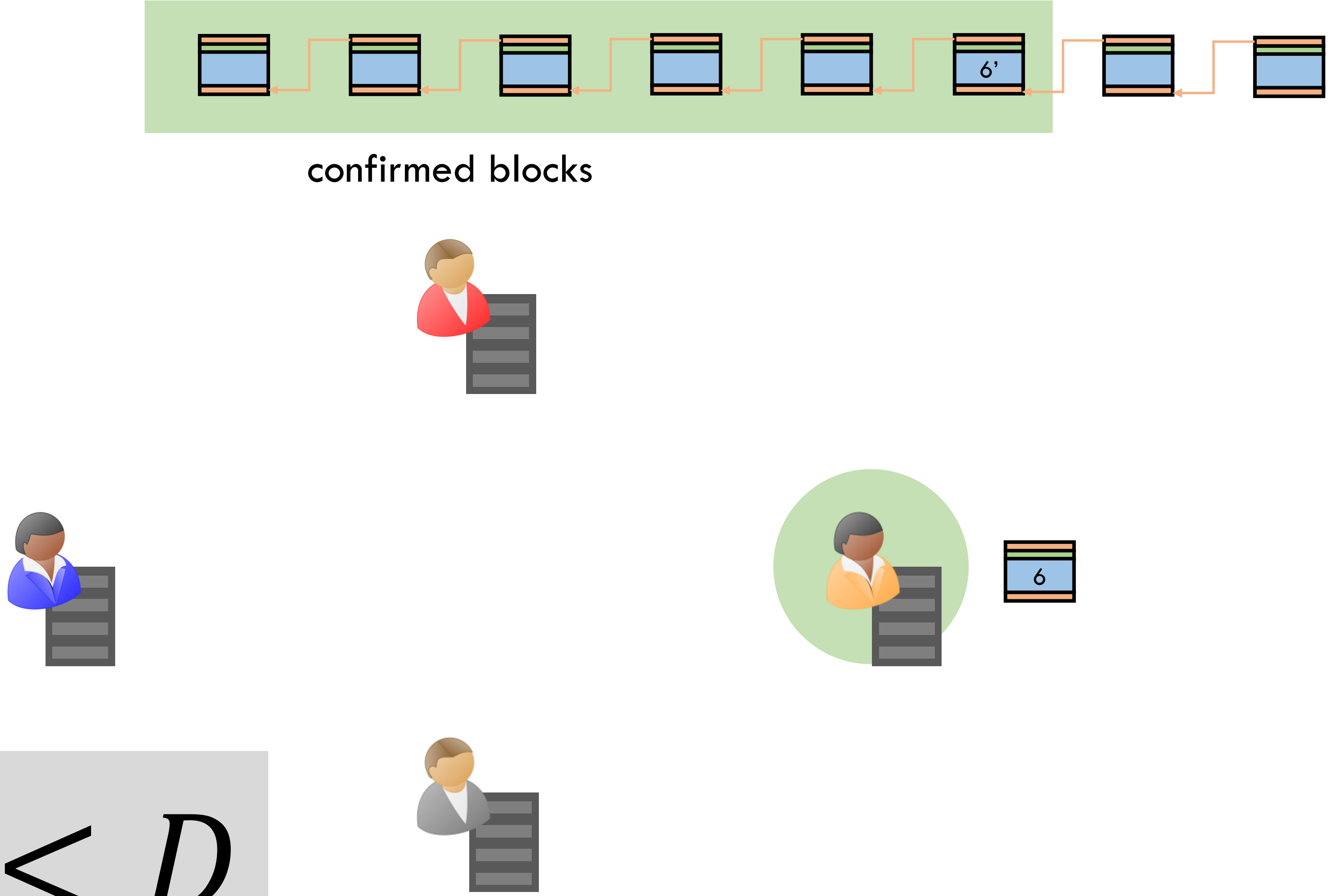

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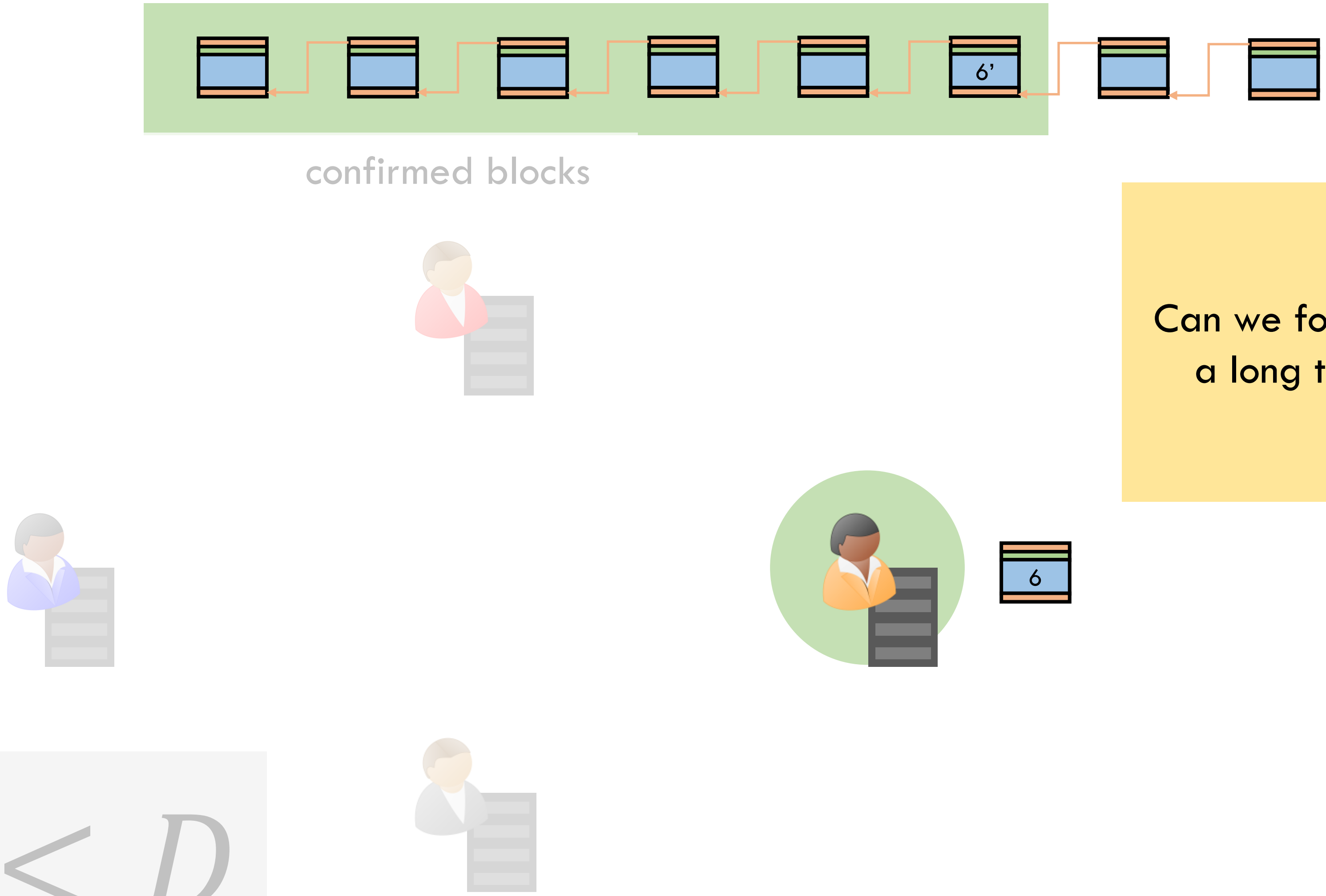

Consider proof of work (PoW) blockchains.

Can we force Extract to take a long time to compute?

Find [nonce] such that $h(\text{block}) < D$

Cryptographically Slow Functions

$$f(x) = x^{2^T} \bmod N$$

$N = p \cdot q$ for primes p and q

x, T, N $\longrightarrow$  $\underbrace{x \longrightarrow x^2 \longrightarrow x^4 \longrightarrow x^8 \cdots \longrightarrow x^{2^T}}_{T \text{ squarings}} \pmod{N}$

Cryptographically Slow Functions

RSW Assumption [Rivest-Shamir-Wagner'96]

$=p{\cdot}q$ for primes p and q

Input: $N = p \cdot q$, $x \in \mathbb{Z}_N^*$, T

Goal: Find $x^{2^T} \bmod N$

$$\underbrace{x \longrightarrow x^2 \longrightarrow x^4 \longrightarrow x^8 \cdots \longrightarrow x^{2^T}}_{T \text{ squarings}} \pmod{N}$$

Any algorithm that computes $x^{2^T} \bmod N$ requires sequential time not much less than T.

Cryptographically Slow Functions

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x, T, N, p, q $\longrightarrow$  $\phi(N) = (p-1)(q-1)$ $\quad \underbrace{z = 2^T \left(\bmod\ \phi(N)\right), \quad x^z \pmod{N}}_{2 \text{ exponentiations}}$

Cryptographically Slow Functions

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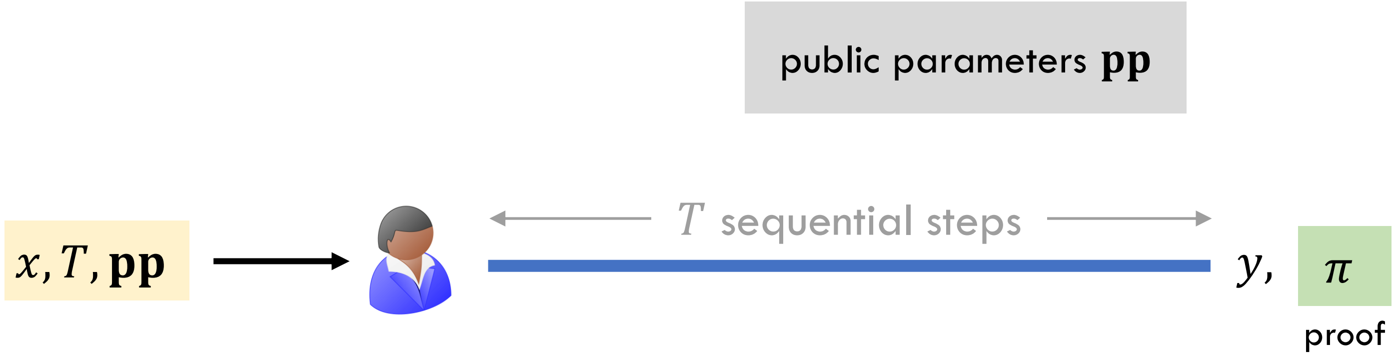
Efficient public verification?

Verifiable Delay Functions [Boneh-Bonneau-Bünz-Fisch'18]



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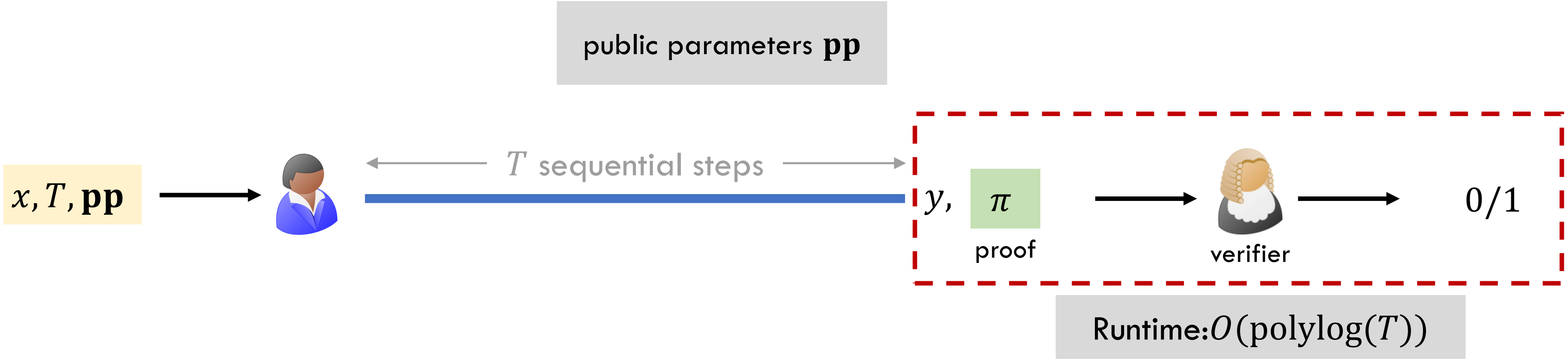

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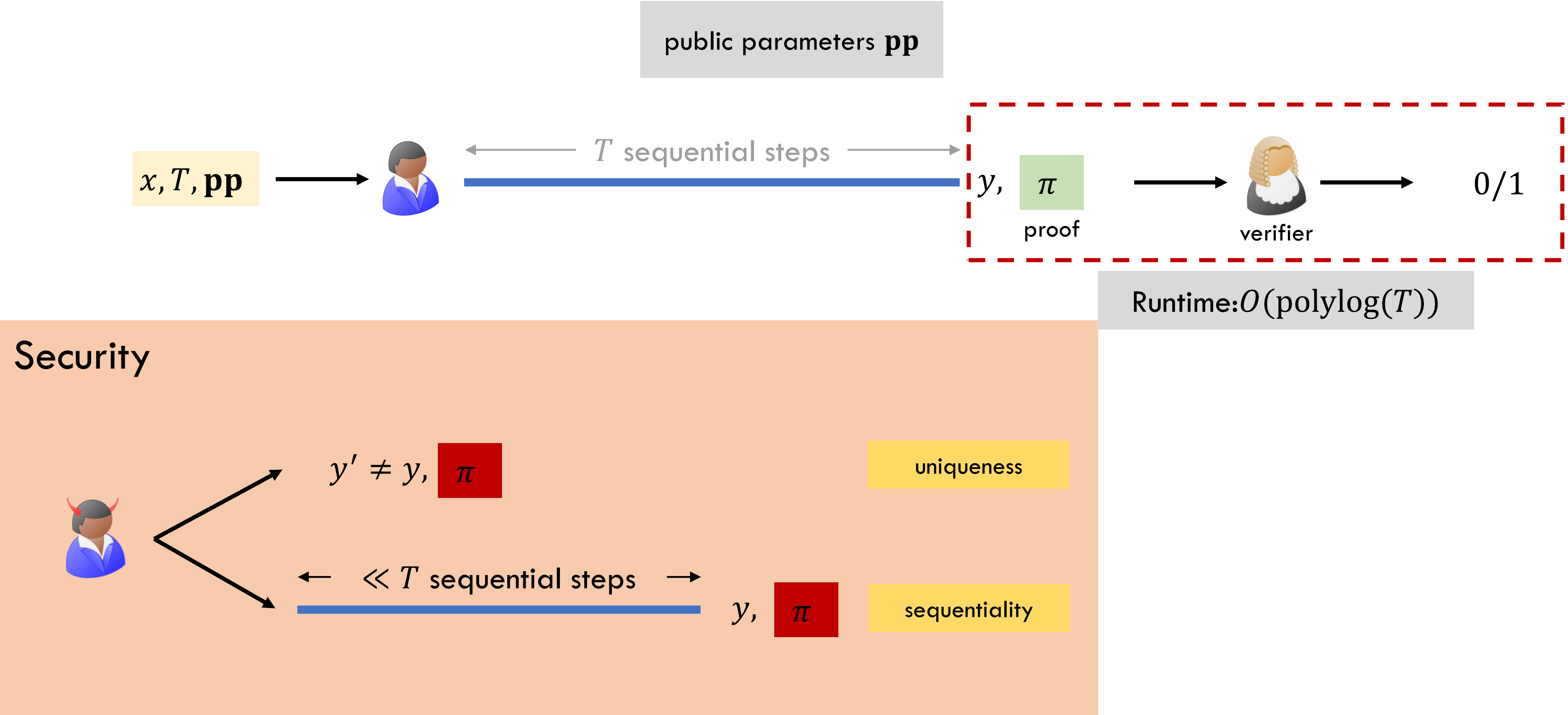

Randomness Beacon via Blockchains

Extractor( )

Consider proof of work (PoW) blockchains.

1) Blocks produced periodically.
2) Solution has some amount of unpredictability.

Find such that $h(\ ) < D$

Randomness Beacon via Blockchains

Extractor(VDF( ))

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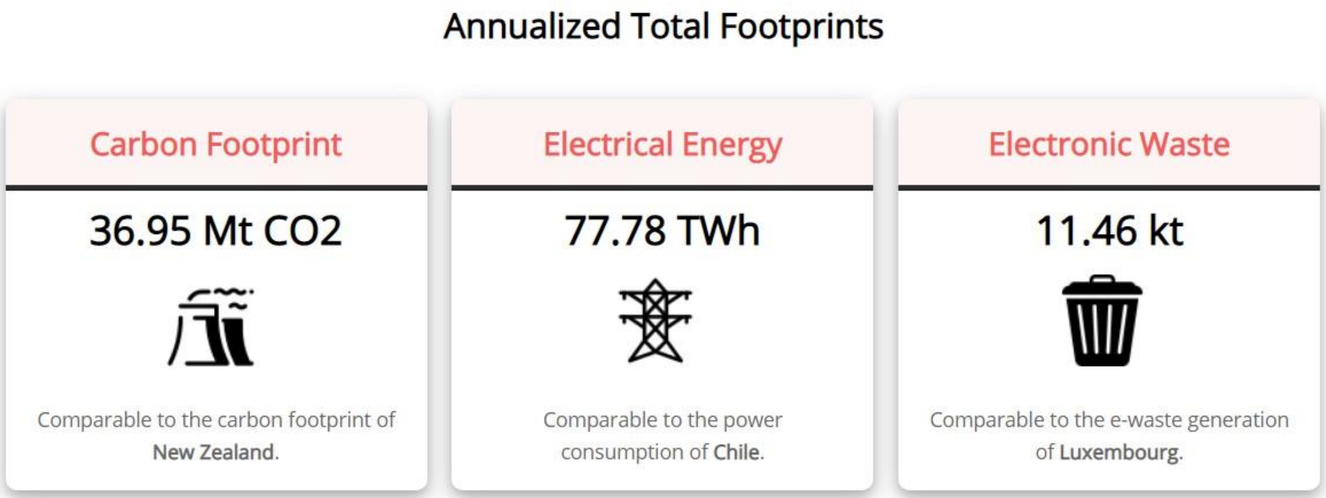
Find such that $h(\;) < D$

VDF Application: Resource Efficient Blockchains

bitcoin



https://digiconomist.net/bitcoin-energy-consumption

VDF Application: Resource Efficient Blockchains

bitcoin

Annualized Total Footprints

Carbon Footprint	Electrical Energy	Electronic Waste
36.95 Mt CO_2	77.78 TWh	11.46 kt
Comparable to the carbon footprint of **New Zealand**.	Comparable to the power consumption of **Chile**.	Comparable to the e-waste generation of **Luxembourg**.

https://digiconomist.net/bitcoin-energy-consumption

chia

https://chia.net/

Blockchain from proofs of space and VDFs.

VDF from Repeated Squaring

[Wesolowski'19,Pietrzak'19]

public parameters N

x, T, N $\longrightarrow$  $\longrightarrow$ $y = x^{2^T} \bmod N$

1

VDF from Repeated Squaring

[Wesolowski'19,Pietrzak'19]

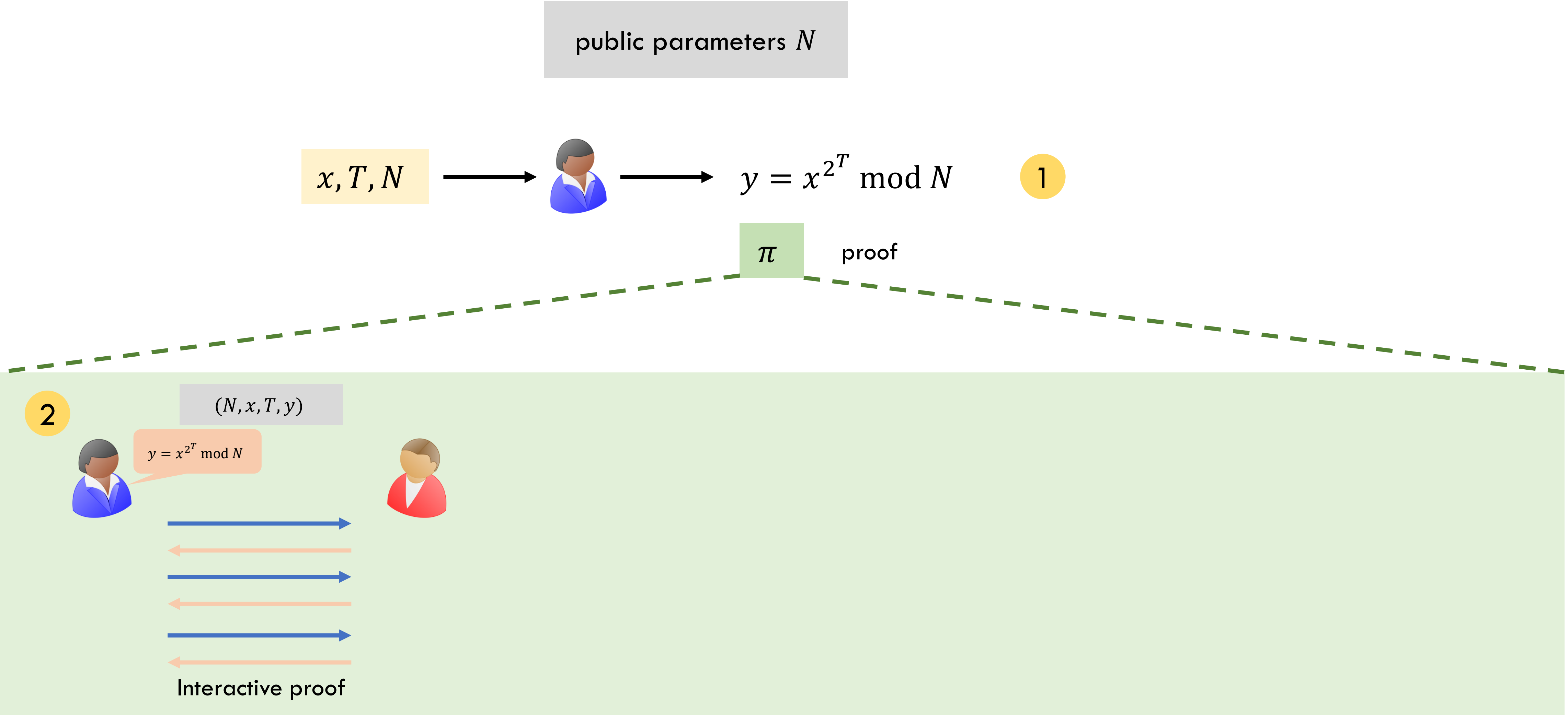
public parameters N

x, T, N →  → $y = x^{2^T} \bmod N$ 1

π proof

VDF from Repeated Squaring

[Wesolowski'19,Pietrzak'19]



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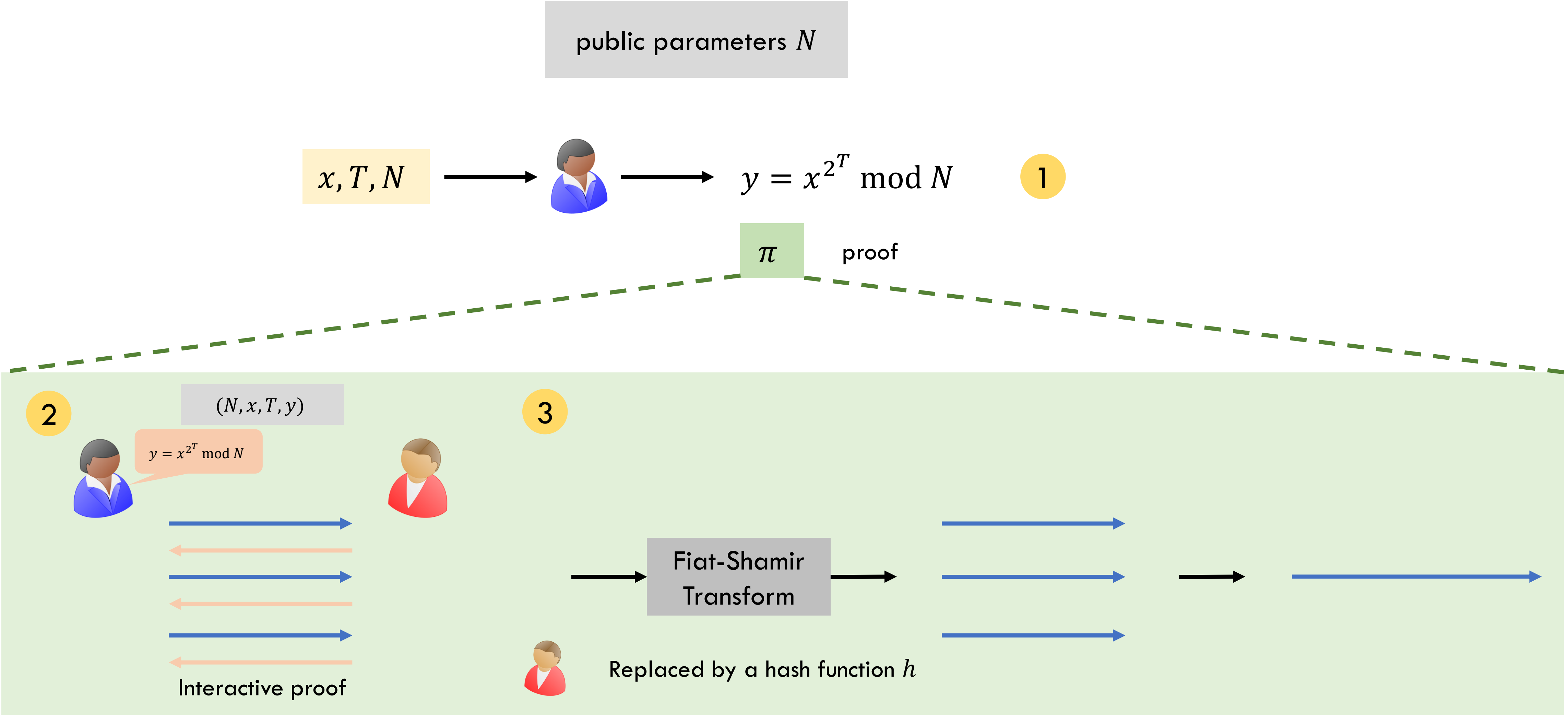

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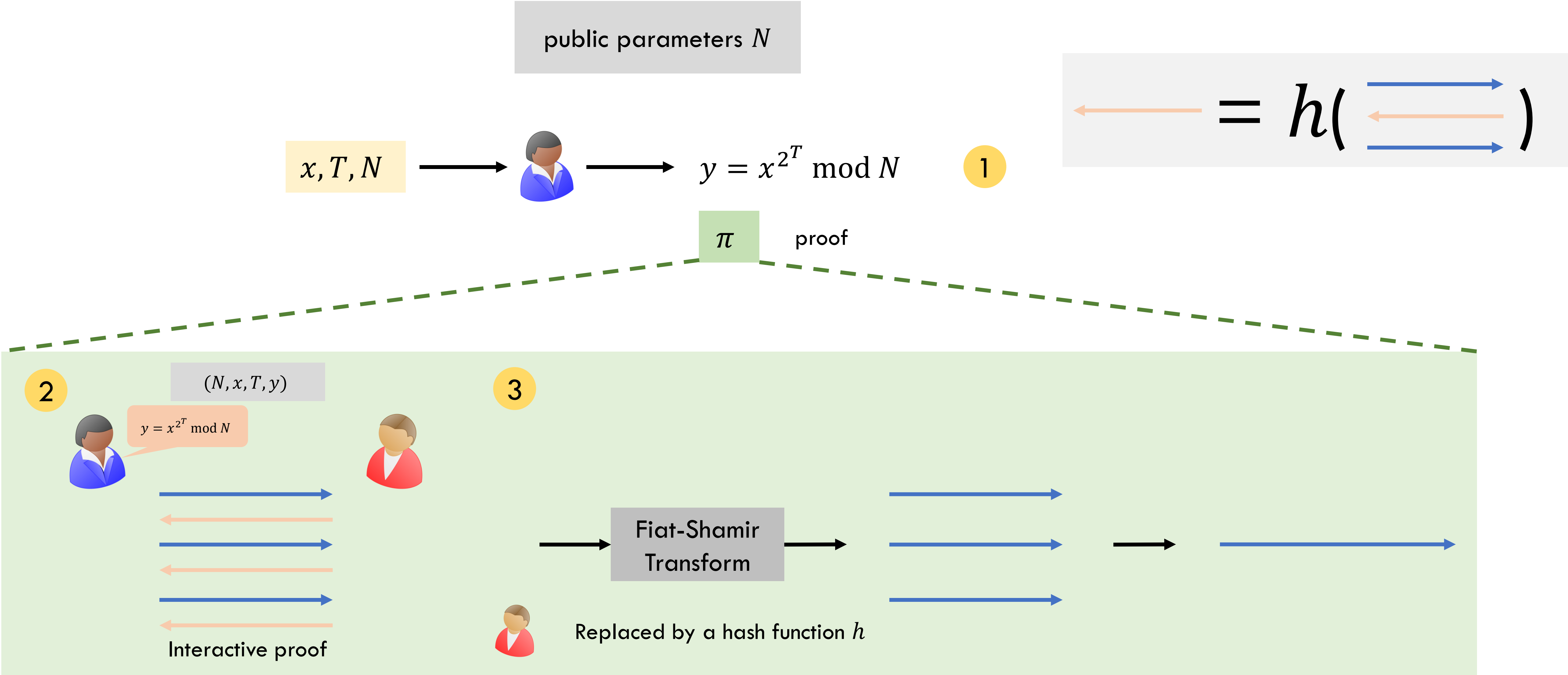

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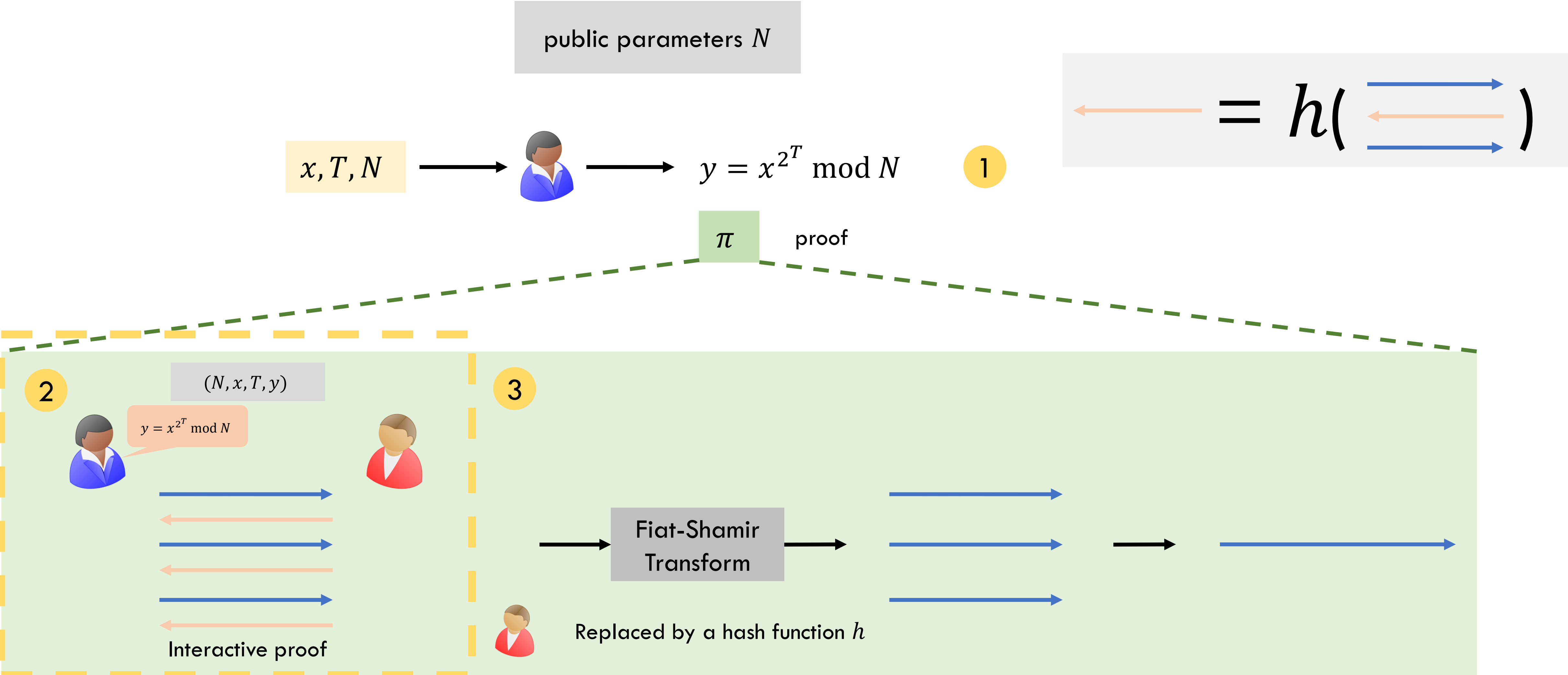

Pietrzak Proof System [Pietrzak'19]

$(N, x, T = 2^t, y)$

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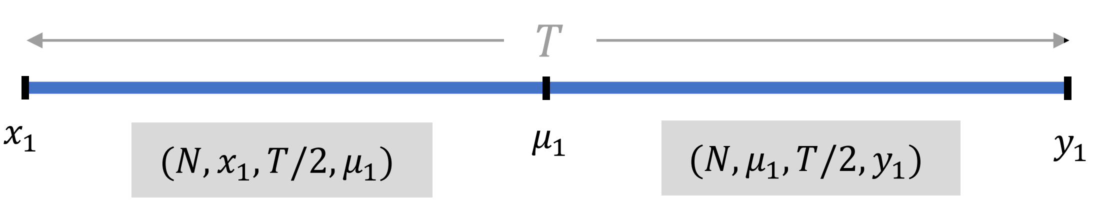

$(N, x, T = 2^t, y)$

$\mu_1 = x_1^{2^{\frac{T}{2}}}$

μ_1

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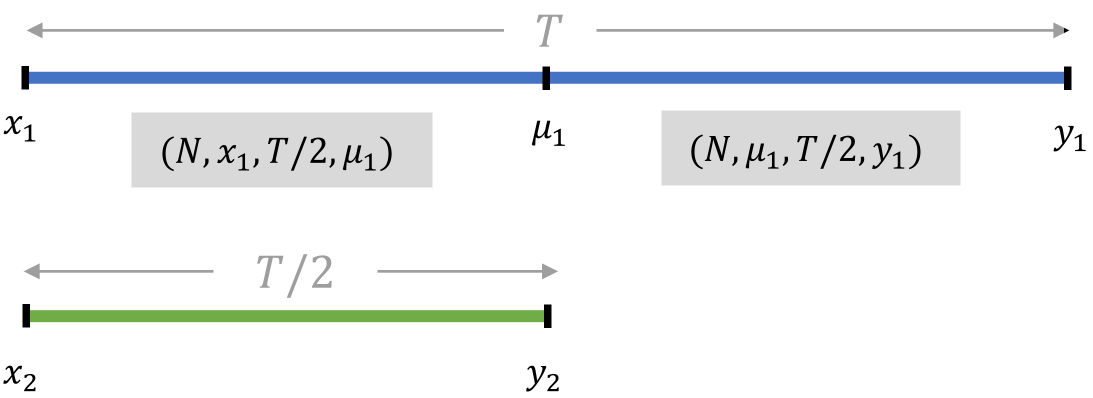

$(N, x, T = 2^t, y)$

$\mu_1 = x_1^{2^{\frac{T}{2}}}$

$\xrightarrow{\mu_1}$

$r_1 \leftarrow \mathbb{Z}_{2^\lambda}$

$\xleftarrow{r_1}$

$x_2 = x_1^{r_1} \cdot \mu_1$
$y_2 = \mu_1^{r_1} \cdot y_1$

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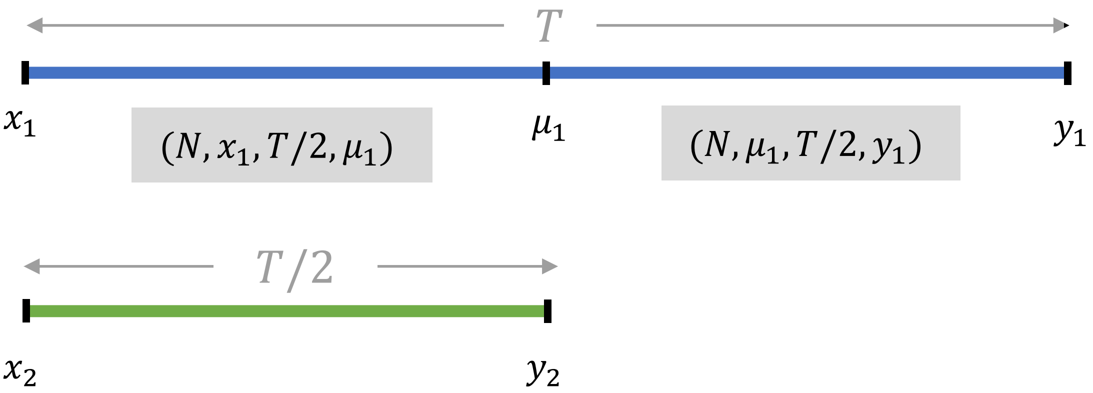

$$x_2 = x_1^{r_1} \cdot \mu_1 = x_1^{r_1 + 2^{\frac{T}{2}}}$$

$$y_2 = \mu_1^{r_1} \cdot y_1 = x_1^{r_1 2^{\frac{T}{2}} + 2^T}$$

$(N, x, T = 2^t, y)$

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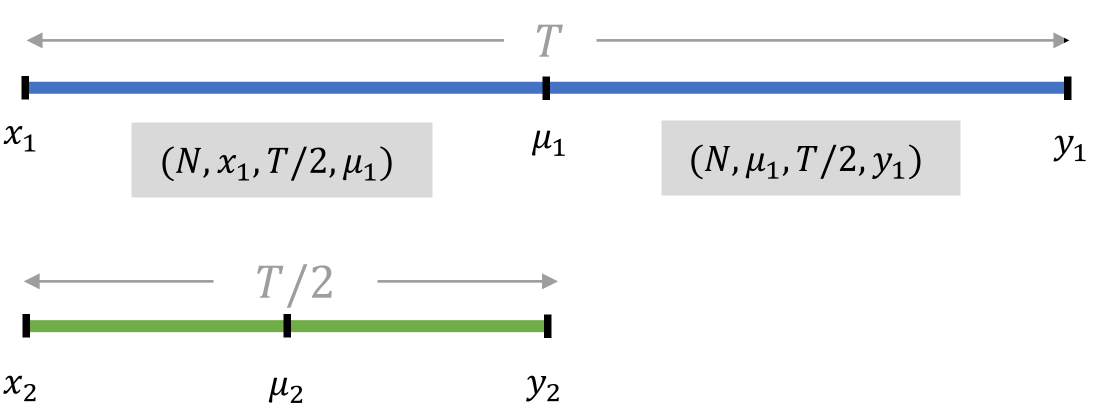

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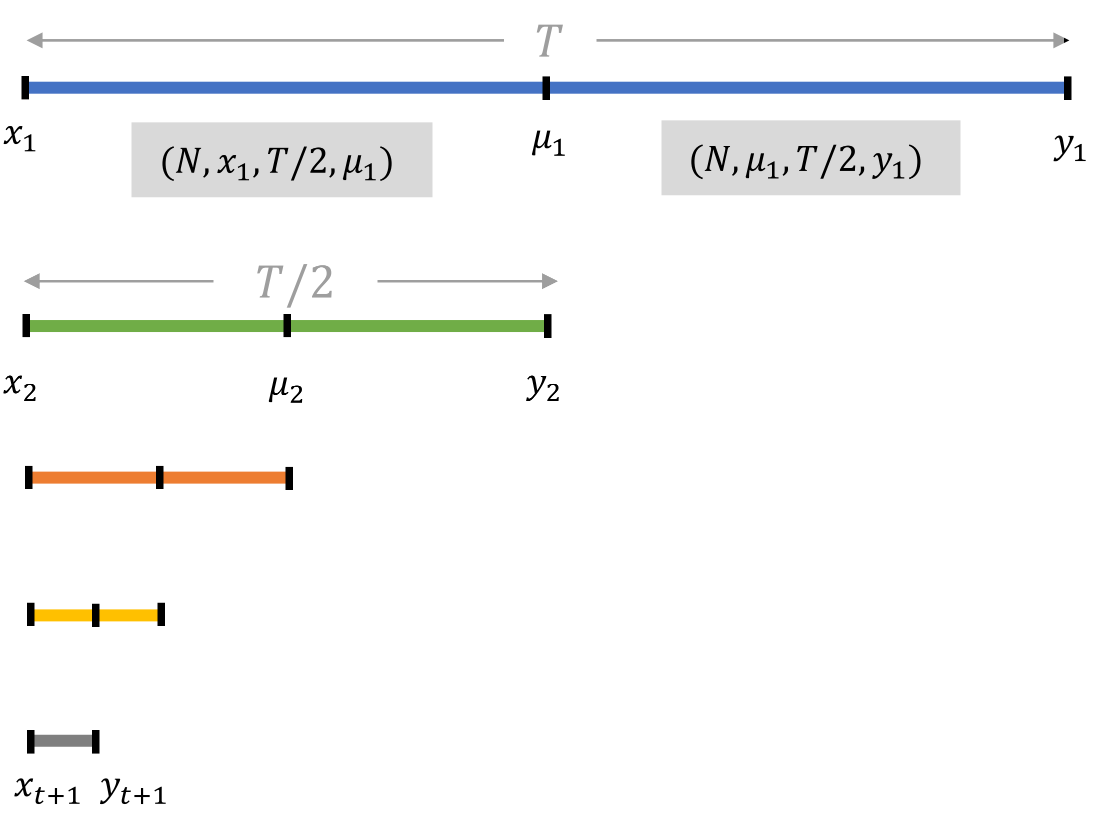

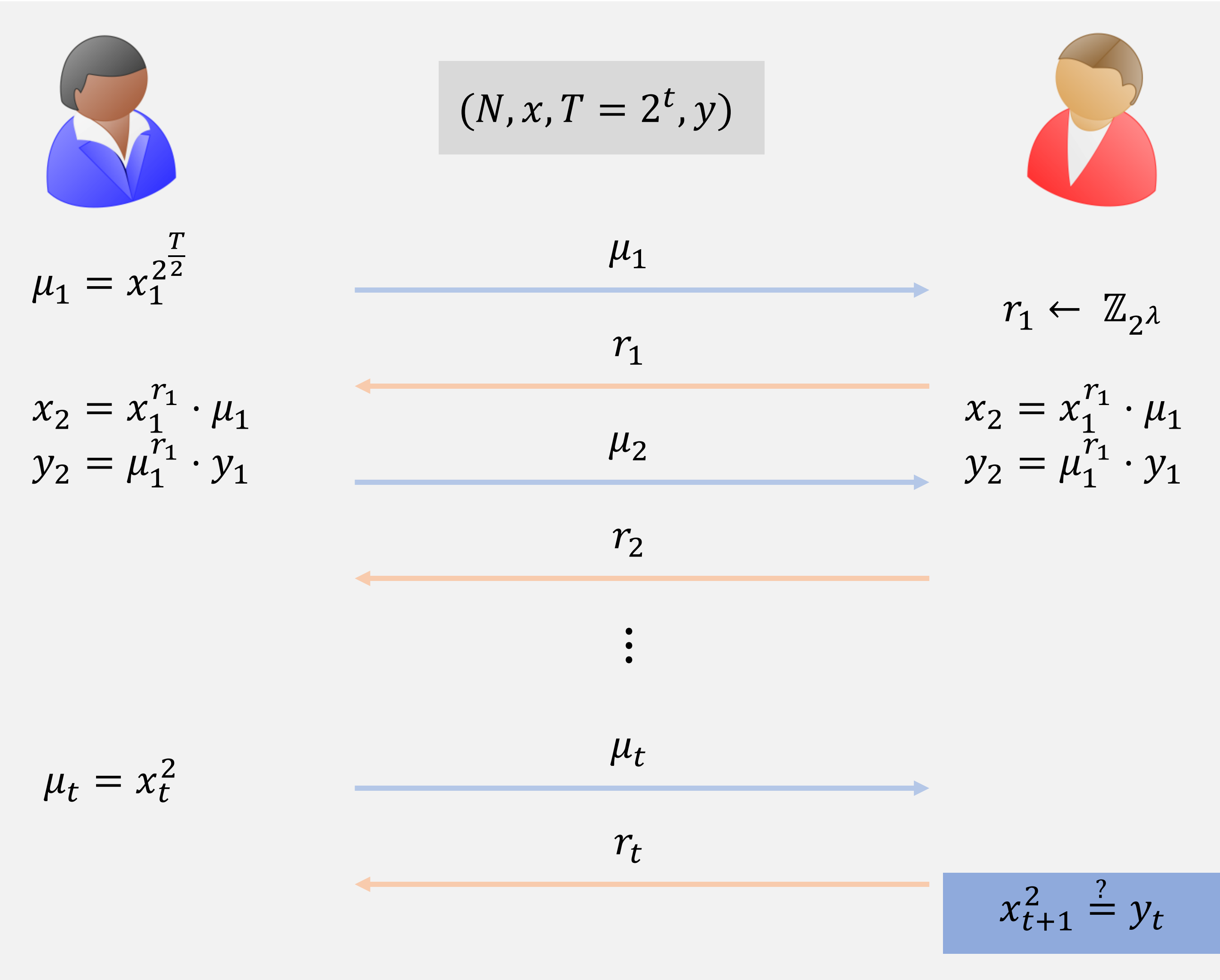

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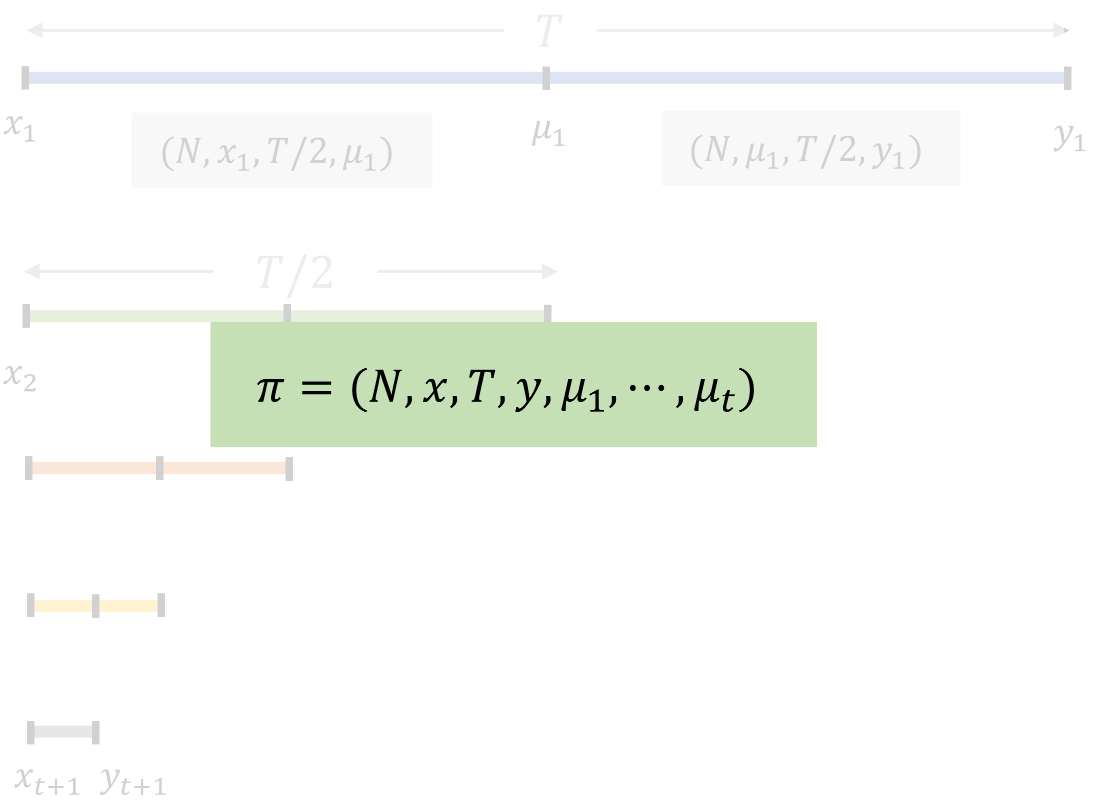

$$\pi = (N, x, T, y, \mu_1, \cdots, \mu_t)$$

$(N, x, T = 2^t, y)$

$\mu_1 = x_1^{2^{\frac{T}{2}}}$ $\xrightarrow{\mu_1}$ $r_1 \leftarrow \mathbb{Z}_{2^\lambda}$

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$y_2 = \mu_1^{r_1} \cdot y_1$

$\xleftarrow{r_2}$

$\vdots$

$\mu_t = x_t^2$ $\xrightarrow{\mu_t}$

$\xleftarrow{r_t}$

$x_{t+1}^2 \stackrel{?}{=} y_t$

Costs of the Pietrzak VDF

Time to compute y + proof

$O(T)$

Size of the proof

$\pi = (N, x, T, y, \mu_1, \cdots, \mu_t)$

$O(\text{polylog}(T))$

Time to verify Proof

$O(\log(T))$ exponentiations - $O(\text{polylog}(T))$

Continuous VDF (cVDF)

[Ephraim-Freitag-Komargodski-Pass’20]

Continuous VDF (cVDF)

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$5 Million prize to compute y

Continuous VDF (cVDF)

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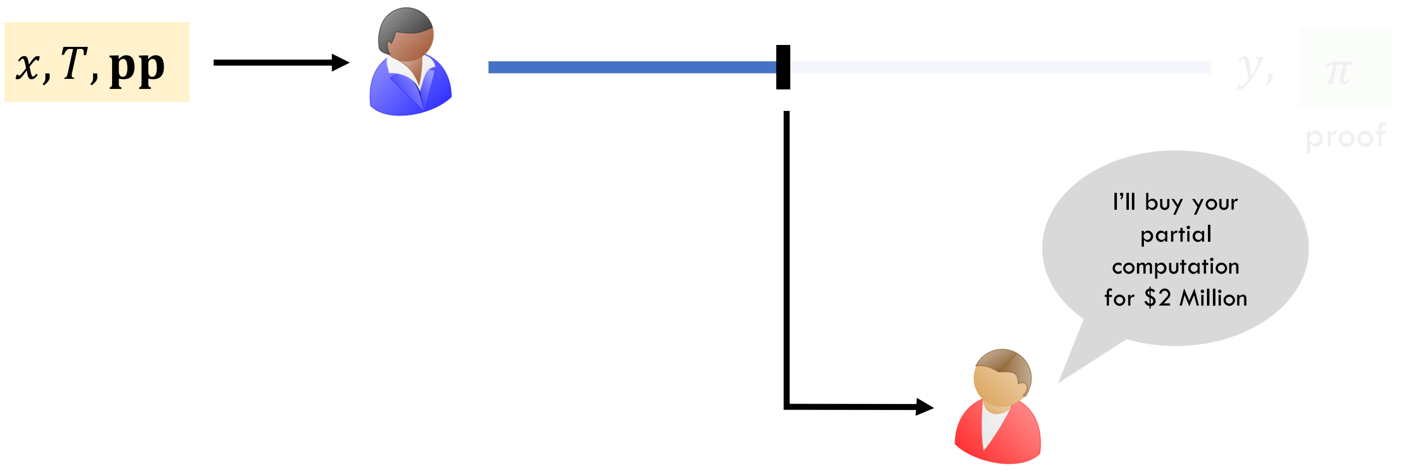

Continuous VDF (cVDF)

[Ephraim-Freitag-Komargodski-Pass'20]

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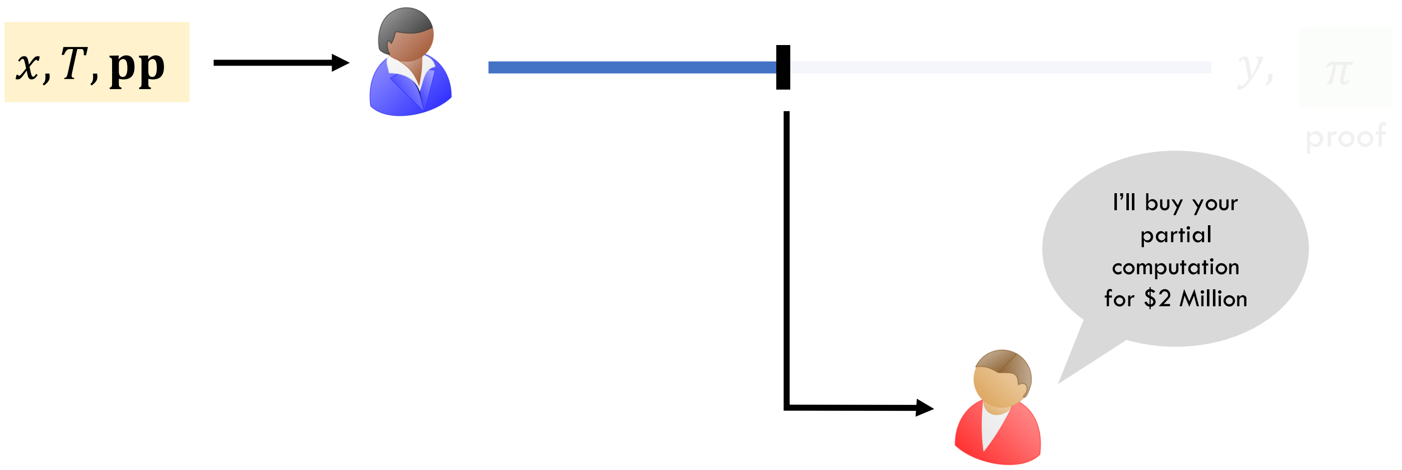


How does Alice transfer a state that Bob is able to verify?

Continuously Verifiable Squaring

$x \xrightarrow{1} x^{2^1}$ $x^{2^1} \xrightarrow{1} x^{2^2}$ $x^{2^2} \xrightarrow{1} x^{2^3}$ $x^{2^2} \xrightarrow{1} x^{2^4}$ $x^{2^4} \xrightarrow{1} x^{2^5}$ $x^{2^5} \xrightarrow{1} x^{2^6}$ $x^{2^6} \xrightarrow{1} x^{2^7}$ $x^{2^7} \xrightarrow{1} x^{2^8}$

Continuously Verifiable Squaring

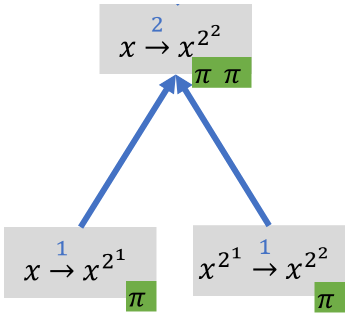
$x \xrightarrow{1} x^{2^1}$ π $\quad$ $x^{2^1} \xrightarrow{1} x^{2^2}$ π $\quad$ $x^{2^2} \xrightarrow{1} x^{2^3}$ π $\quad$ $x^{2^2} \xrightarrow{1} x^{2^4}$ π $\quad$ $x^{2^4} \xrightarrow{1} x^{2^5}$ π $\quad$ $x^{2^5} \xrightarrow{1} x^{2^6}$ π $\quad$ $x^{2^6} \xrightarrow{1} x^{2^7}$ π $\quad$ $x^{2^7} \xrightarrow{1} x^{2^8}$ π

Continuously Verifiable Squaring

$x \xrightarrow{1} x^{2^1}$ π

$x^{2^1} \xrightarrow{1} x^{2^2}$ π

Continuously Verifiable Squaring



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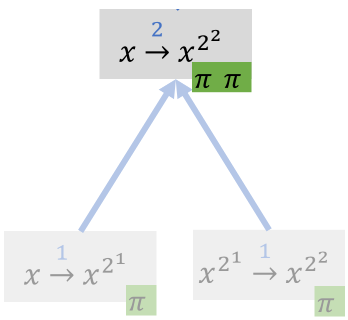

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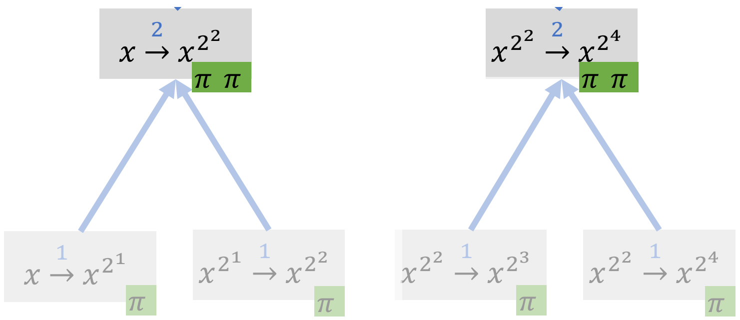

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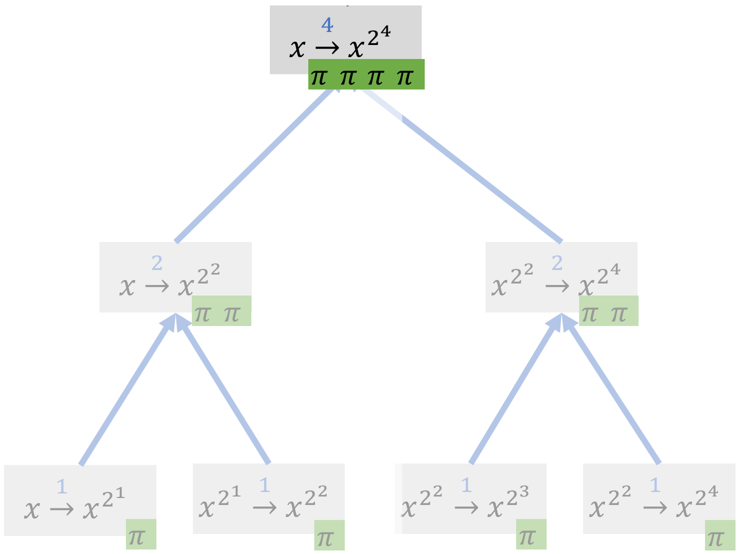

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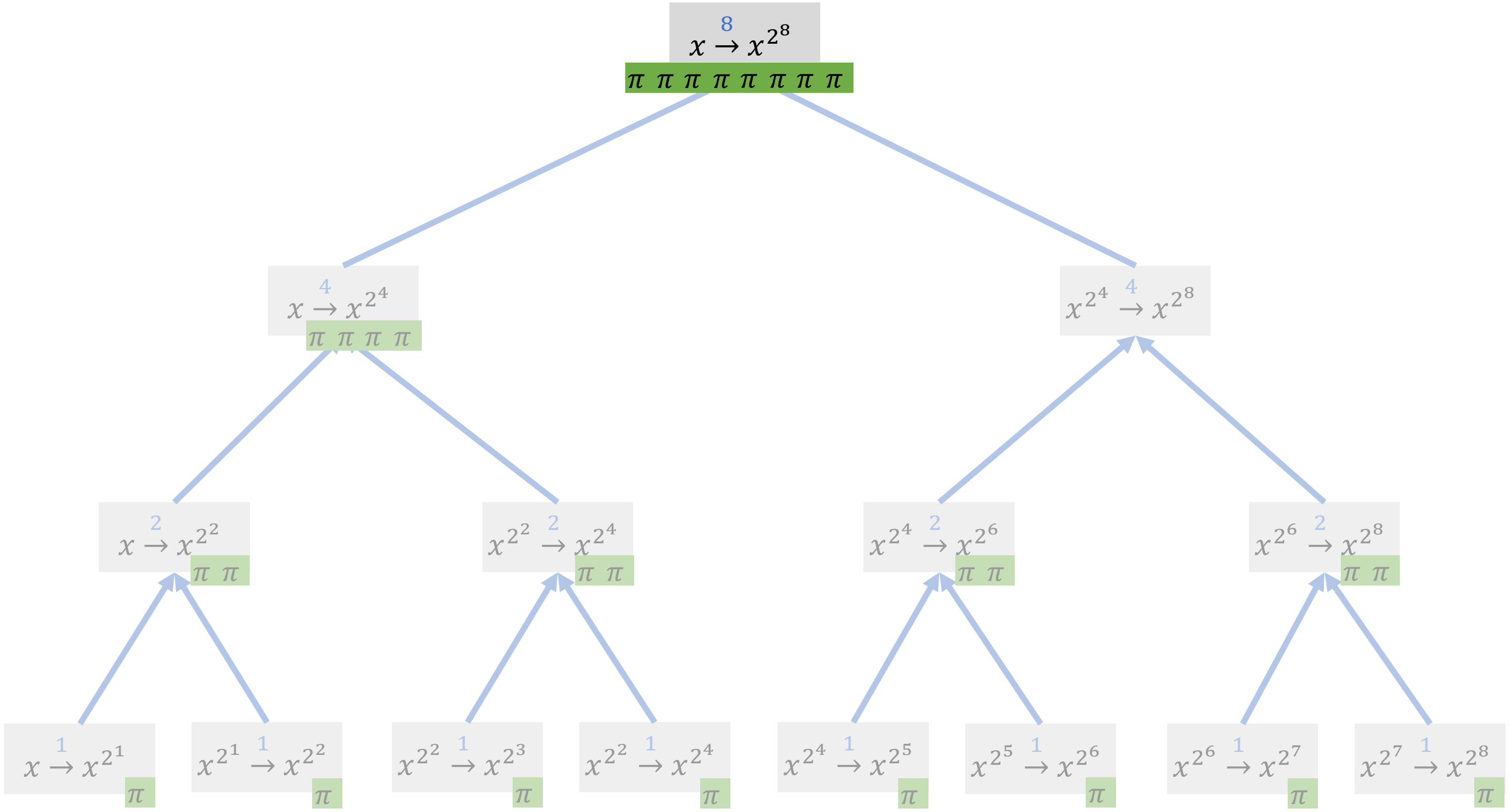

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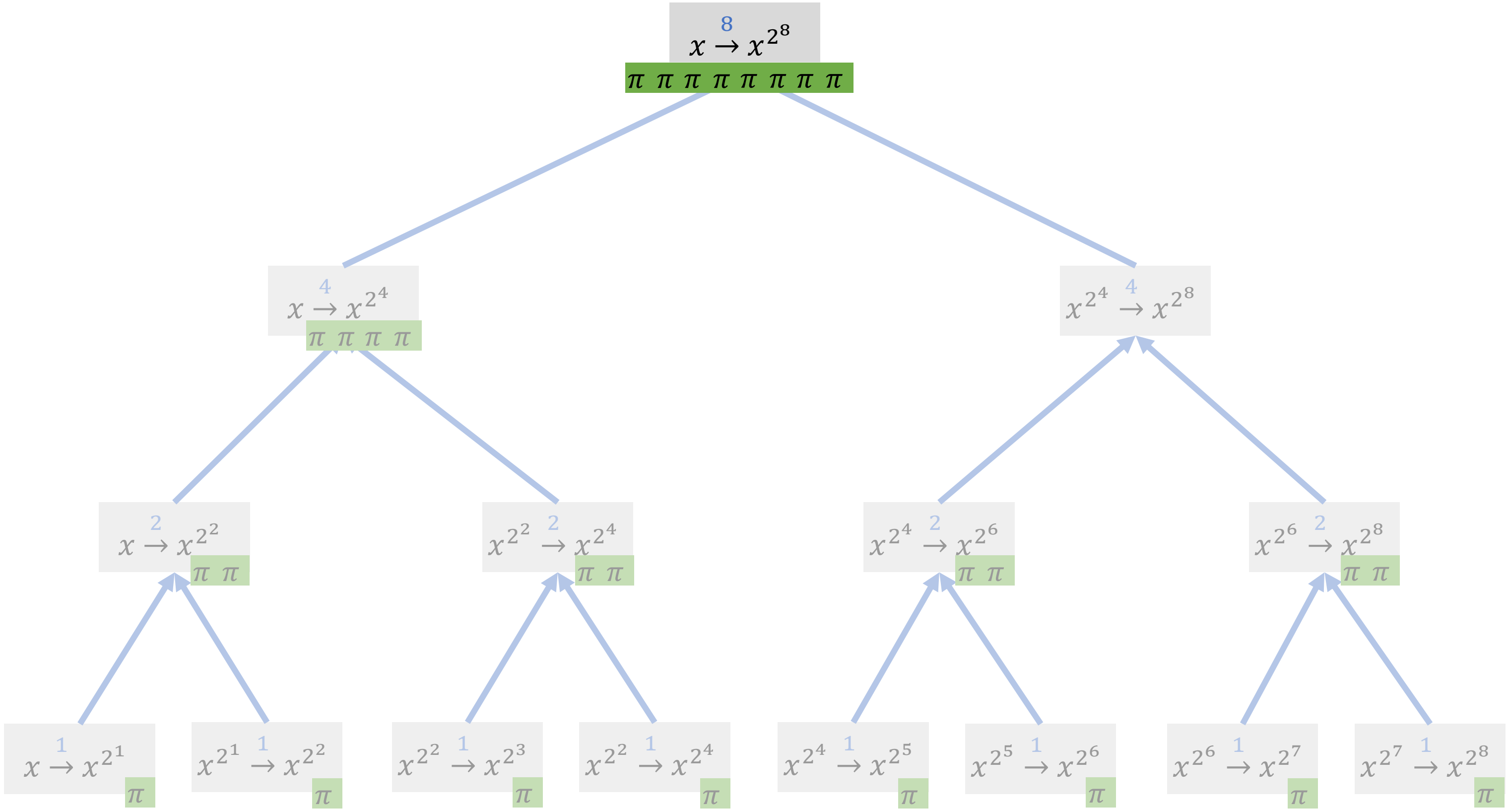


For T squarings, number of proofs is $O(T)$!

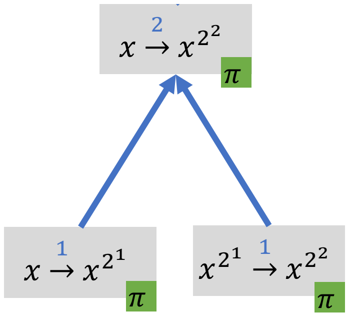
Merge Proofs [Valiant'06]

$x \xrightarrow{1} x^{2^1}$ π

$x^{2^1} \xrightarrow{1} x^{2^2}$ π

Merge Proofs [Valiant'06]

Merge proofs into a single proof in poly(λ) time



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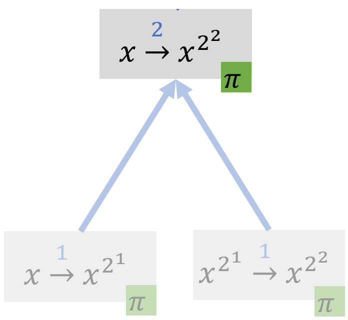

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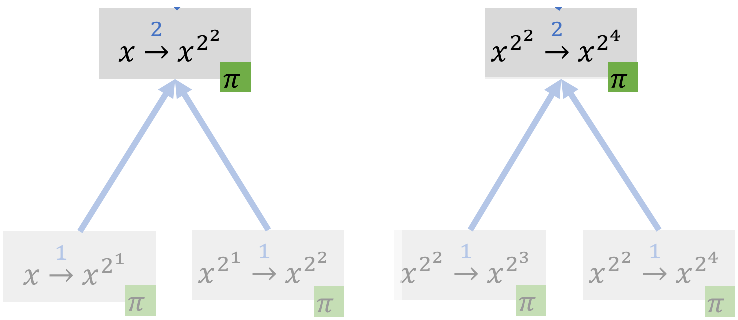

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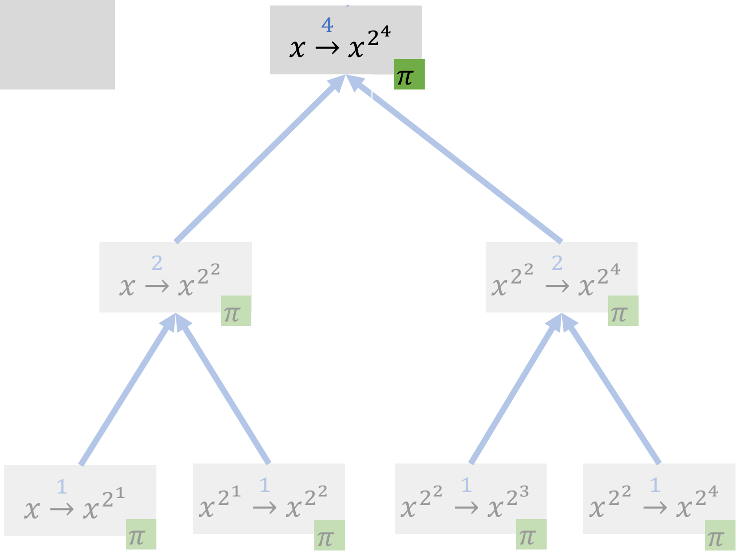

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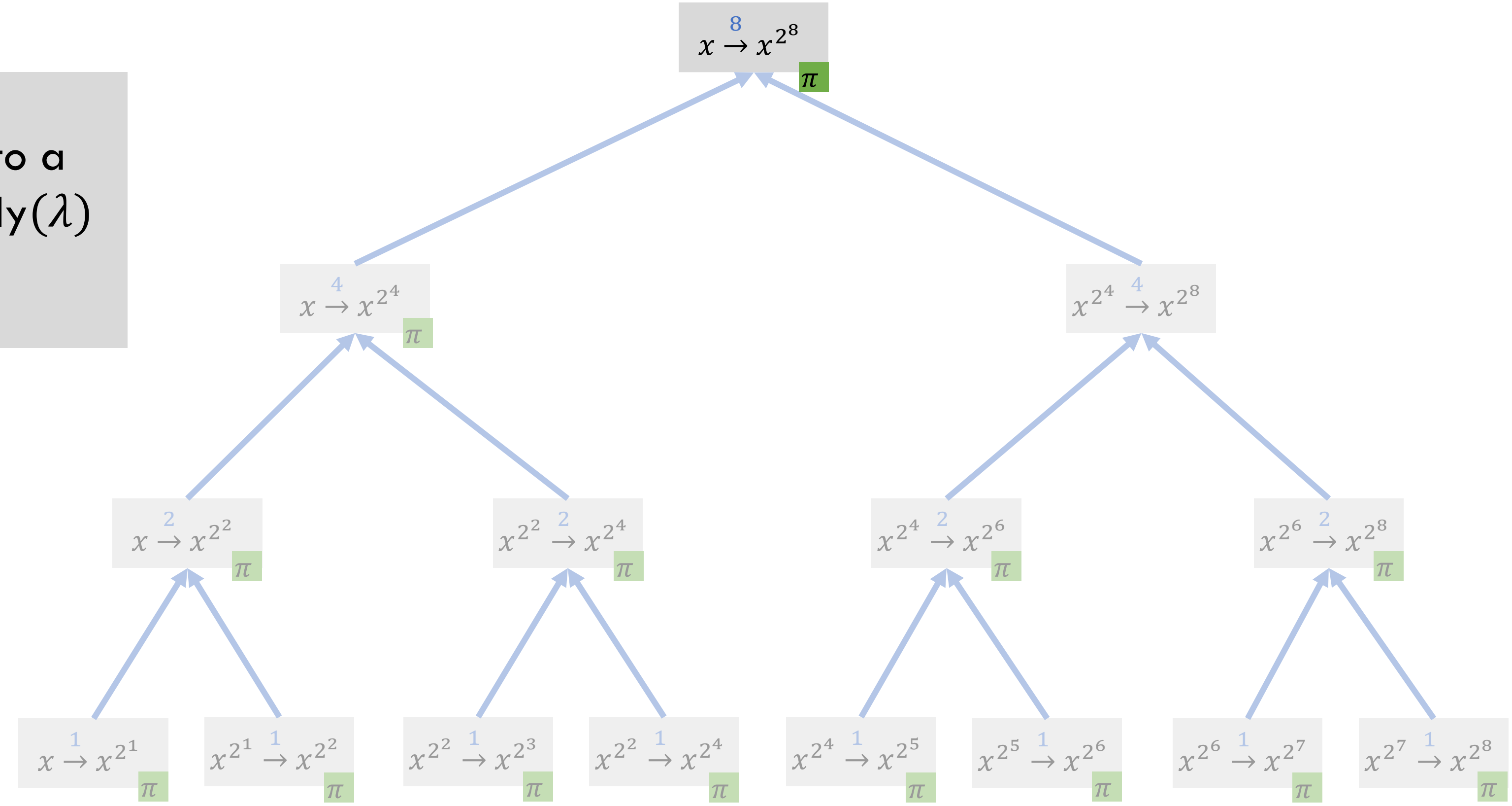

Merge Proofs [Valiant'06]

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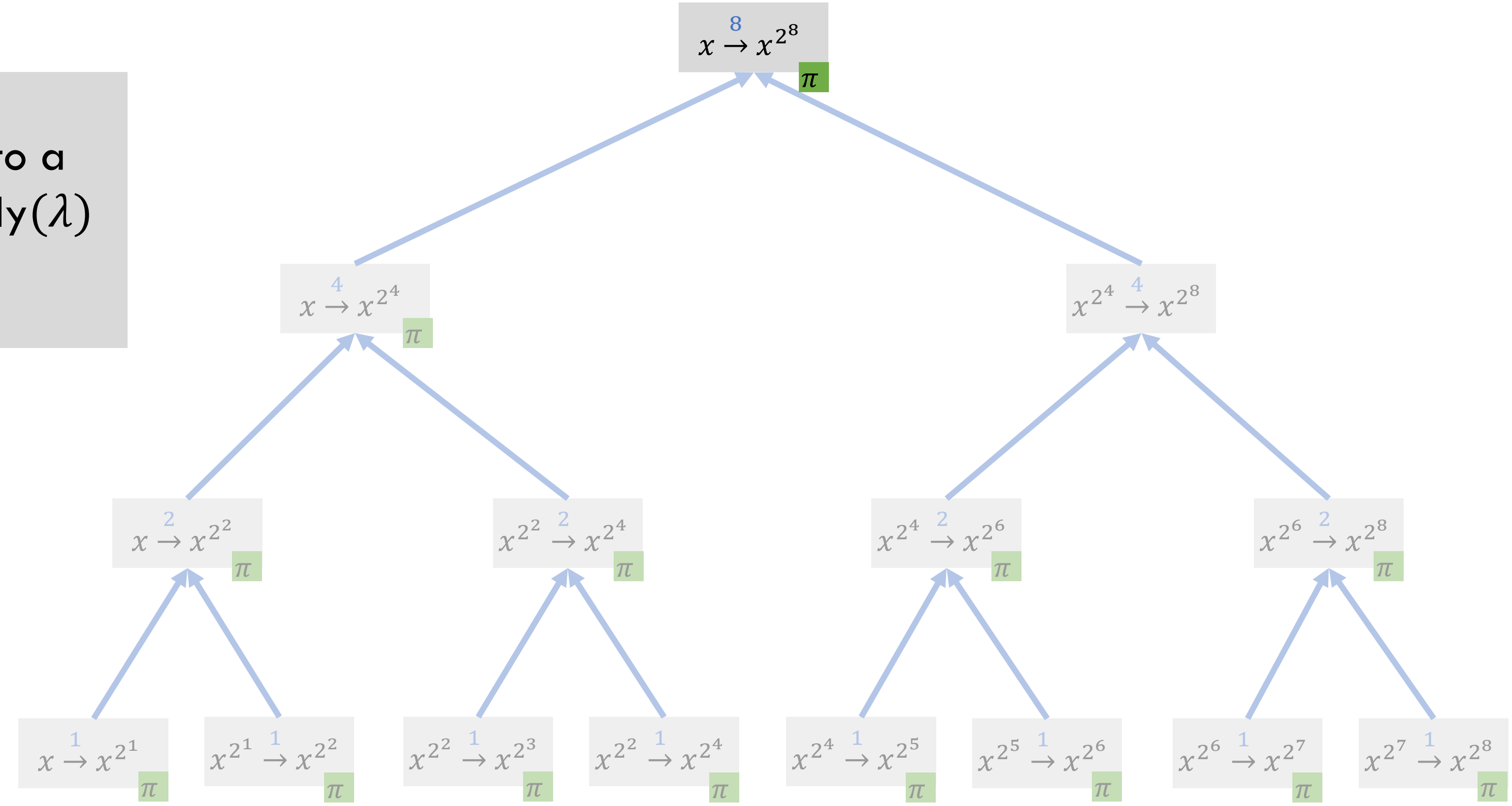
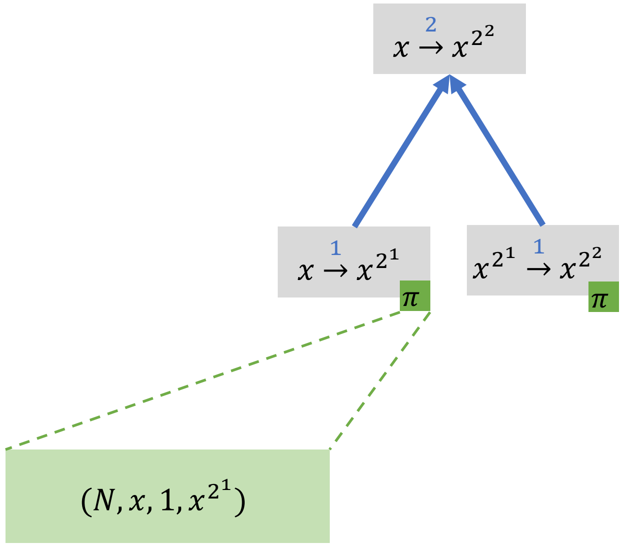


For T squarings, number of proofs is $O(1)$!

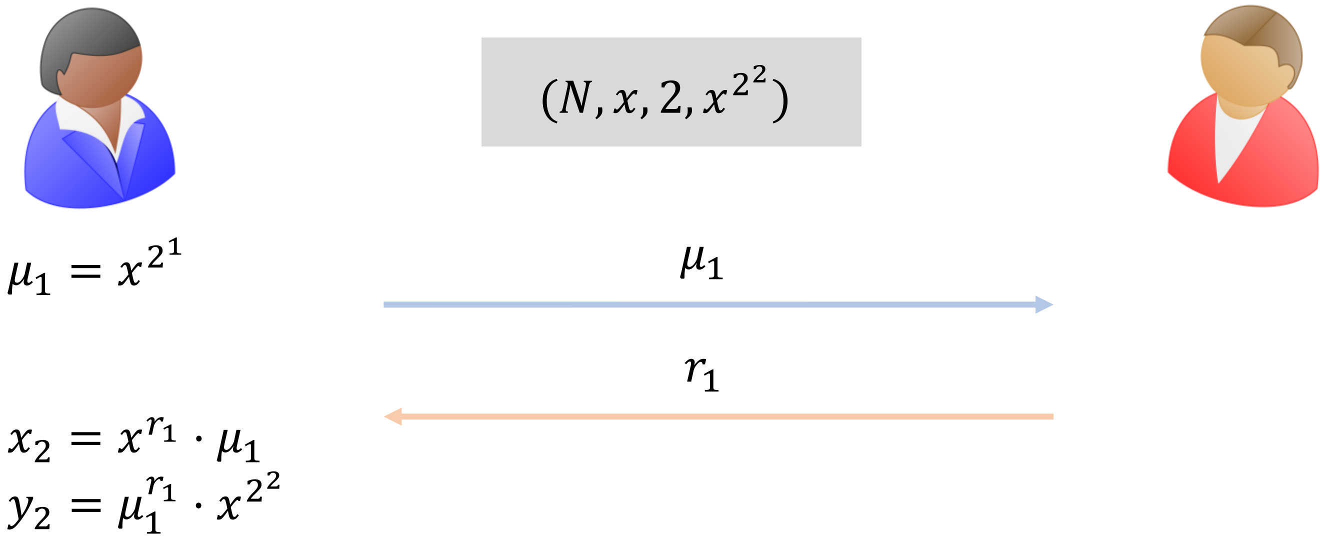
Non-standard assumptions.

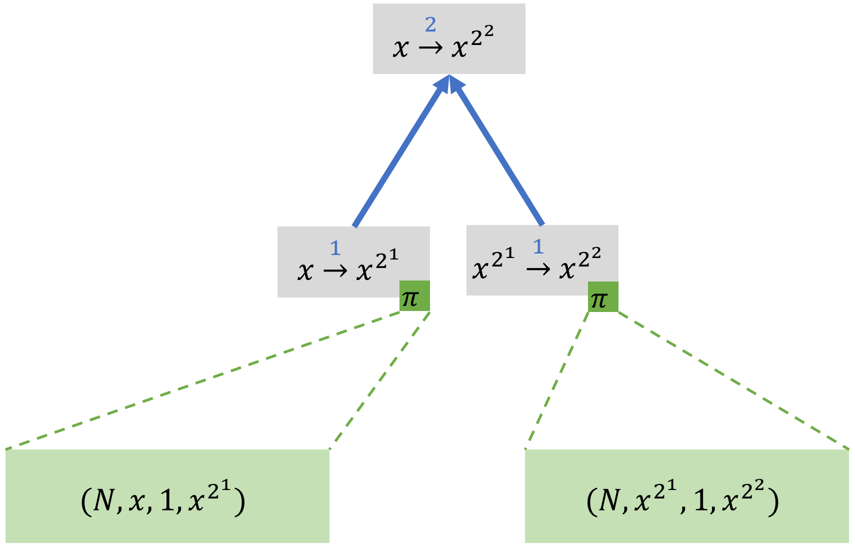
Incremental Merge

[C-Hubáček-Kamth-Pietrzak-Rosen-Rothblum'19]



Incremental Merge





$$\pi = (N, x, 2, x^{2^2}, \mu_1)$$

Incremental Merge

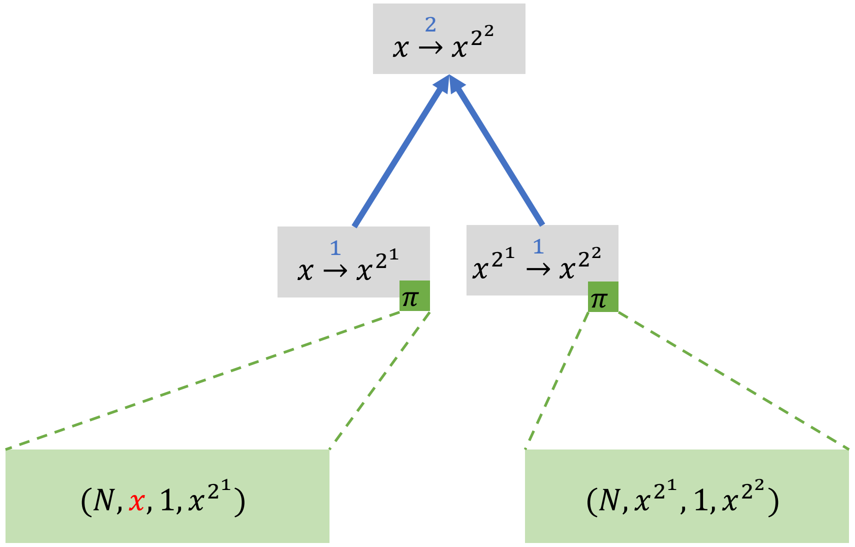
$$(N, x, 2, x^{2^2})$$

$\mu_1 = x^{2^1}$

$\xrightarrow{\mu_1}$

$\xleftarrow{r_1}$

$$x_2 = x^{r_1} \cdot \mu_1$$
$$y_2 = \mu_1^{r_1} \cdot x^{2^2}$$



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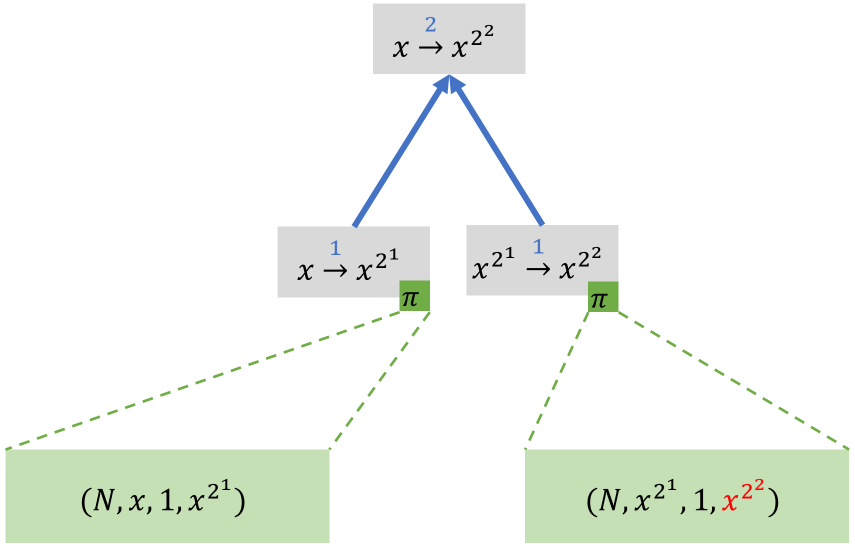
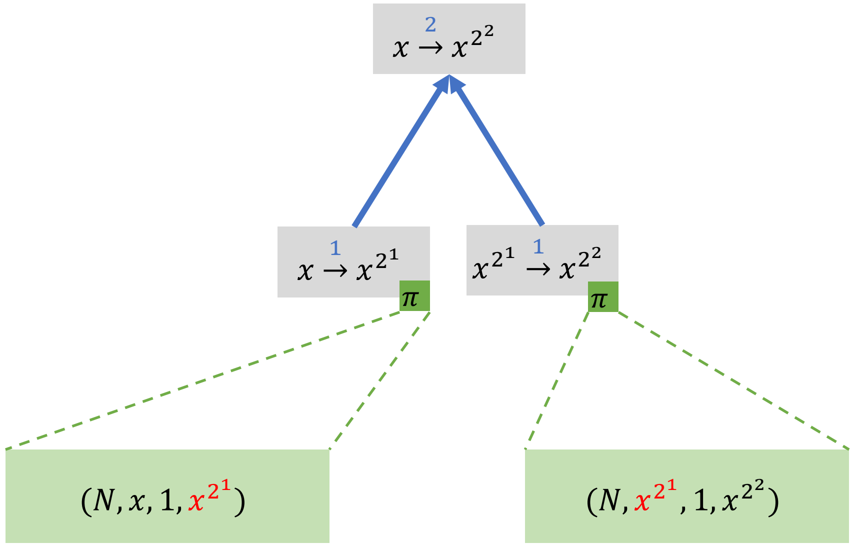


Incremental Merge



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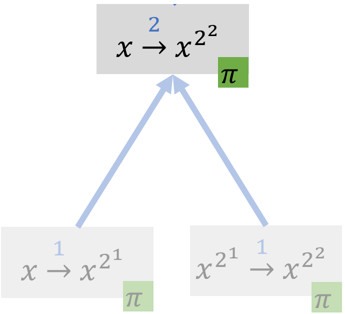
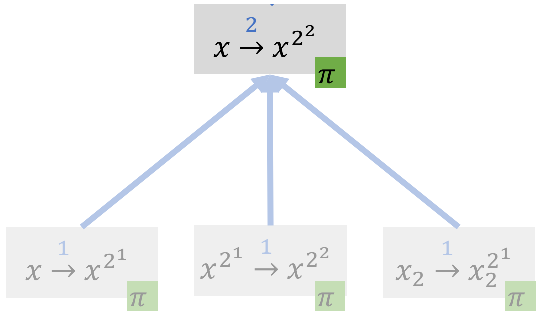


Incremental Merge



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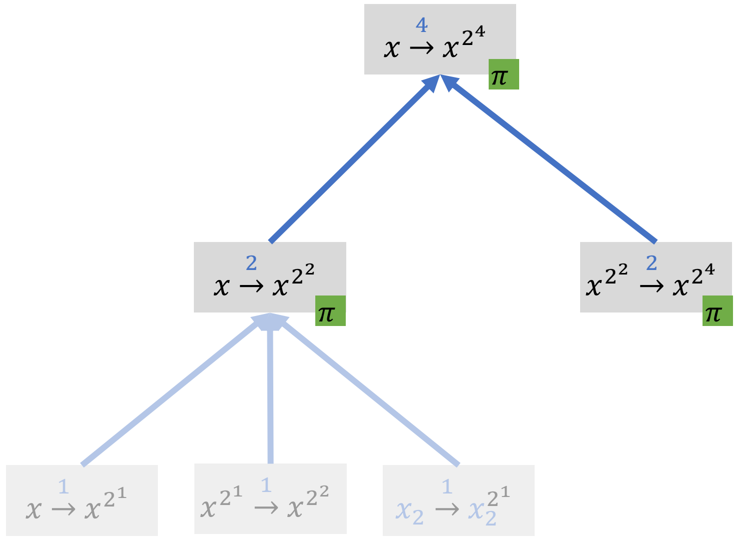
Incremental Merge



$(N, x, 4, x^{2^4})$

$\mu_1 = x^{2^2}$ $\quad \xrightarrow{\mu_1}$

$\xleftarrow{r_1}$

$x_2 = x^{r_1} \cdot \mu_1$

$y_2 = \mu_1^{r_1} \cdot x^{2^4}$

$\mu_2 = x_2^{2^1}$ $\quad \xrightarrow{\mu_2}$

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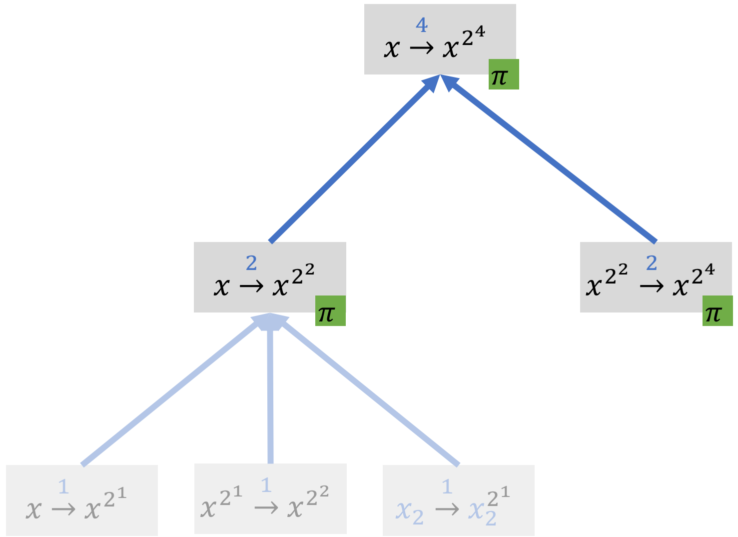
Incremental Merge



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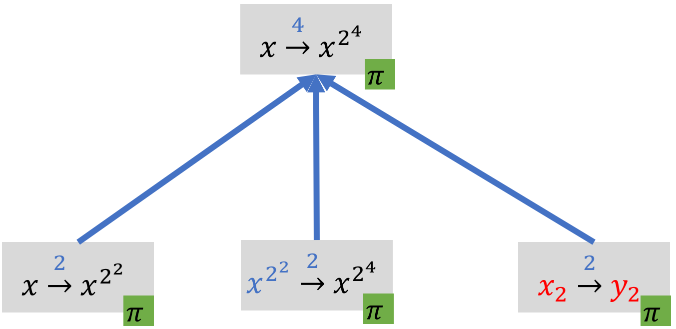

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r_1

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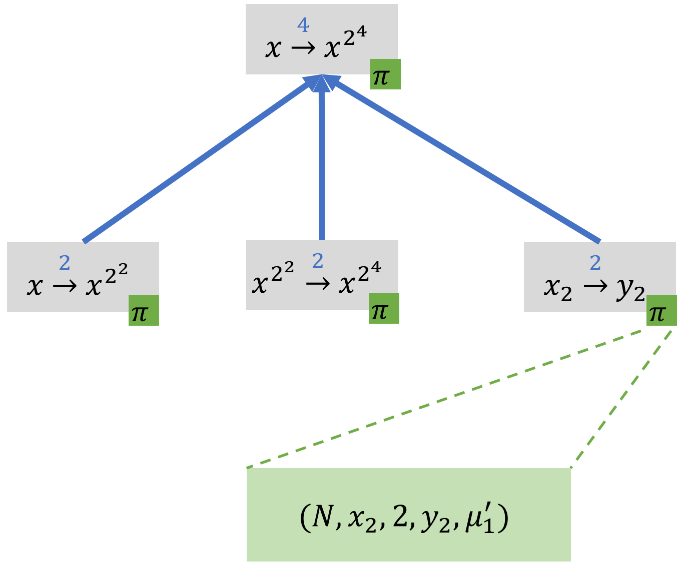

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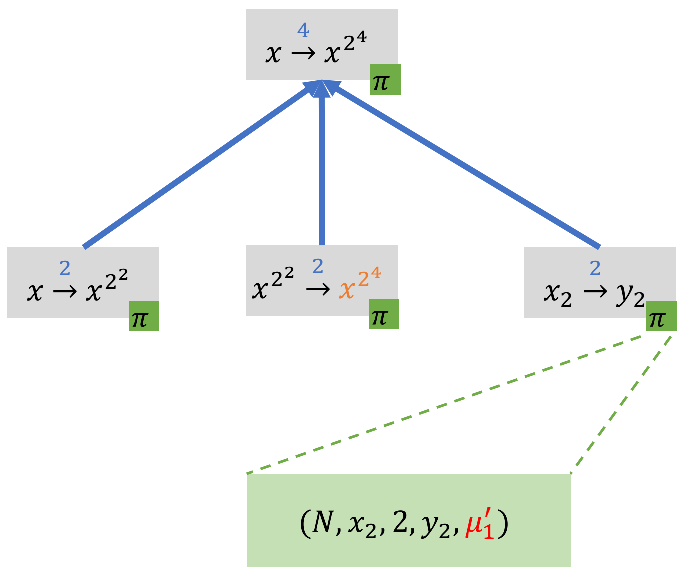
Incremental Merge



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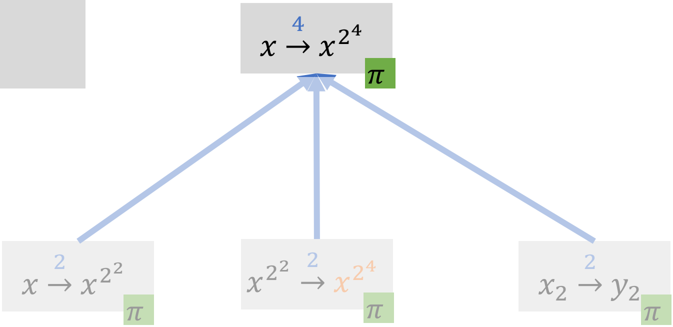
Incremental Merge

Merge two proof for $T/2$ squarings in $O(T/2)$ time.



$(N, x, 4, x^{2^2})$

$\mu_1 = x^{2^2}$

μ_1

r_1

$x_2 = x^{r_1} \cdot \mu_1$

$y_2 = \mu_1^{r_1} \cdot x^{2^4}$

$\mu_2 = x_2^{2^1}$

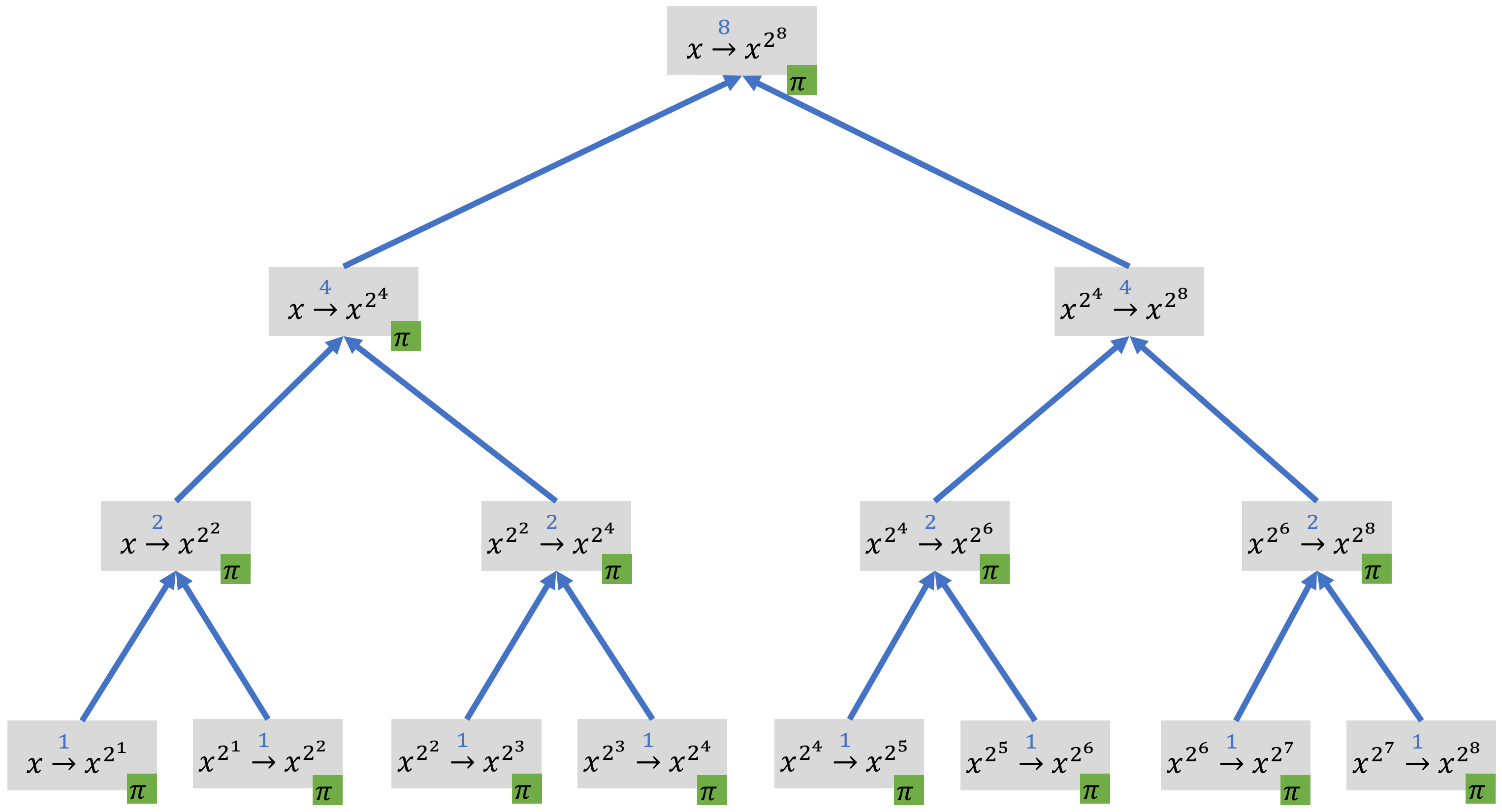
μ_2

r_2

$x_3 = x_2^{r_2} \cdot \mu_2$

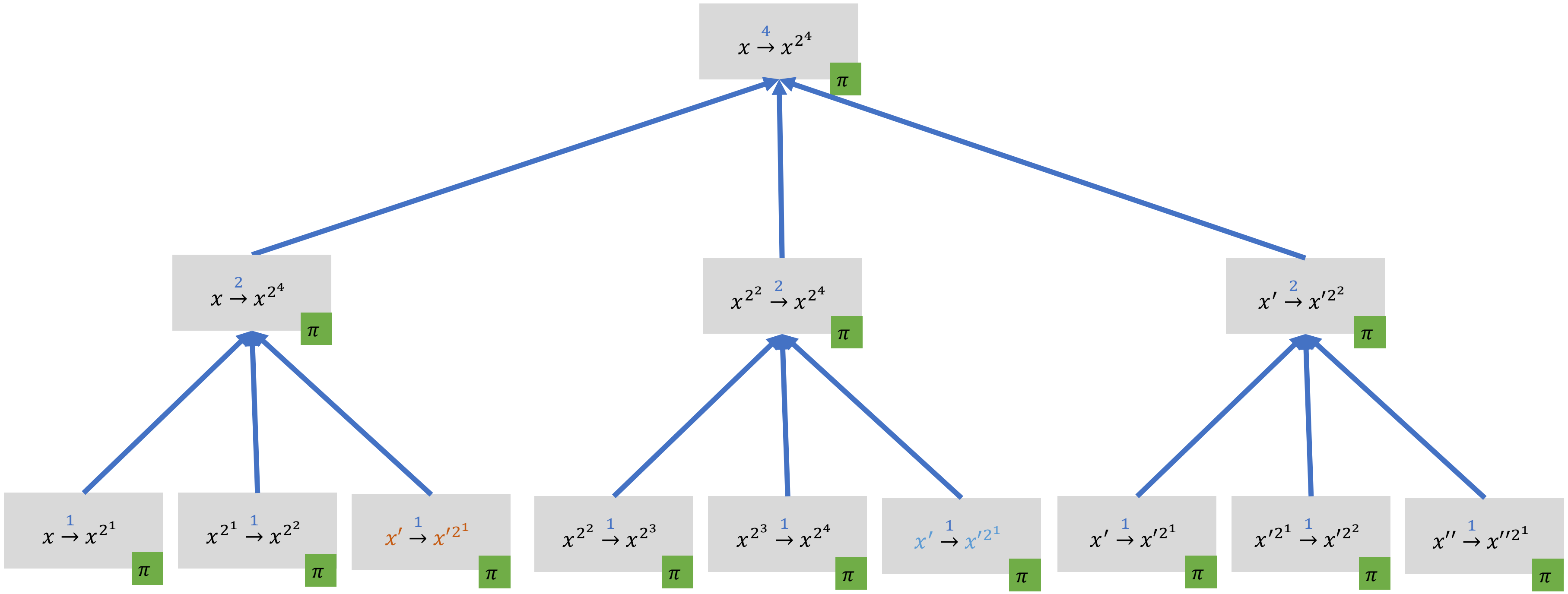
$y_3 = \mu_2^{r_2} \cdot y_2$

$\pi = (N, x, 4, x^{2^4}, \mu_1, \mu_2)$



$x \xrightarrow{8} x^{2^8}$ π
$x \xrightarrow{4} x^{2^4}$ π
$x^{2^4} \xrightarrow{4} x^{2^8}$
$x \xrightarrow{2} x^{2^2}$ π
$x^{2^2} \xrightarrow{2} x^{2^4}$ π
$x^{2^4} \xrightarrow{2} x^{2^6}$ π
$x^{2^6} \xrightarrow{2} x^{2^8}$ π
$x \xrightarrow{1} x^{2^1}$ π
$x^{2^1} \xrightarrow{1} x^{2^2}$ π
$x^{2^2} \xrightarrow{1} x^{2^3}$ π
$x^{2^3} \xrightarrow{1} x^{2^4}$ π
$x^{2^4} \xrightarrow{1} x^{2^5}$ π
$x^{2^5} \xrightarrow{1} x^{2^6}$ π
$x^{2^6} \xrightarrow{1} x^{2^7}$ π
$x^{2^7} \xrightarrow{1} x^{2^8}$ π

Internal State



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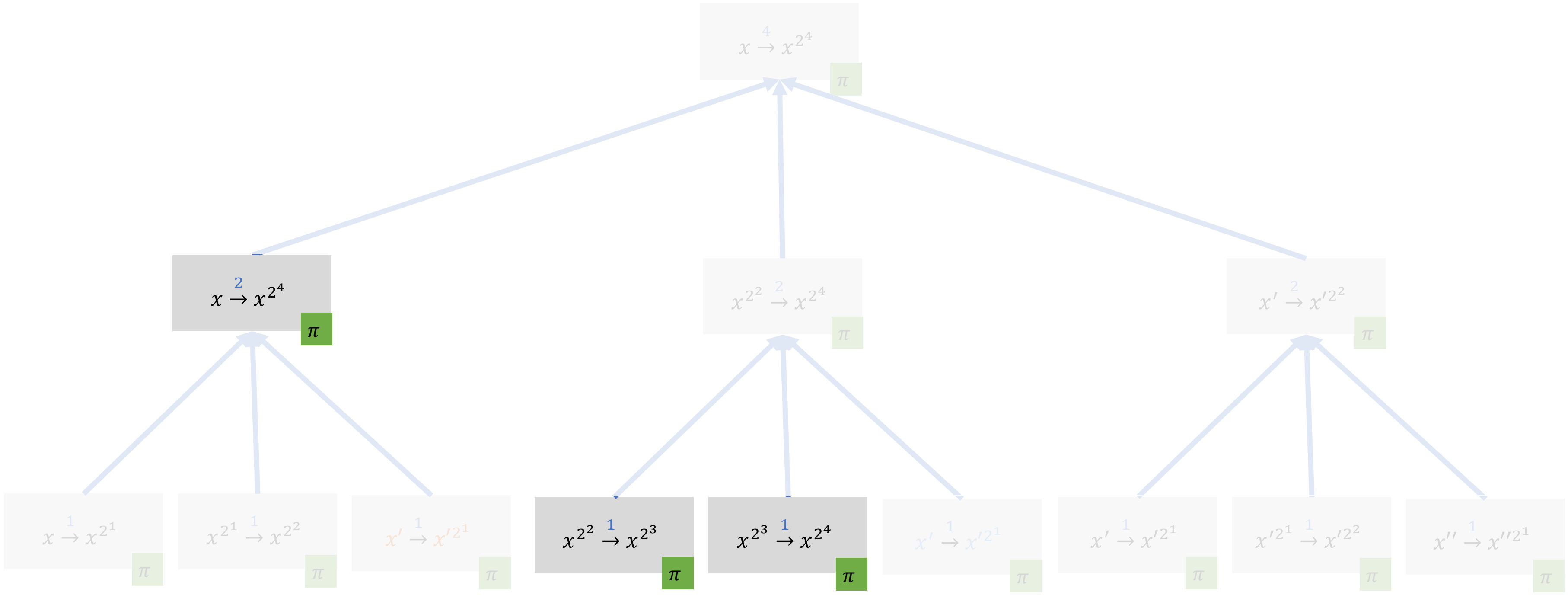

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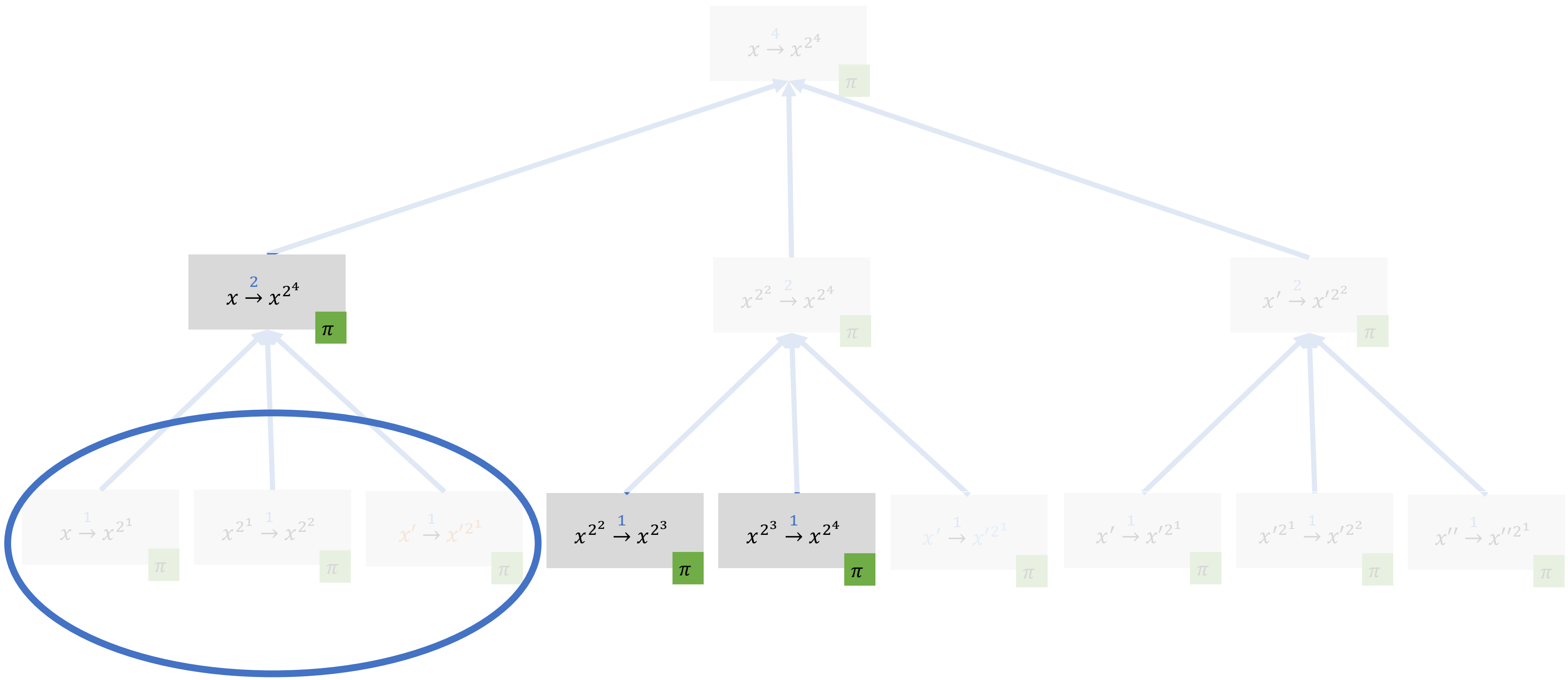
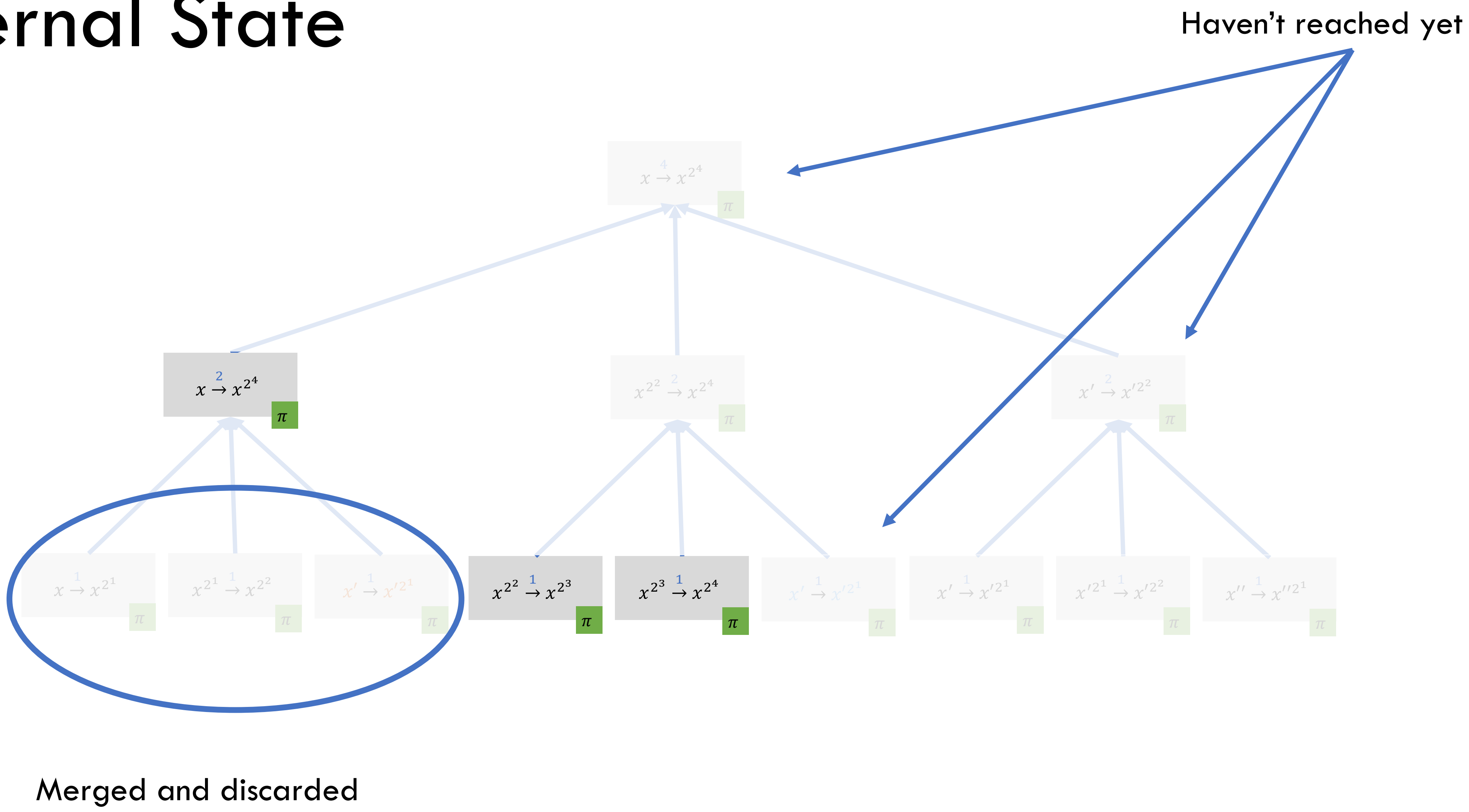


Merged and discarded

Internal State



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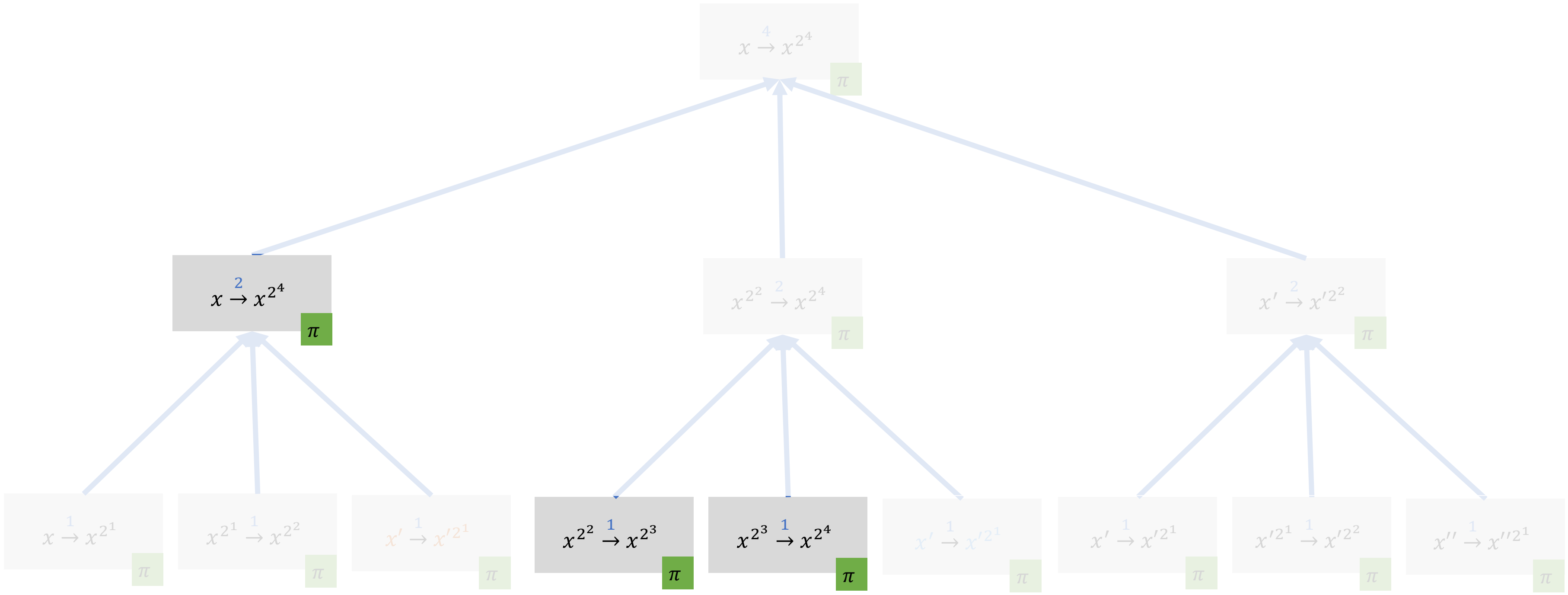

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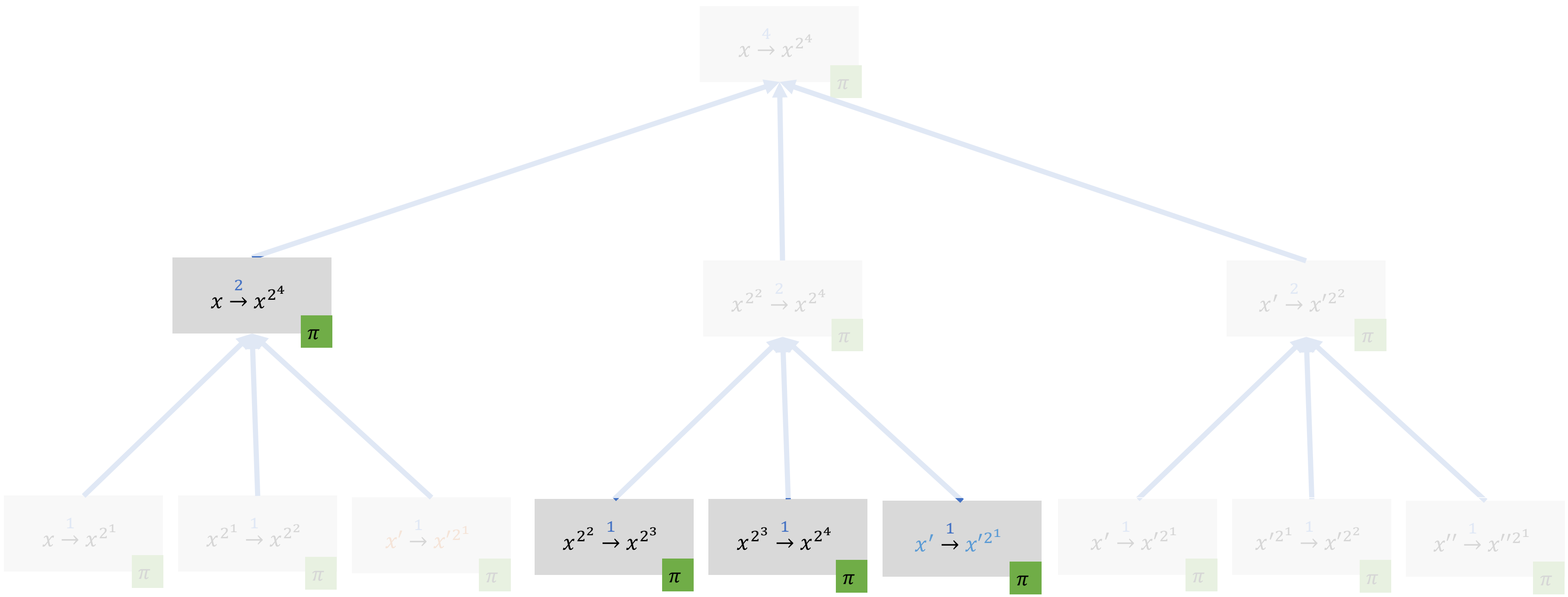

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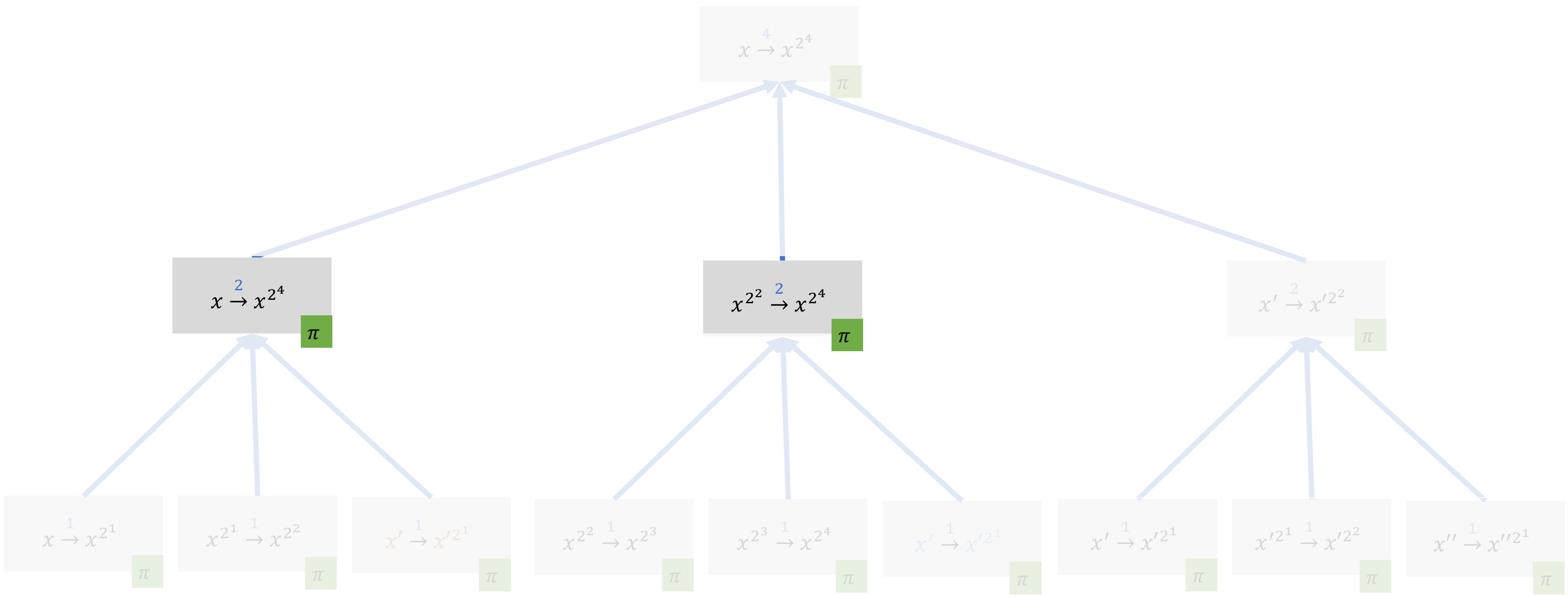

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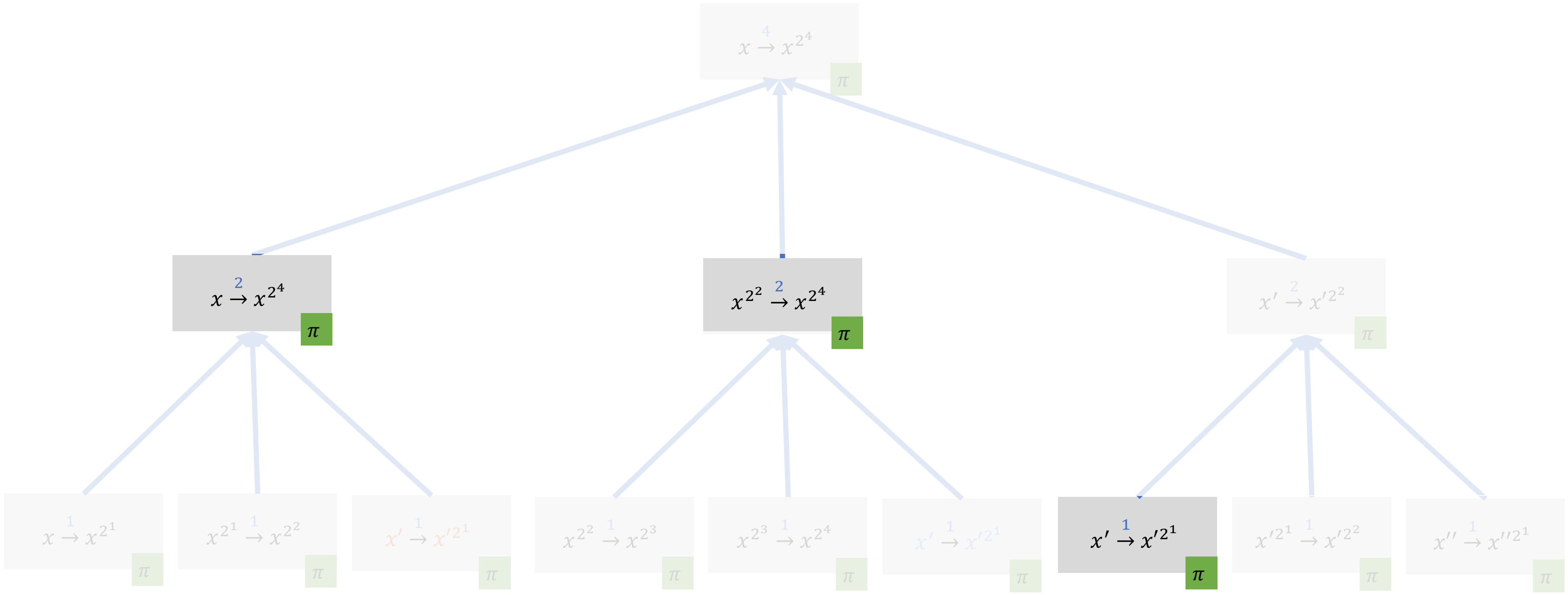
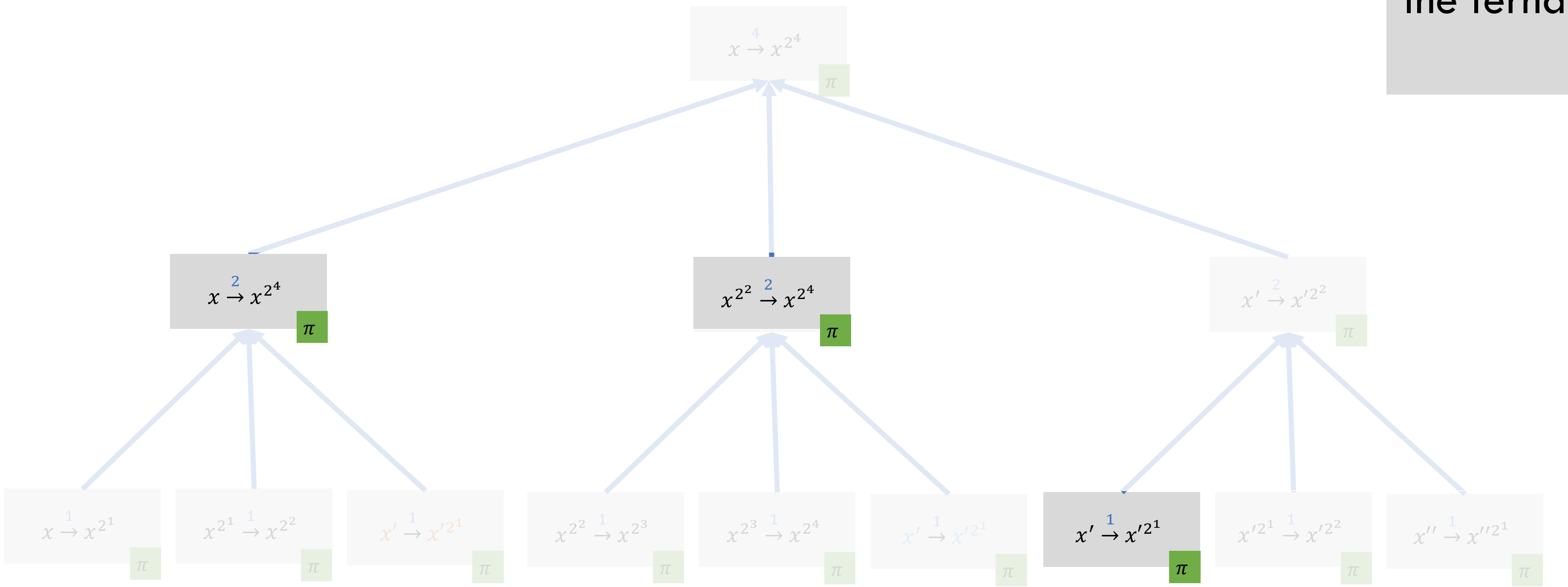


Internal State

Depth first traversal of the ternary tree



Verifying i-th state:

1. Determine which nodes are active in i-th step of depth first traversal.
2. Verify proofs in each active node.

Putting it together: cVDF

Compute $x \xrightarrow{T} x^{2^T}$ in a continuous verifiable manner

Compute root of ternary tree

Prover cost

$$P(T) = 3P(T/2)$$

Proof size

$$O(\text{polylog}(T))$$

Part 2: Nash Equilibrium

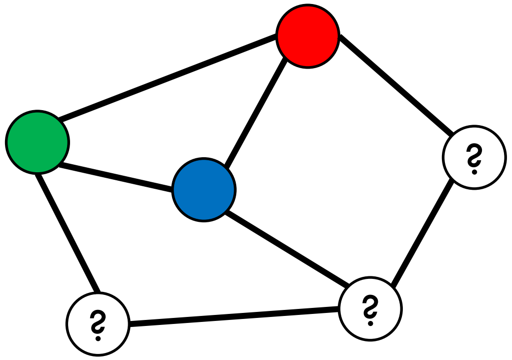
Sink of Verifiable Line (SVL)

Game Theory and Nash Equilibrium

	Left	Right
Left	1 \ -1	-1\ 1
Right	-1 \ 1	1 \ -1

[Nash'51]: A (mixed) equilibrium always exists

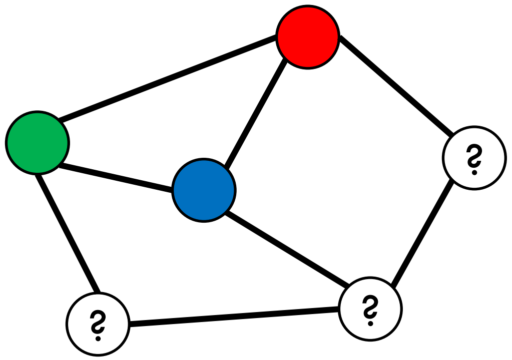
How hard is finding a Nash Equilibrium?



Reduction?

	Left	Right
Left	1 \ -1	-1\ 1
Right	-1 \ 1	1 \ -1

How hard is finding a Nash Equilibrium?



	Left	Right
Left	1 \ -1	-1\ 1
Right	-1 \ 1	1 \ -1

Complexity of Computing a Nash Equilibrium

Computing Nash unlikely to be FNP-hard

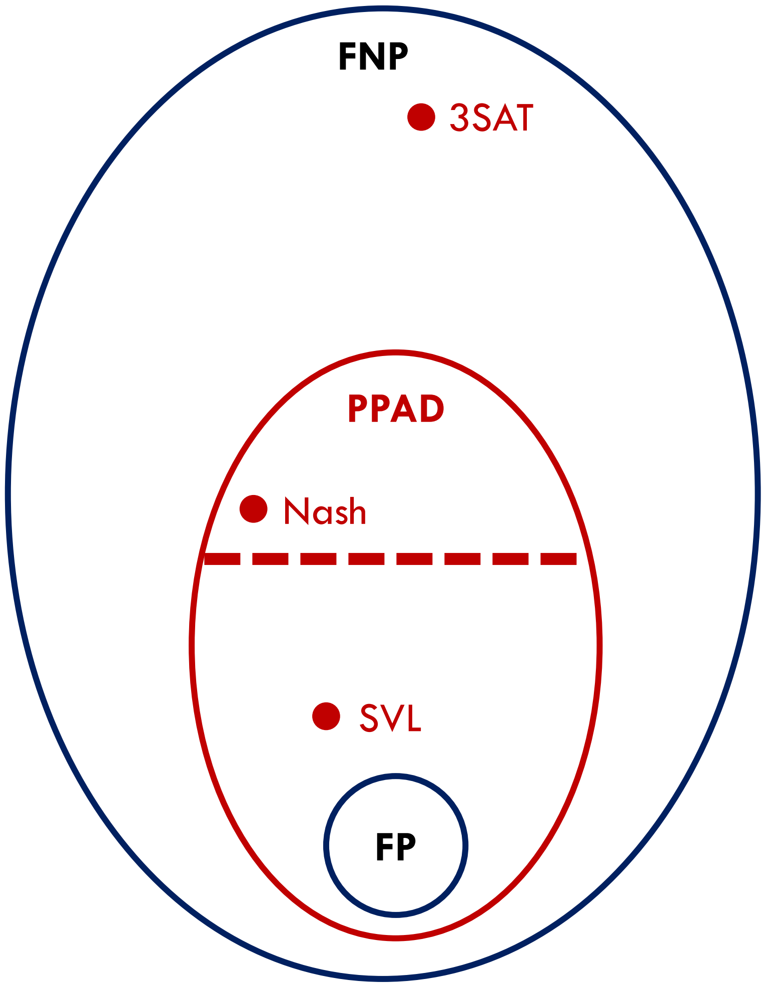
Look to Cryptography for hardness

Known from strong assumptions of **obfuscation**

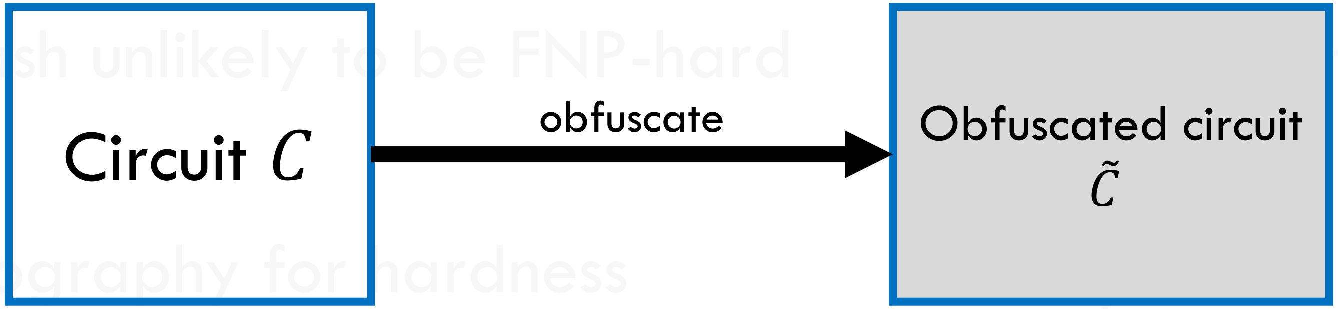
[Bitansky-Paneth-Rosen'15]

[Garg-Pandey-Srinivasan'16]

[Komorgodski-Segev'17]



Complexity of Computing a Nash Equilibrium



Can only observe input-output behavior

Known from strong assumptions of **obfuscation**

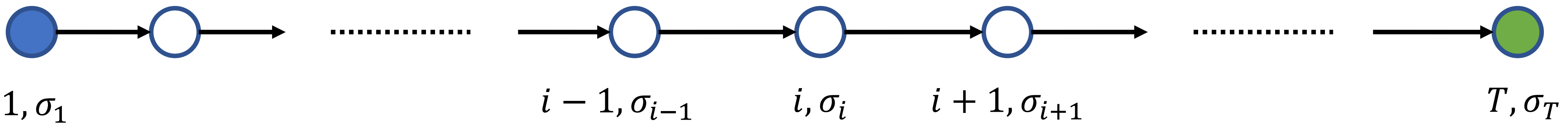
[Bitansky-Paneth-Rosen'15]

[Garg-Pandey-Srinivasan'16]

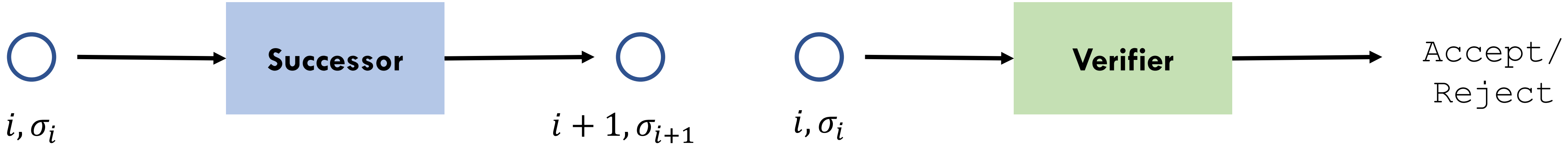
[Komorgodski-Segev'17]

Sink of Verifiable Line (SVL)

[Abbott-Kane-Valiant'04,Bitansky-Paneth Rosen'15]

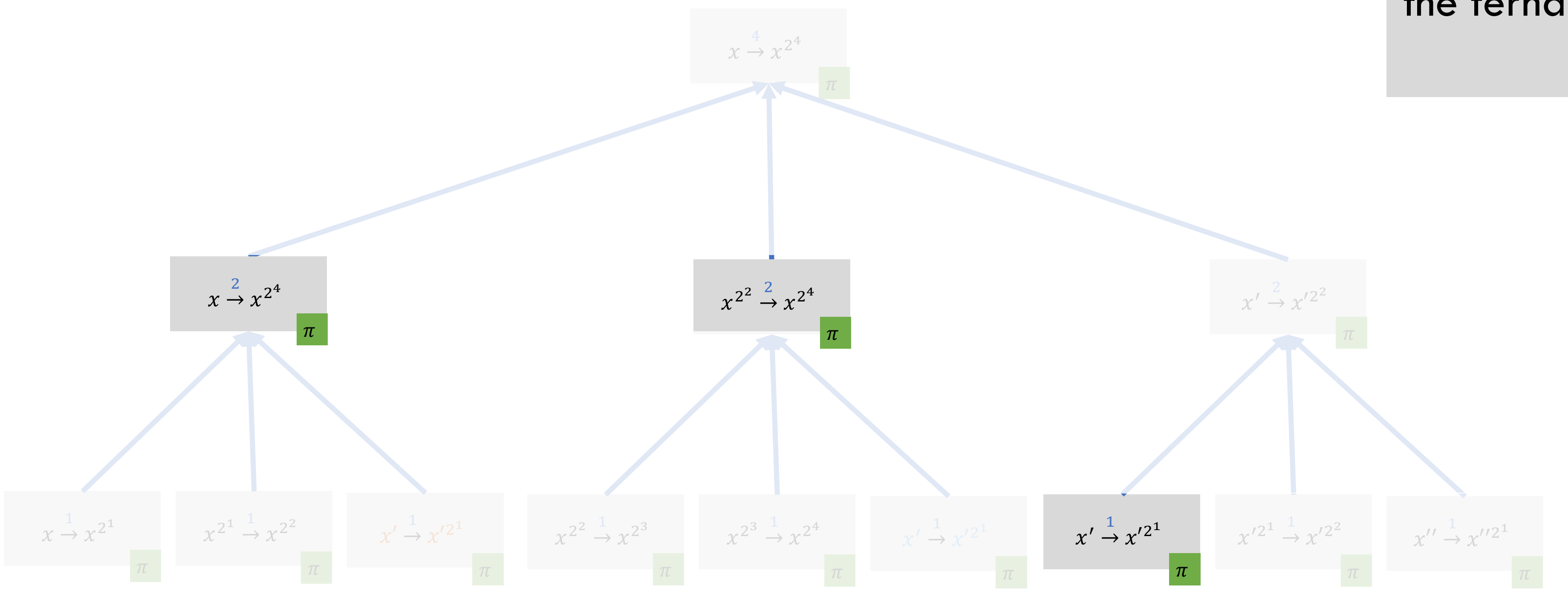


Goal: Find (T, σ_T) that verifies for an exponential T



Internal State of cVDF

Depth first traversal of the ternary tree



Verifying i-th state:

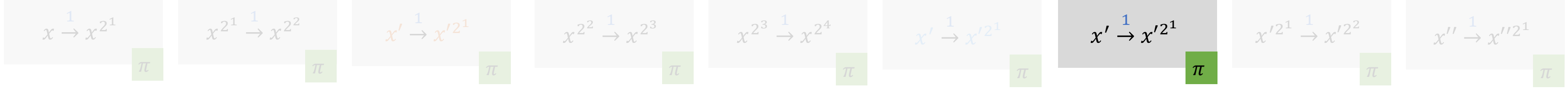
1. Determine which nodes are active in i-th step of depth first traversal.
2. Verify proofs in each active node.

Internal State of cVDF

Depth first traversal of the ternary tree

1. Set T to be exponential in λ.
2. Verification time $\mathrm{polylog}(T) = \mathrm{poly}(\lambda)$.
3. Hard for $\mathrm{poly}(\lambda)$ time adversary to compute $x^{2^T} \bmod N$.

Hard instance of SVL from hardness of repeated squaring (and Fiat-Shamir heuristic).



Verifying i-th state:

1. Determine which nodes are active in i-th step of depth first traversal.
2. Verify proofs in each active node.

Open Problems

VDFs from different assumptions?

VDFs from supersingular isogenies

Instantiating the Fiat-Shamir Heuristic in VDFs?

[Lombardi-Vaikuntanathan'19]

Other applications of continuous VDFs?

Hardness of Nash based on Factoring or other assumptions?

Thank you. Questions?

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