DIZK

A Distributed Zero Knowledge Proof System

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University of California Berkeley

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August 16, 2018

Zero Knowledge Proof

[GMR 85]

Zero Knowledge Proof

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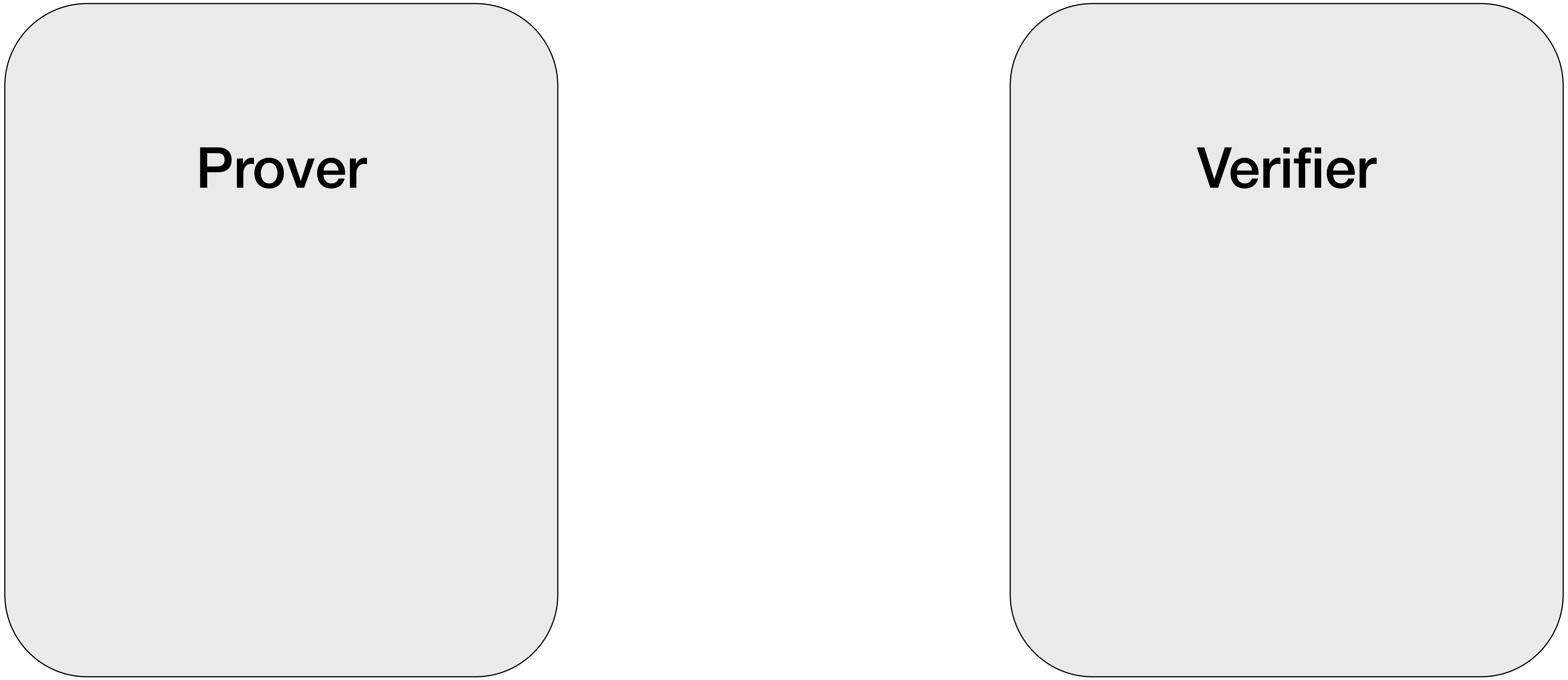

Zero Knowledge Proof

[GMR 85]

Prover

F	function
y	claimed output

Verifier

F	function
y	claimed output

Zero Knowledge Proof

[GMR 85]

I know x s.t. F(x) = y

Prover

F	function
y	claimed output
x	private input

Verifier

F	function
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Zero Knowledge Proof

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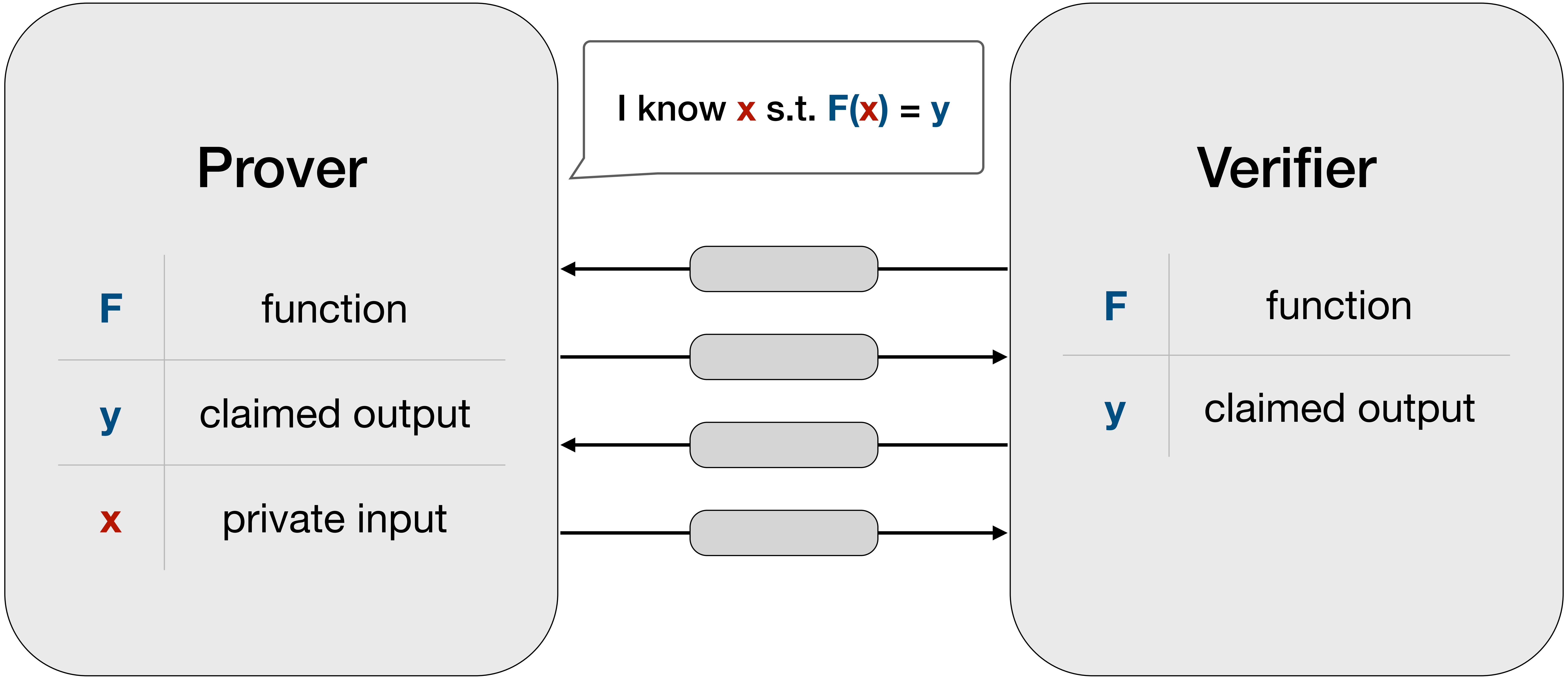
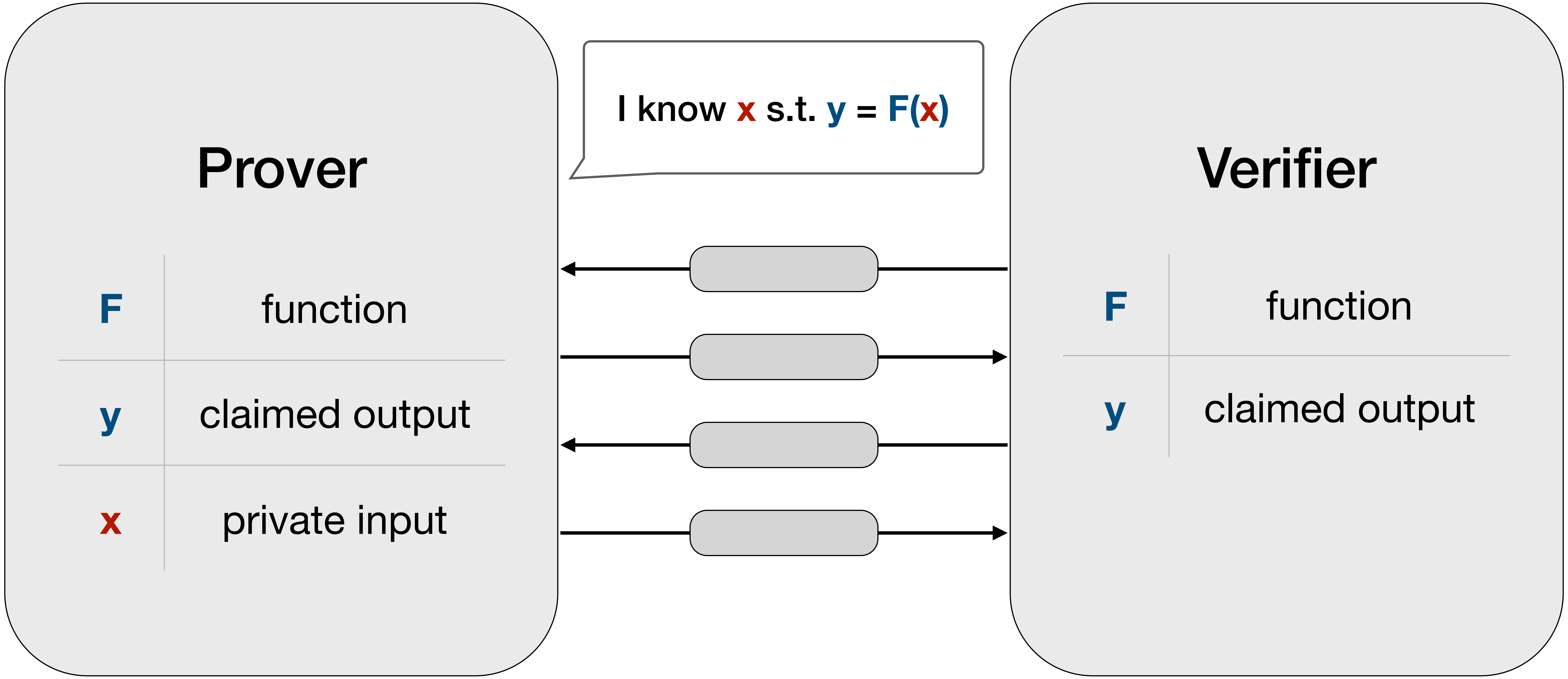
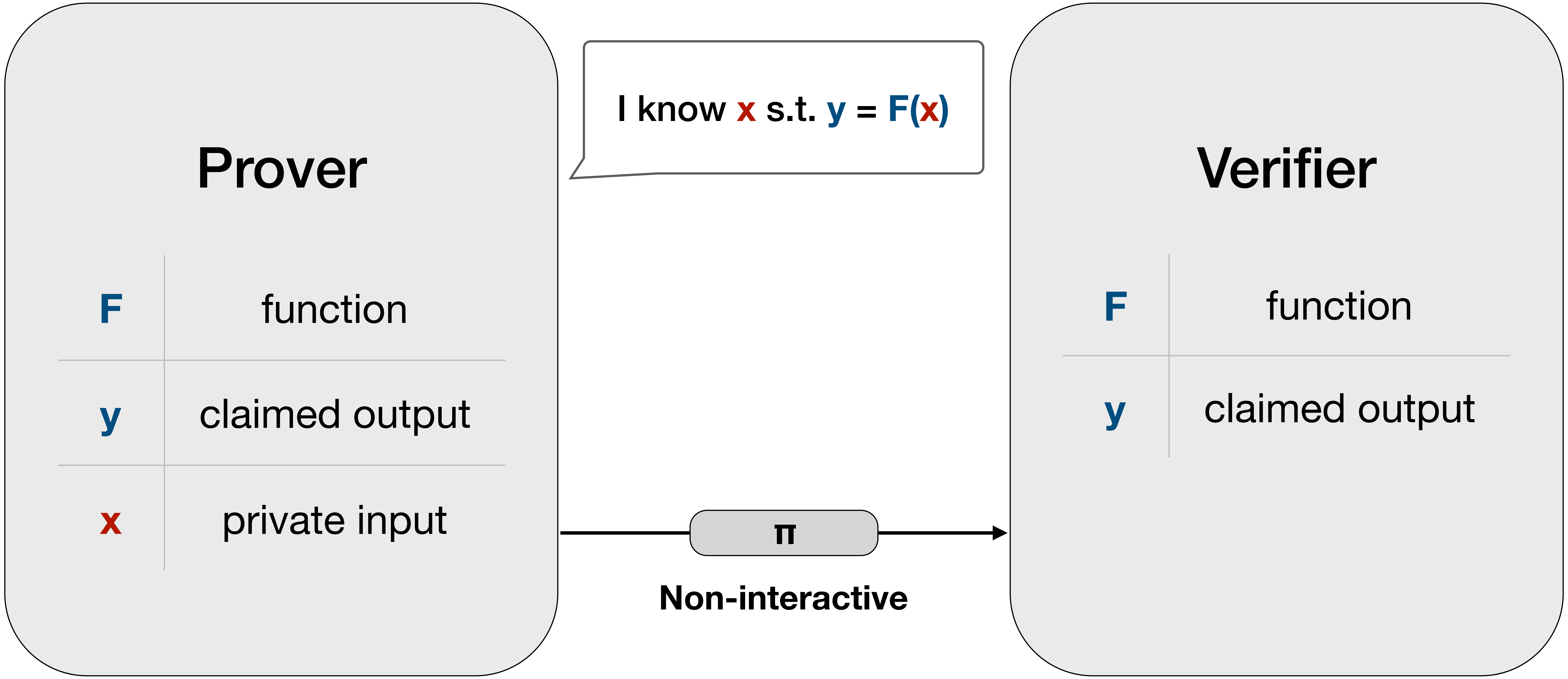


zkSNARK



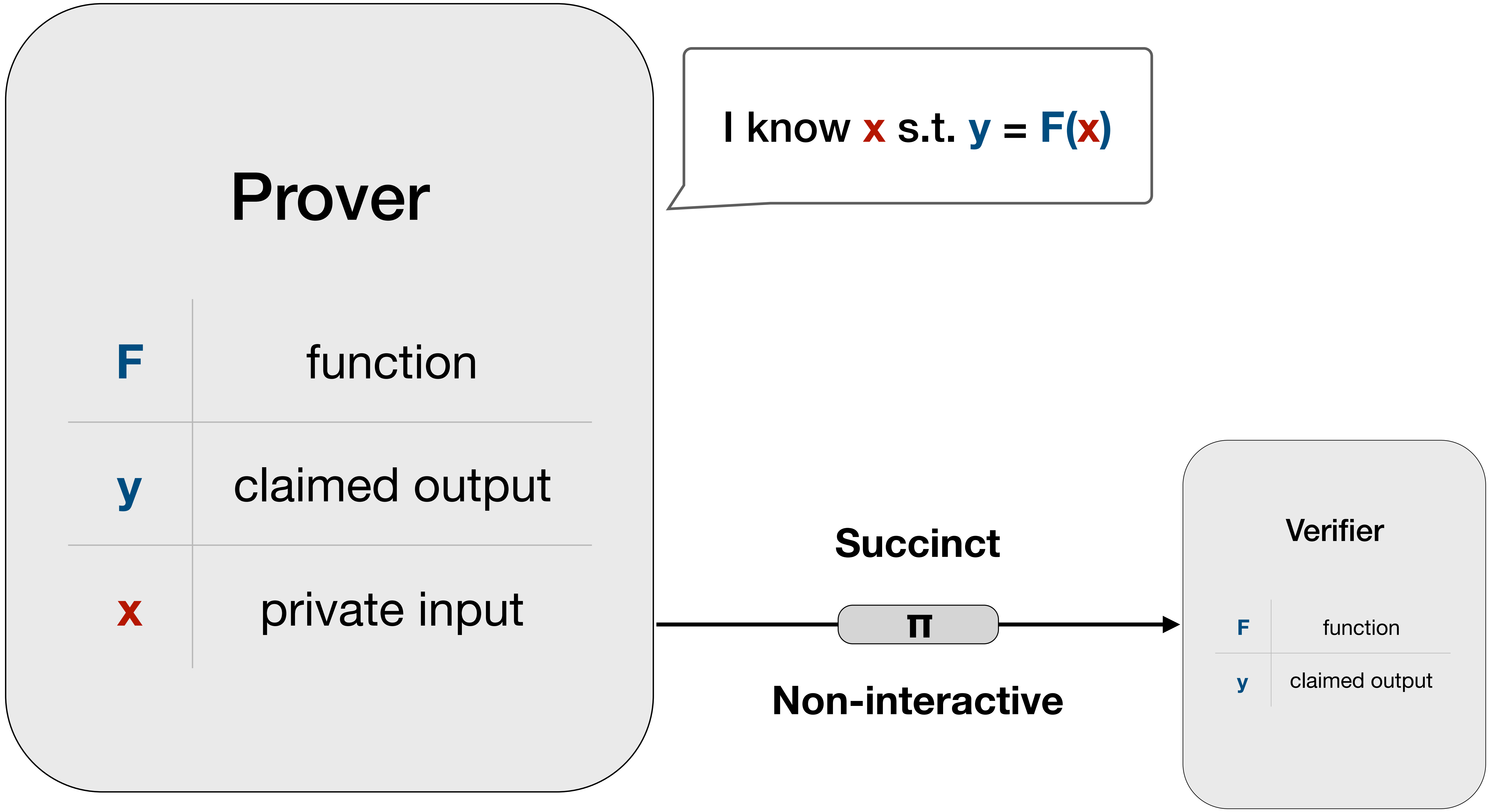
I know x s.t. y = F(x)
Prover
F
function
y
claimed output
x
private input
Verifier
F
function
y
claimed output

zkSNARK

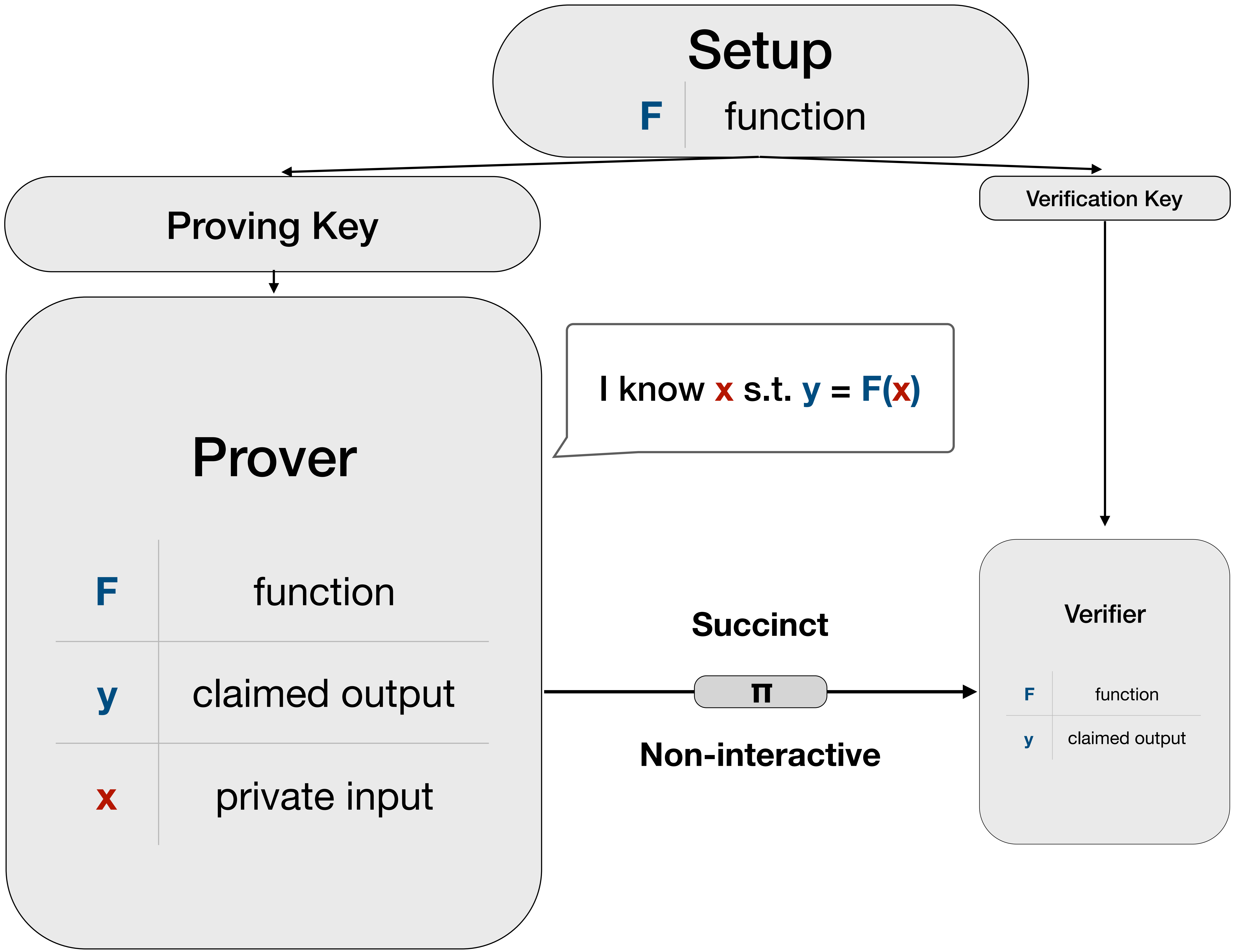


Prover
F function
y claimed output
x private input
I know x s.t. y = F(x)
π
Non-interactive
Verifier
F function
y claimed output

zkSNARK


Prover
F
function
y
claimed output
x
private input
I know x s.t. y = F(x)
Succinct
π
Non-interactive
Verifier
F
function
y
claimed output

preprocessing zkSNARK



Application #1

[BCGGMTV 14]

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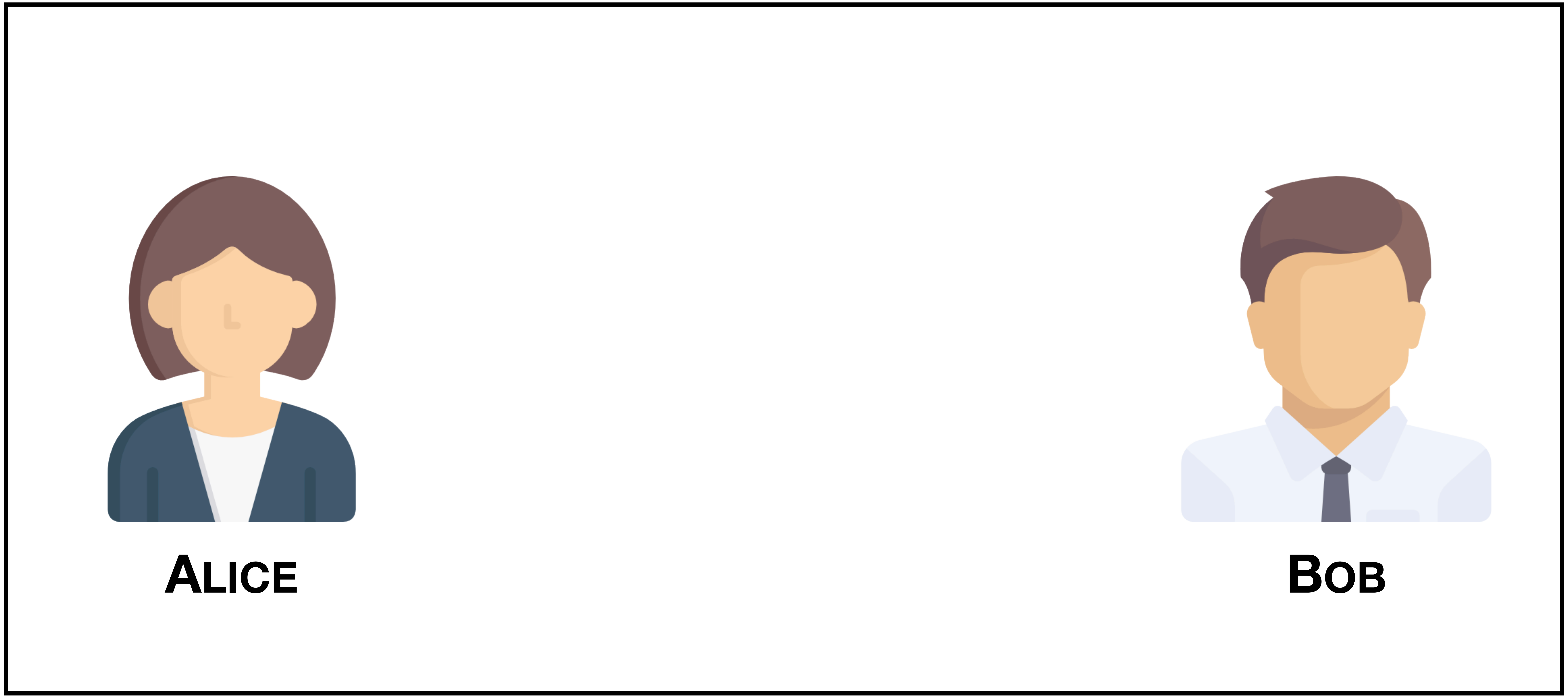

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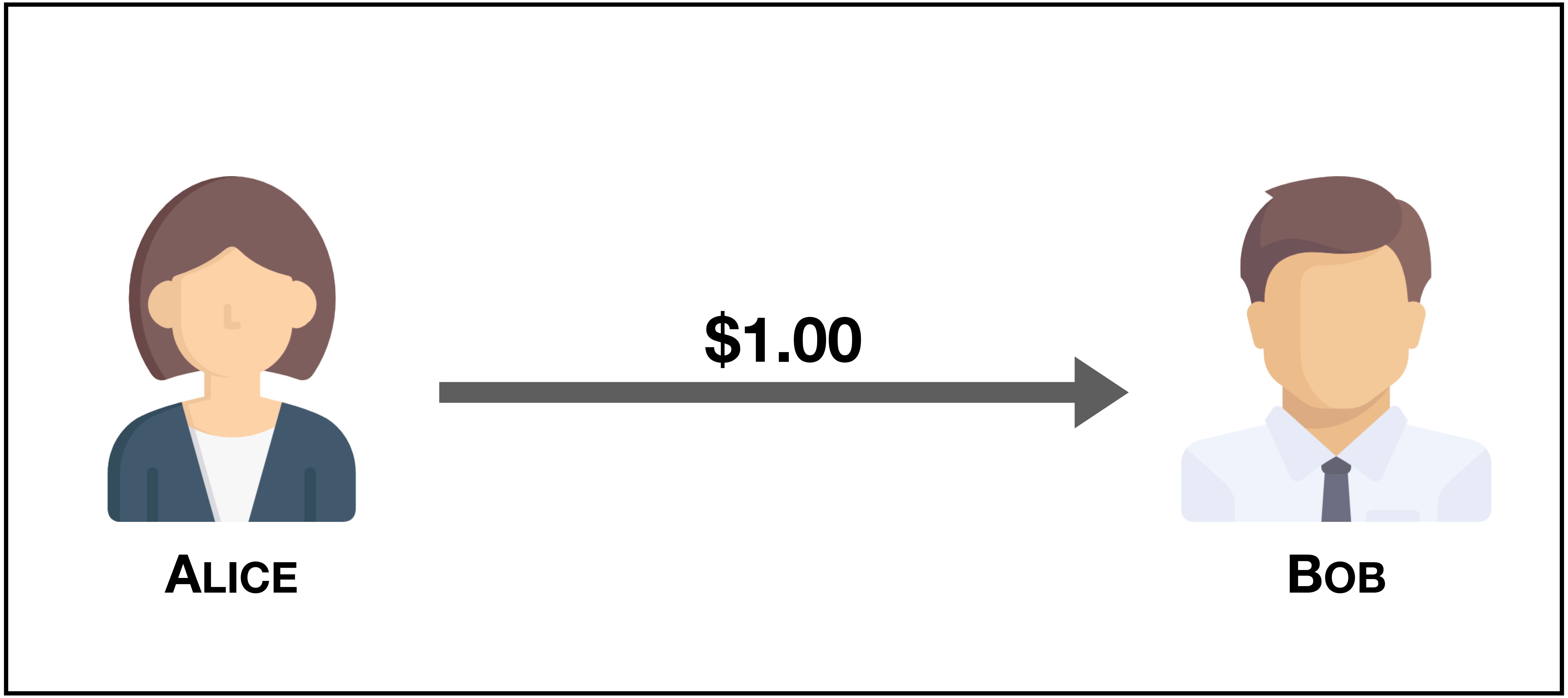
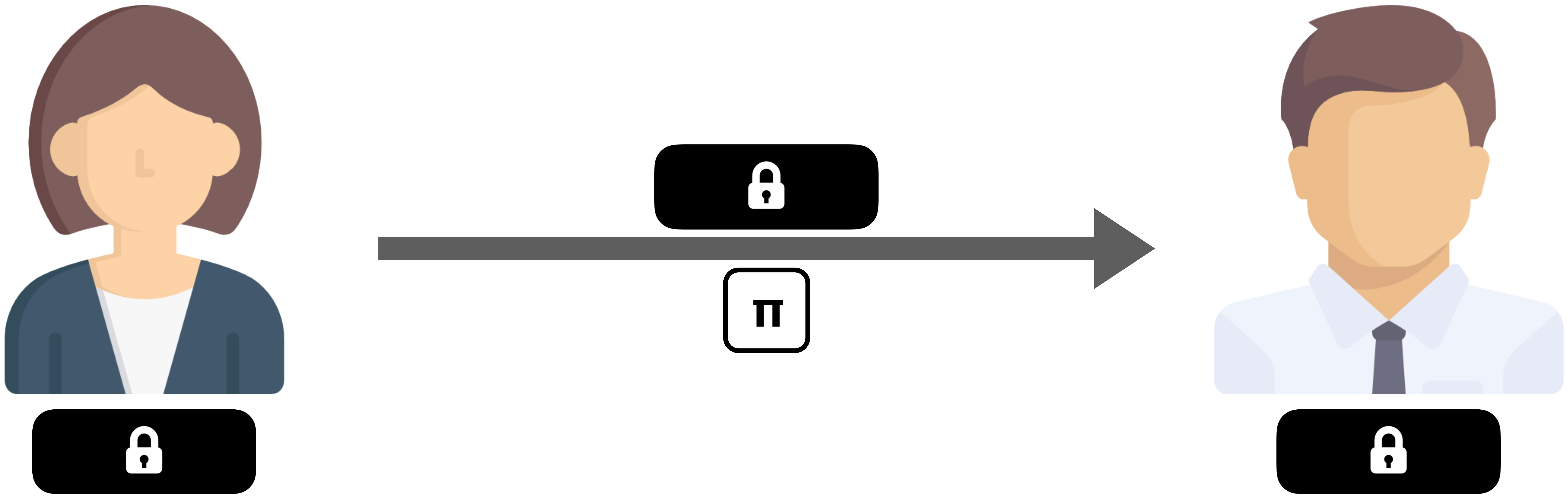
[BCGGMTV 14]



Application #1

[BCGGMTV 14]

Anonymous P2P Payments



Application #2

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Smart Contracts

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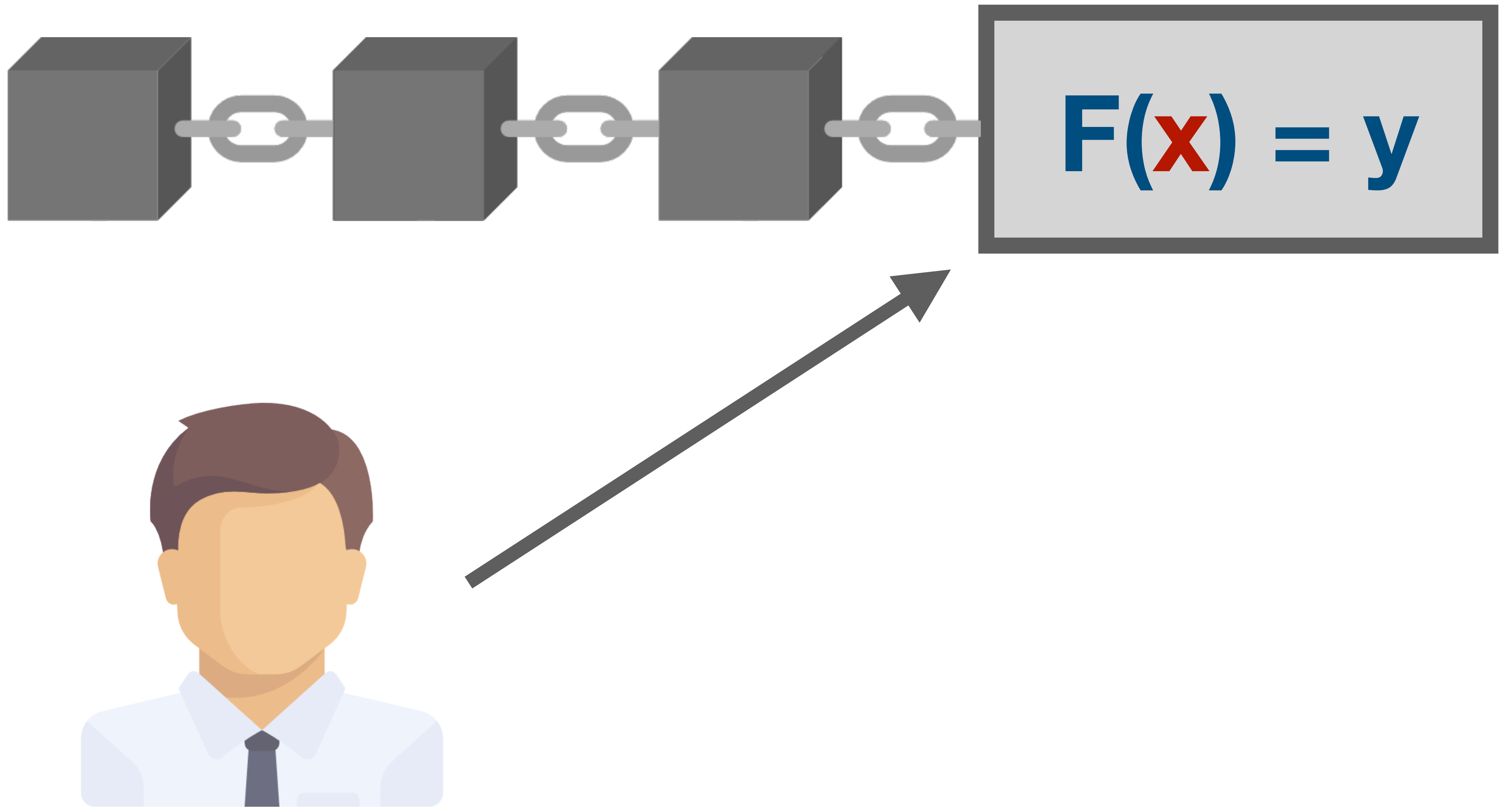
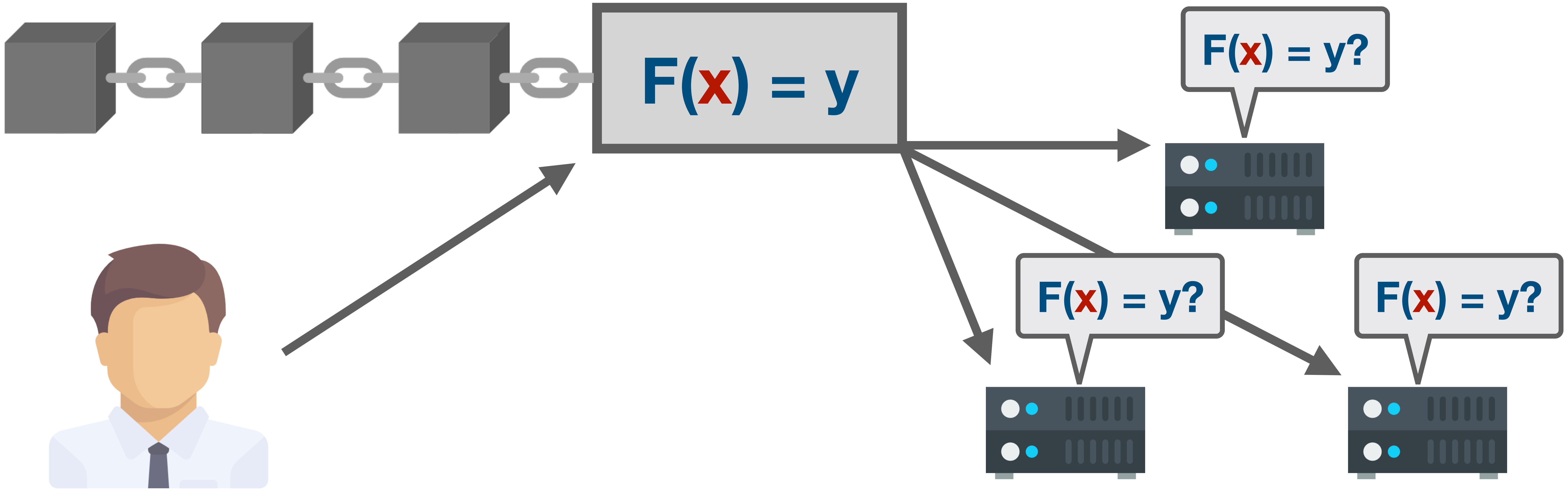


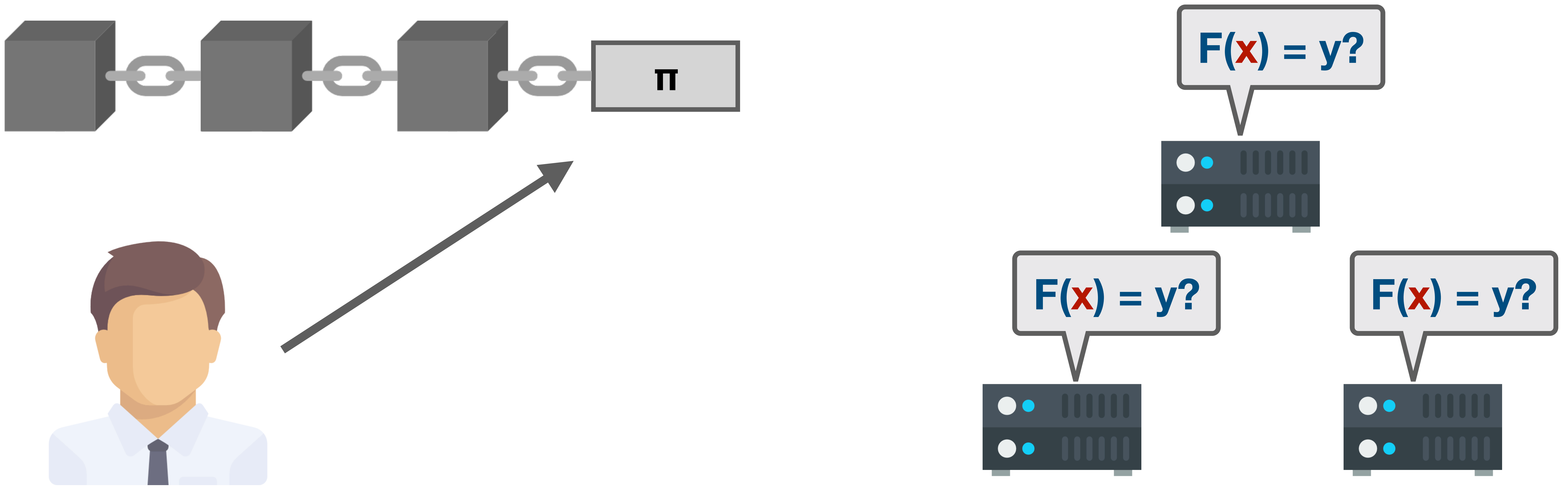
Application #2

Smart Contracts



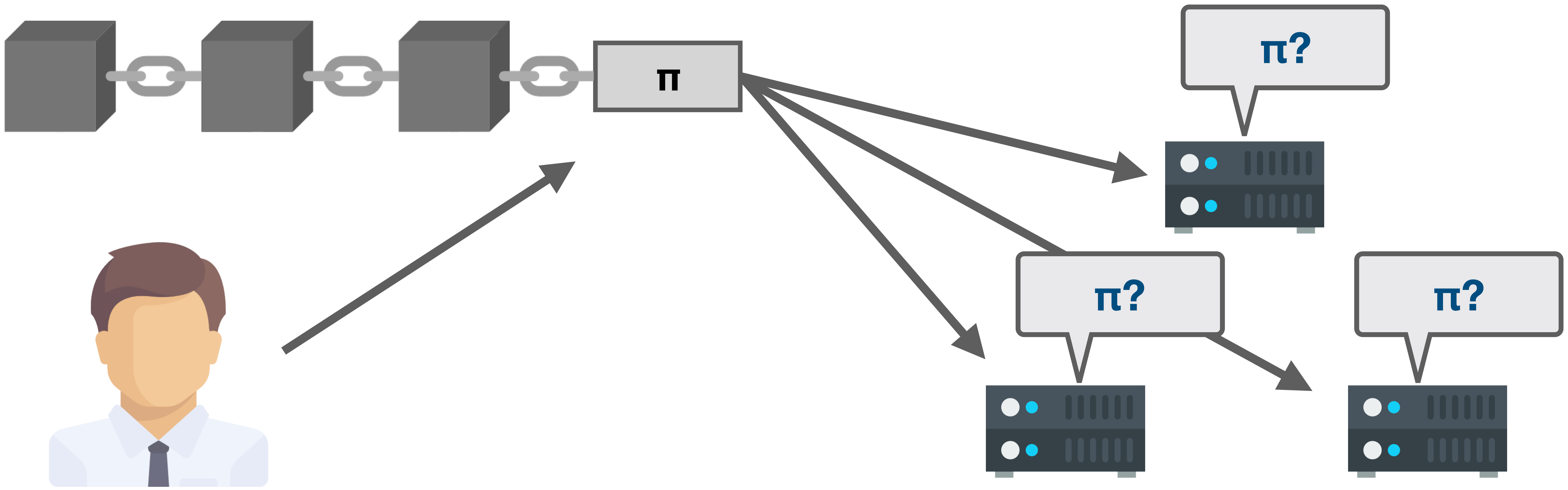
Application #2

Smart Contracts



Application #2

Smart Contracts



Good News & Bad News

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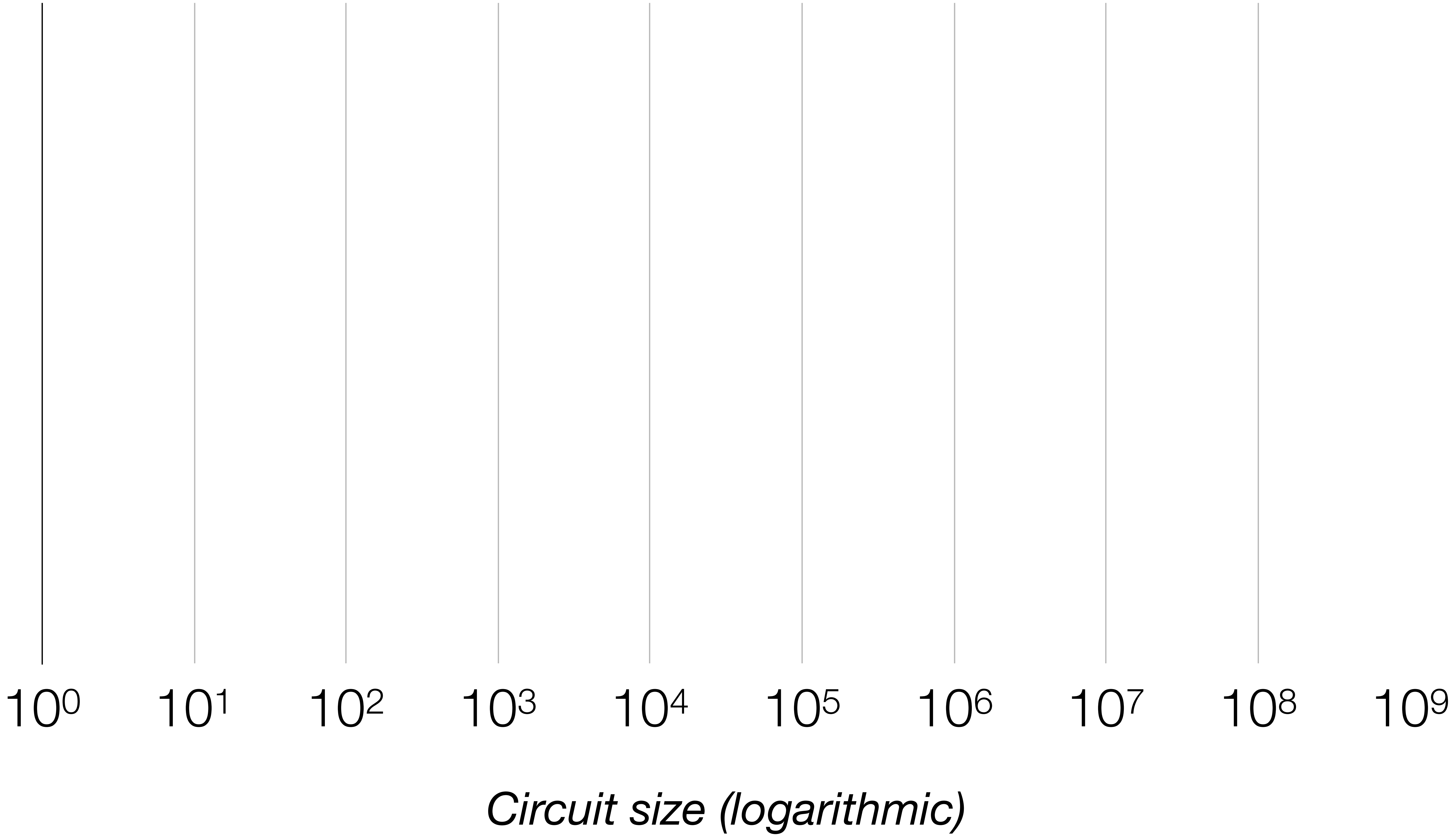

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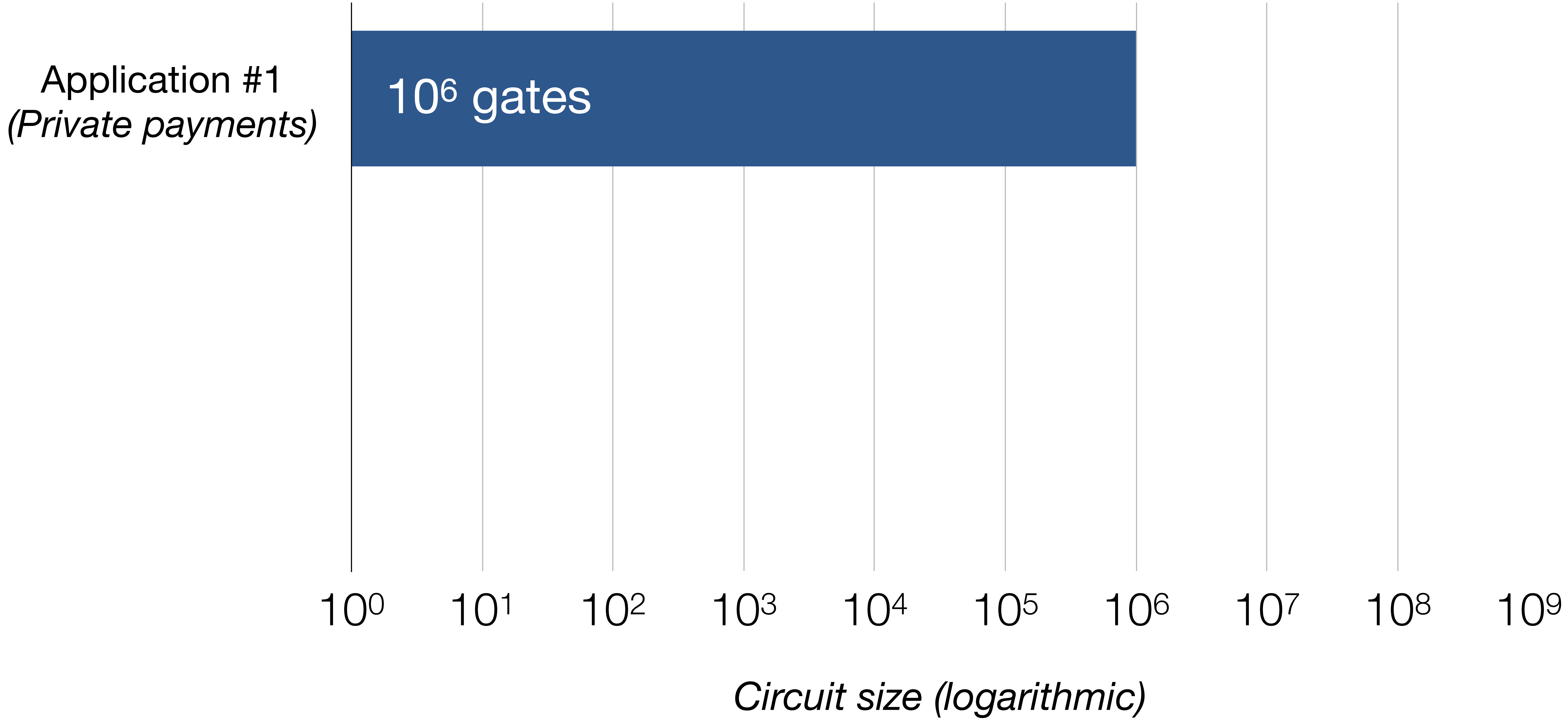

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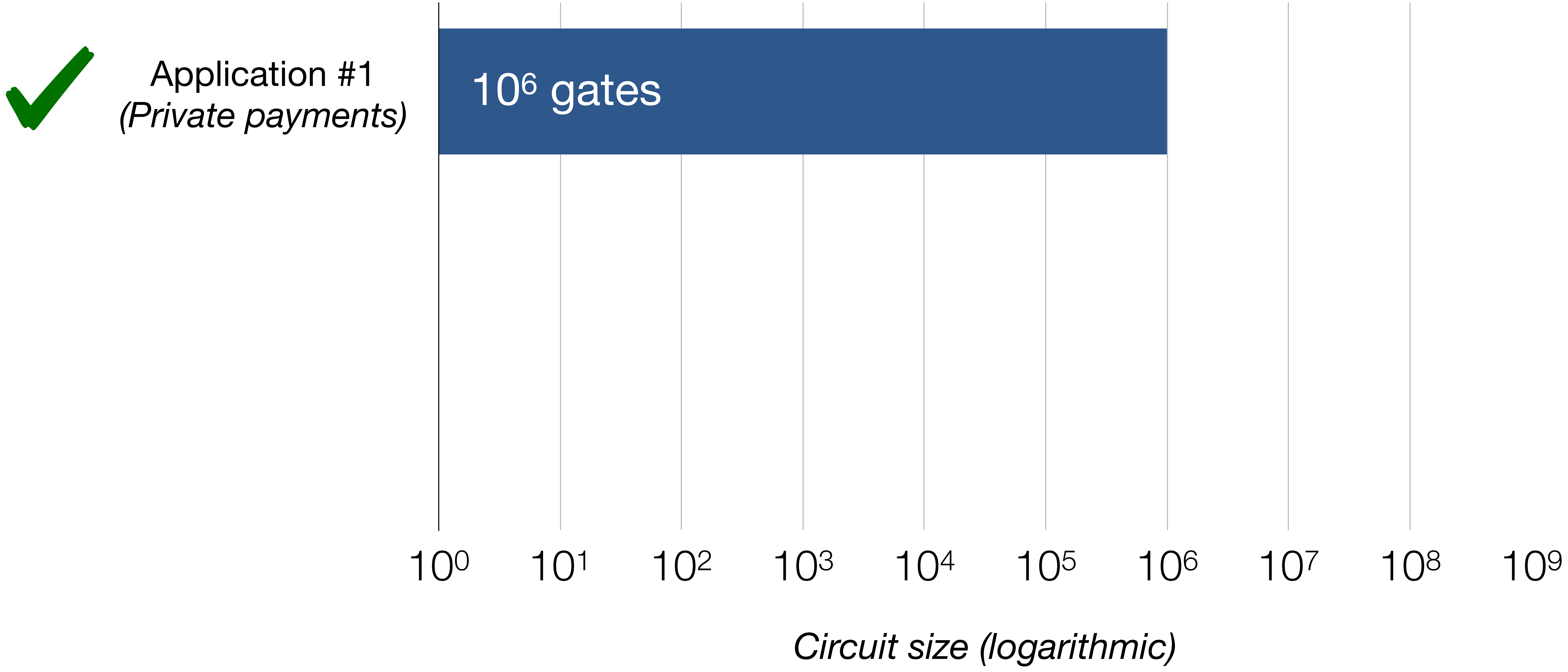

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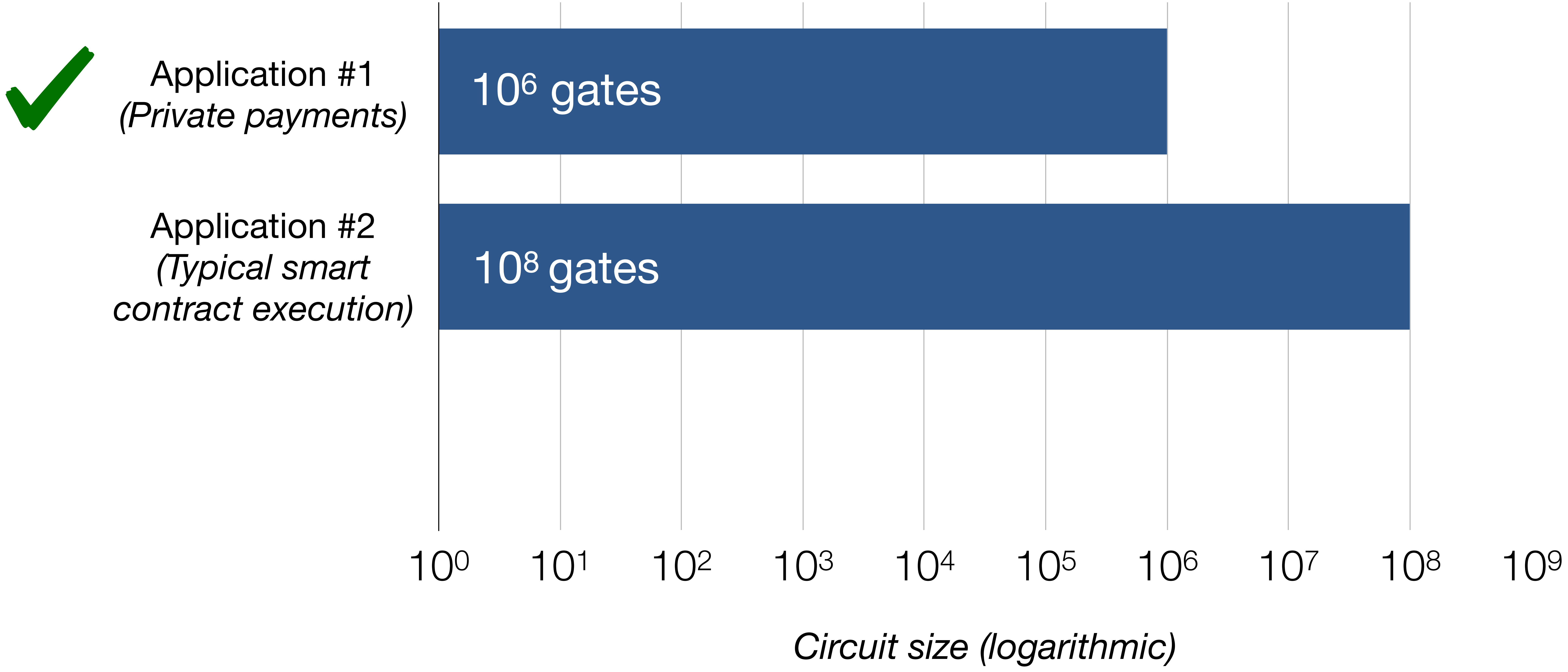

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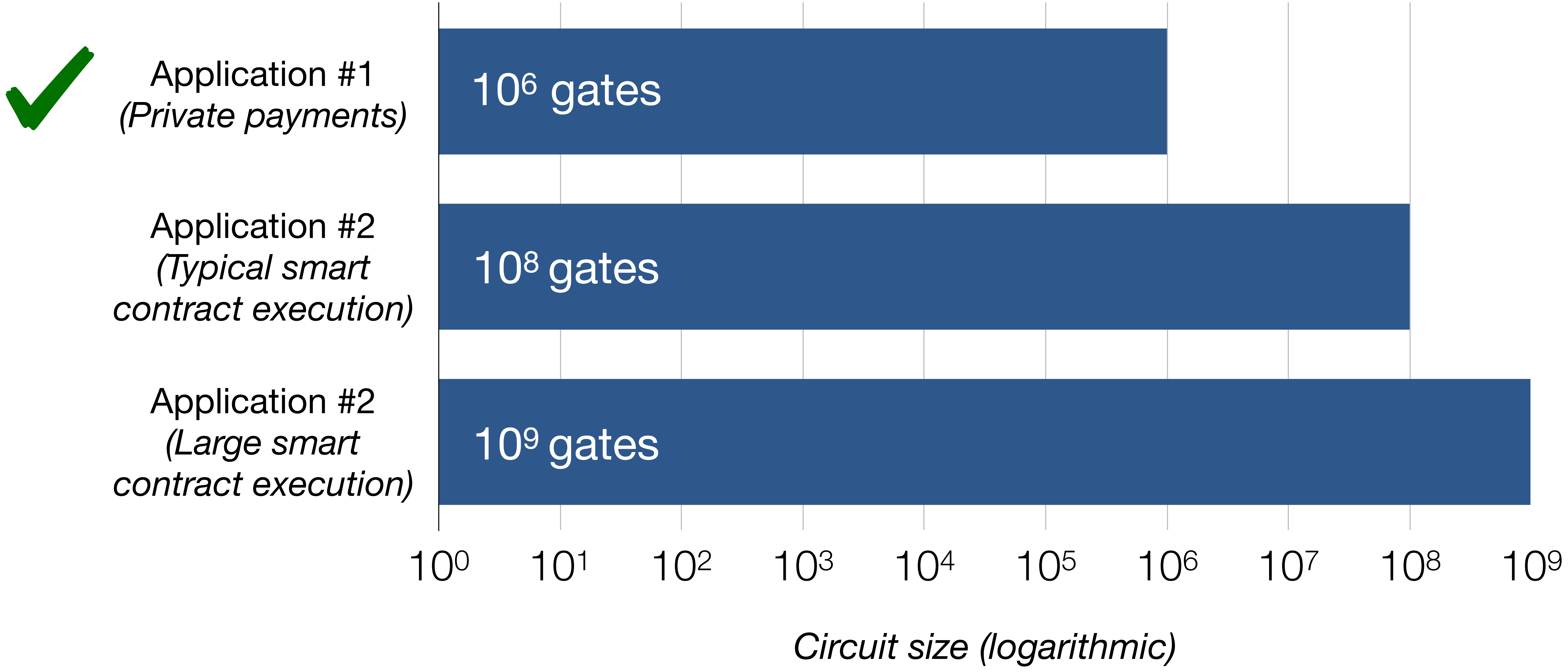

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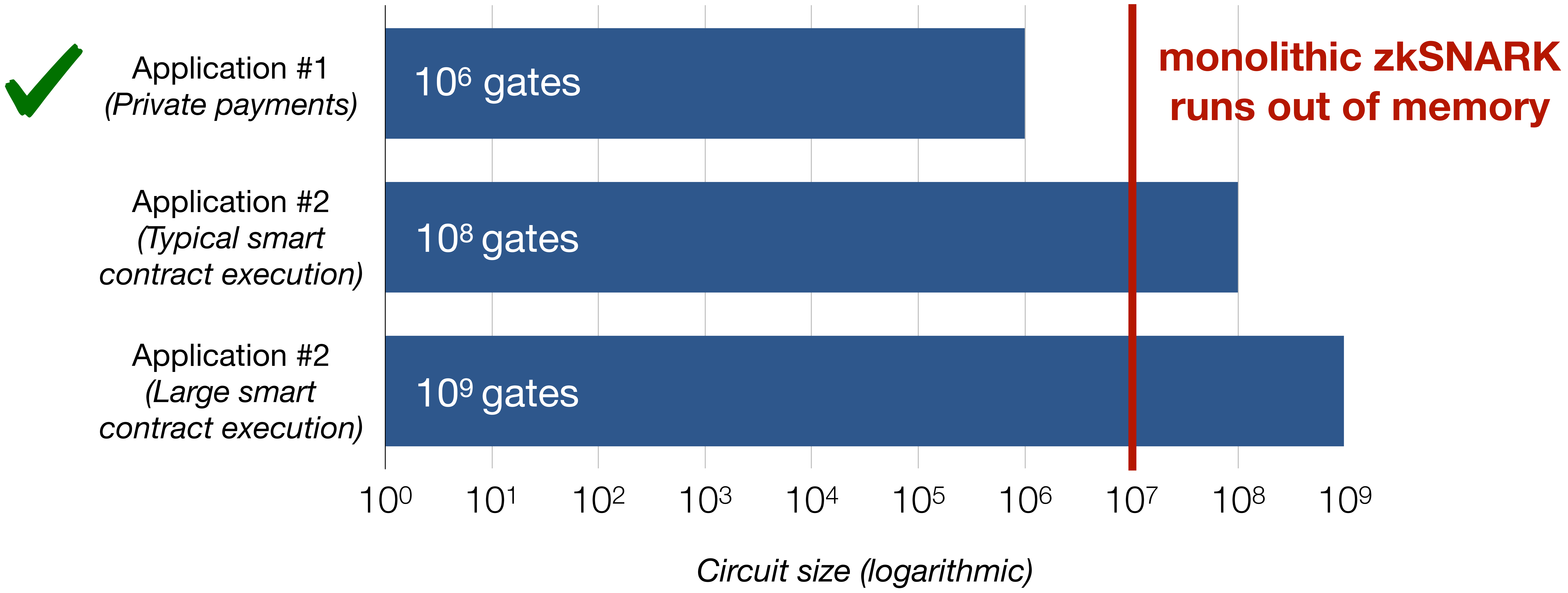

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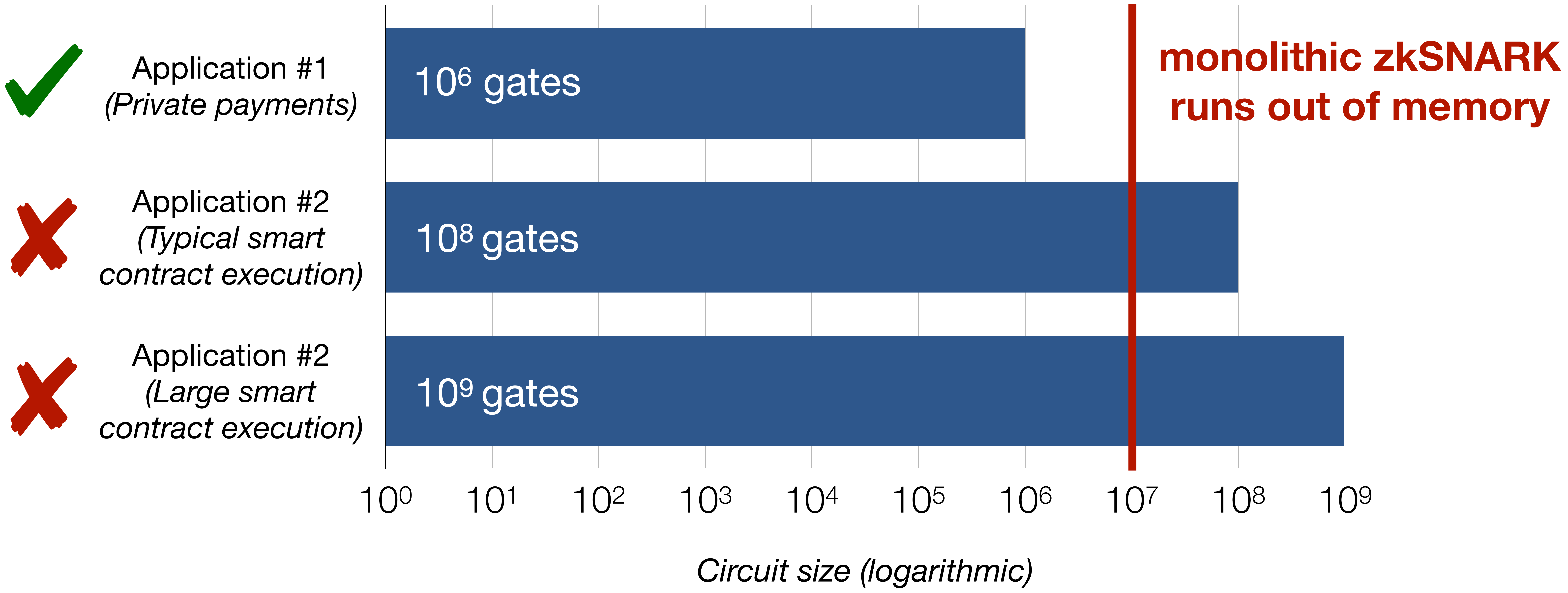

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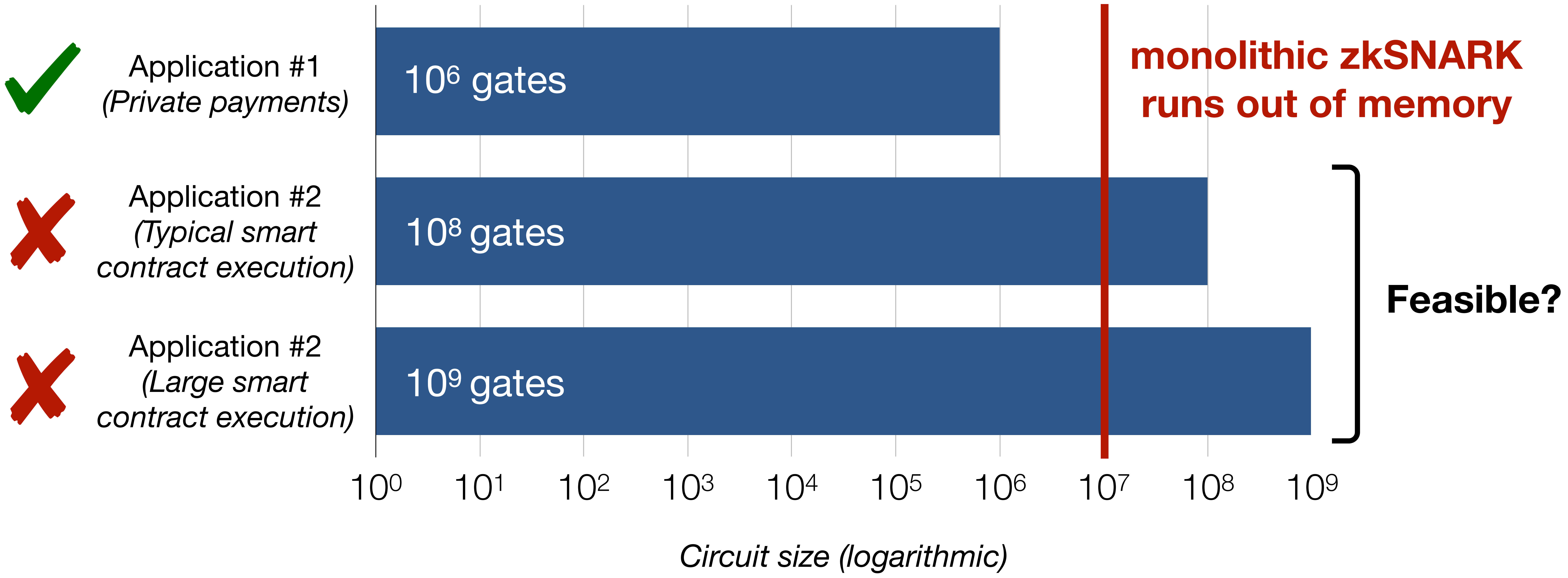

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DISTRIBUTED

Enables the execution of a zkSNARK
Setup and Prover across a **compute cluster**

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SCALABLE

Reaches heretofore unreachable circuit sizes (up to ***billions*** of gates)

Double the number of machines → twice the circuit size

DIZK is a zero knowledge proof system that is:

Distributed

Enables the execution of a zkSNARK
Setup and Prover across a **compute cluster**

Scalable

Reaches heretofore unreachable circuit sizes (up to ***billions*** of gates)

Double the number of machines → twice the circuit size

Parallel

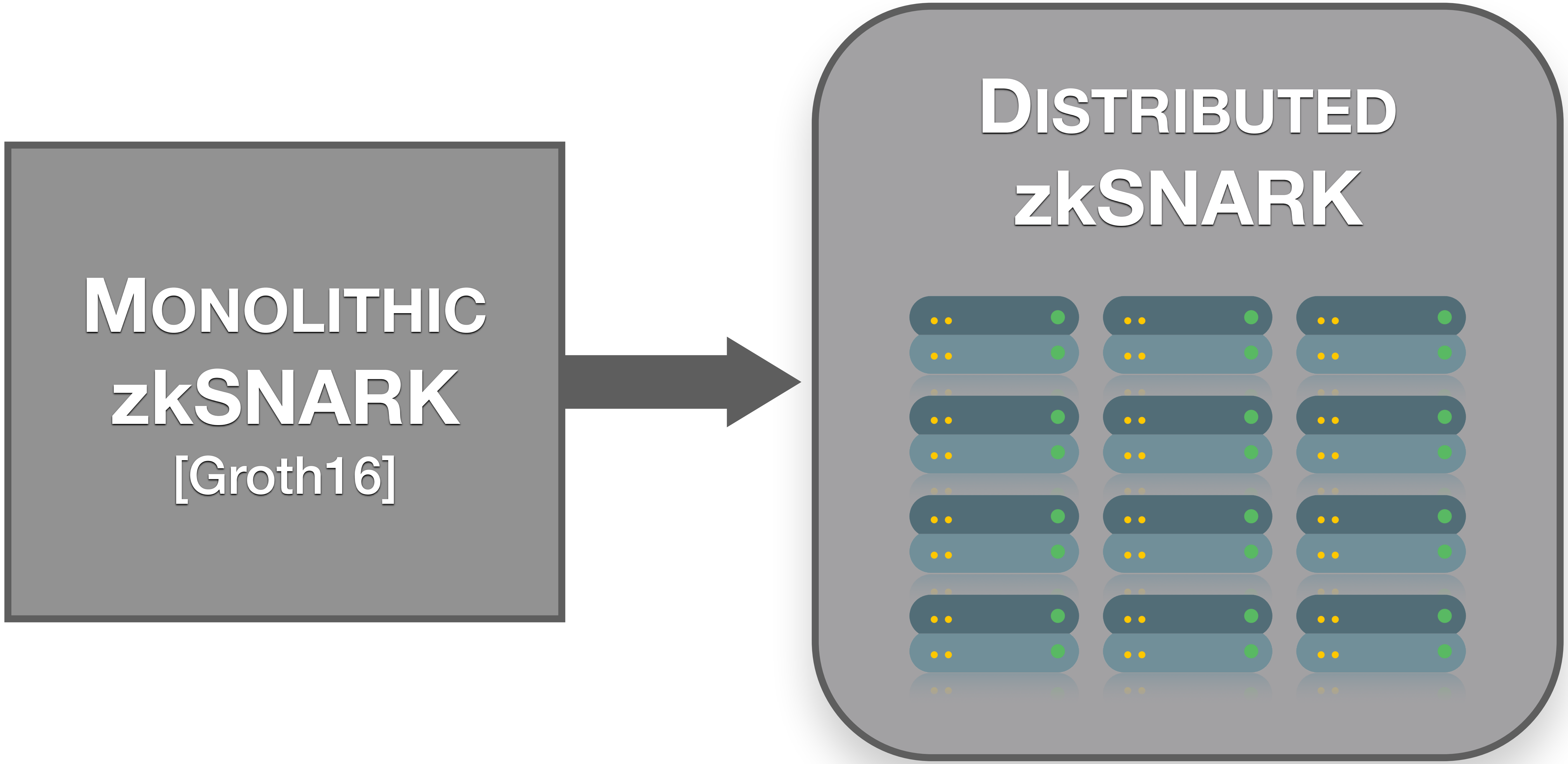
Speeds up the time it takes to generate a proof

Double the number of machines → twice as fast

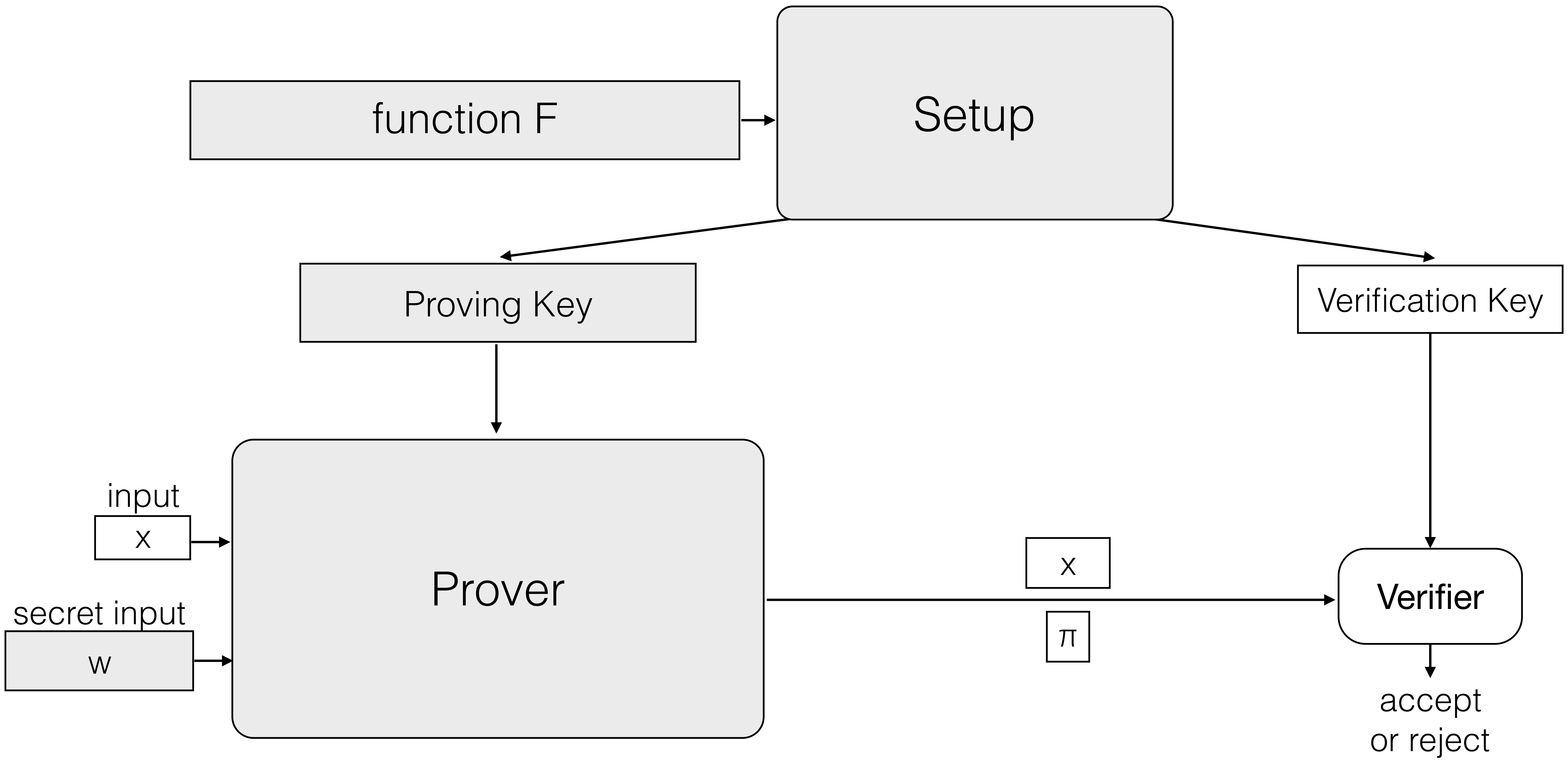
Our Approach

MONOLITHIC
zkSNARK
[Groth16]

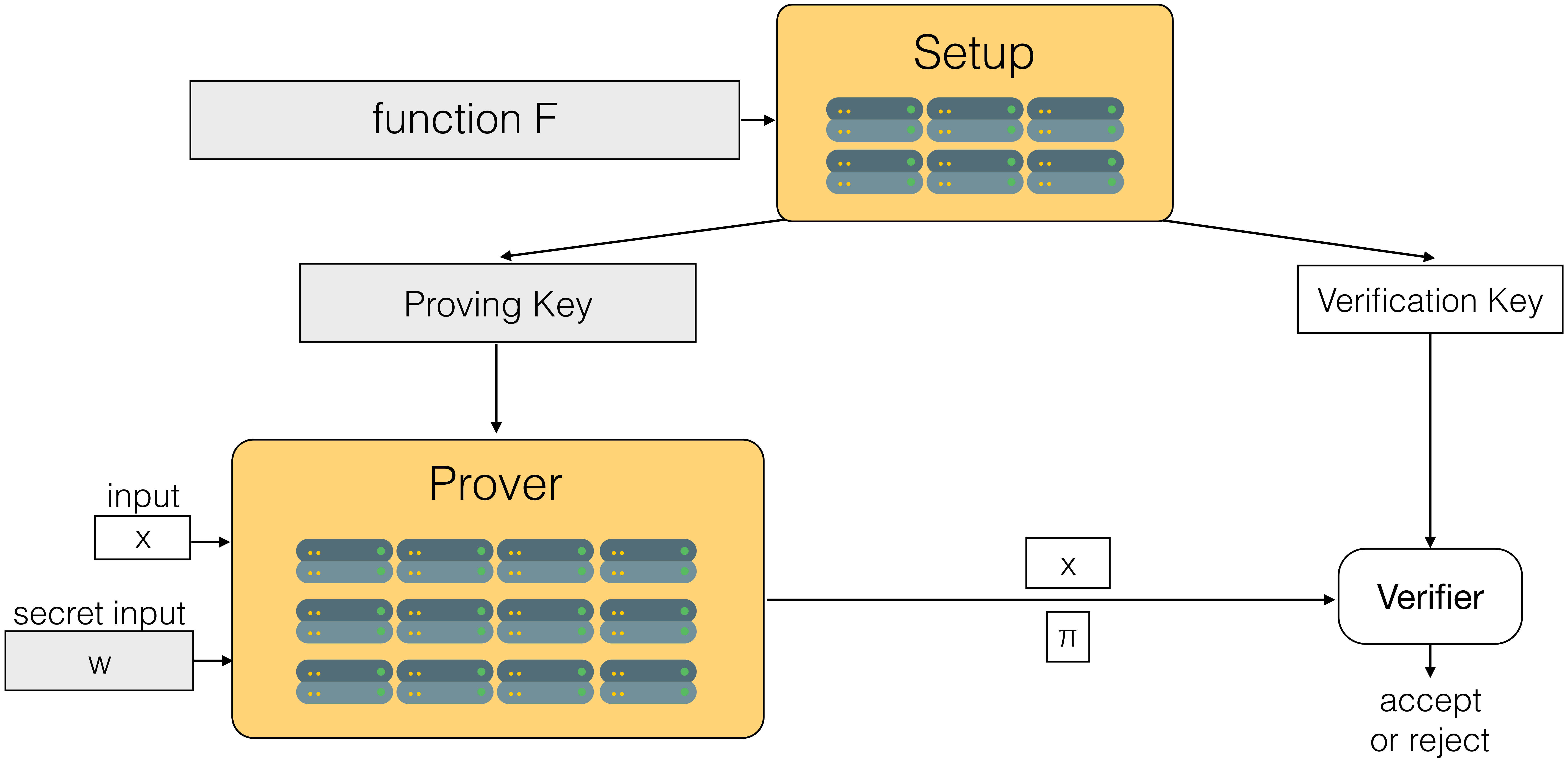
Our Approach



Challenges


function F
Setup
Proving Key
Verification Key
input
x
secret input
w
Prover
x
π
Verifier
accept
or reject

Challenges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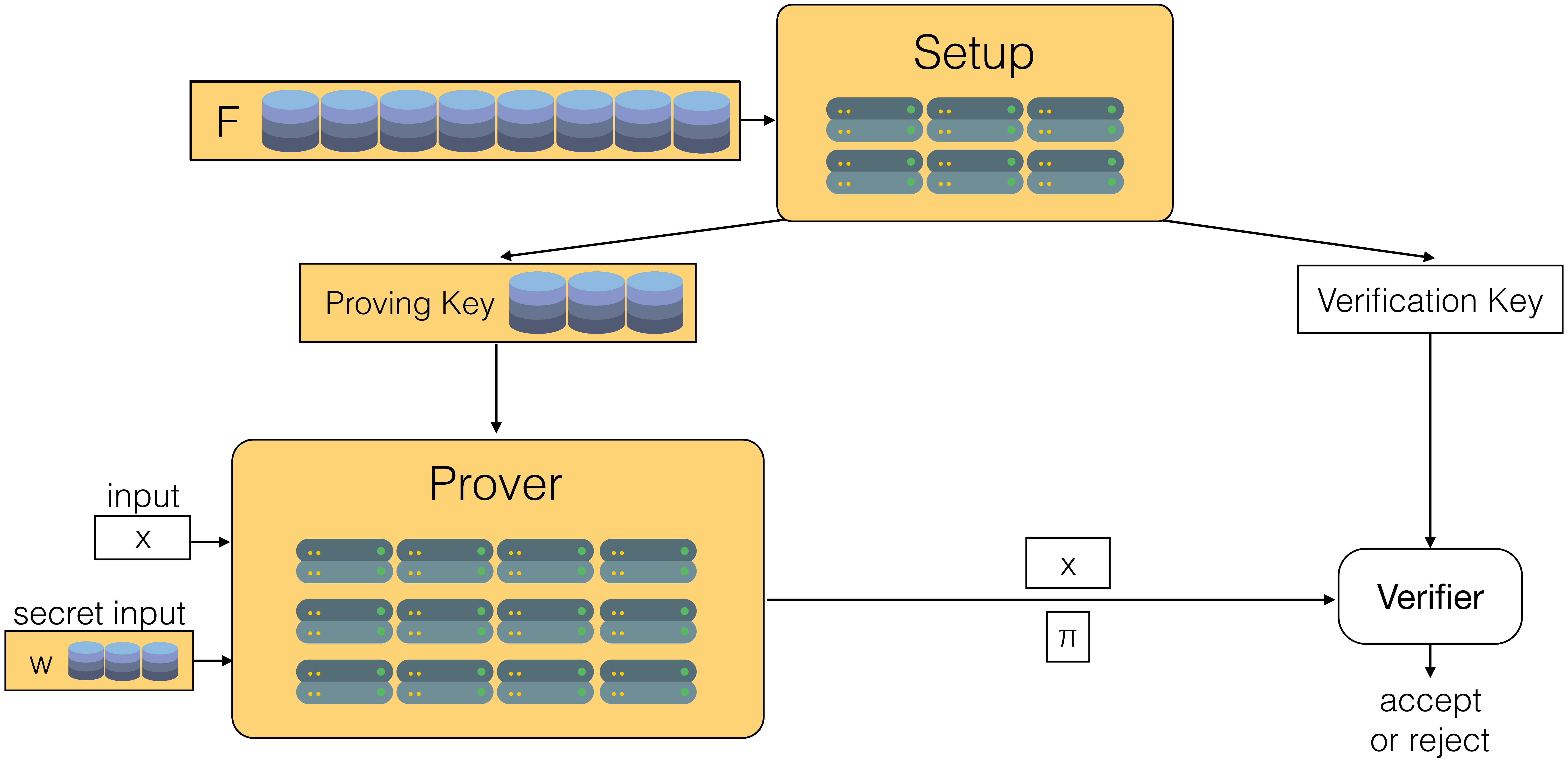

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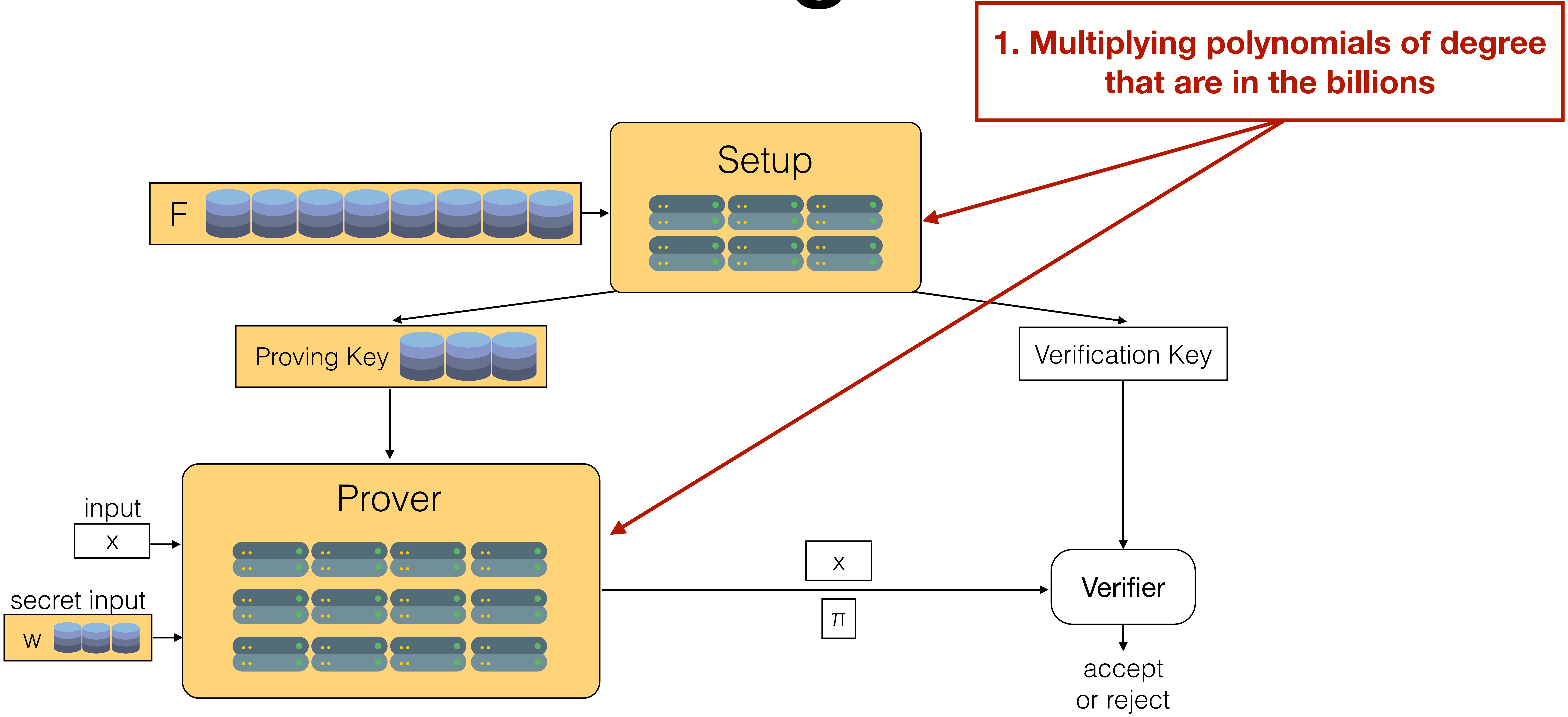

1. Multiplying polynomials of degree that are in the billions
Setup
F
Proving Key
Verification Key
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input
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π
Verifier
accept
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Challenges

2. Representing these polynomials as terabit-sized arrays

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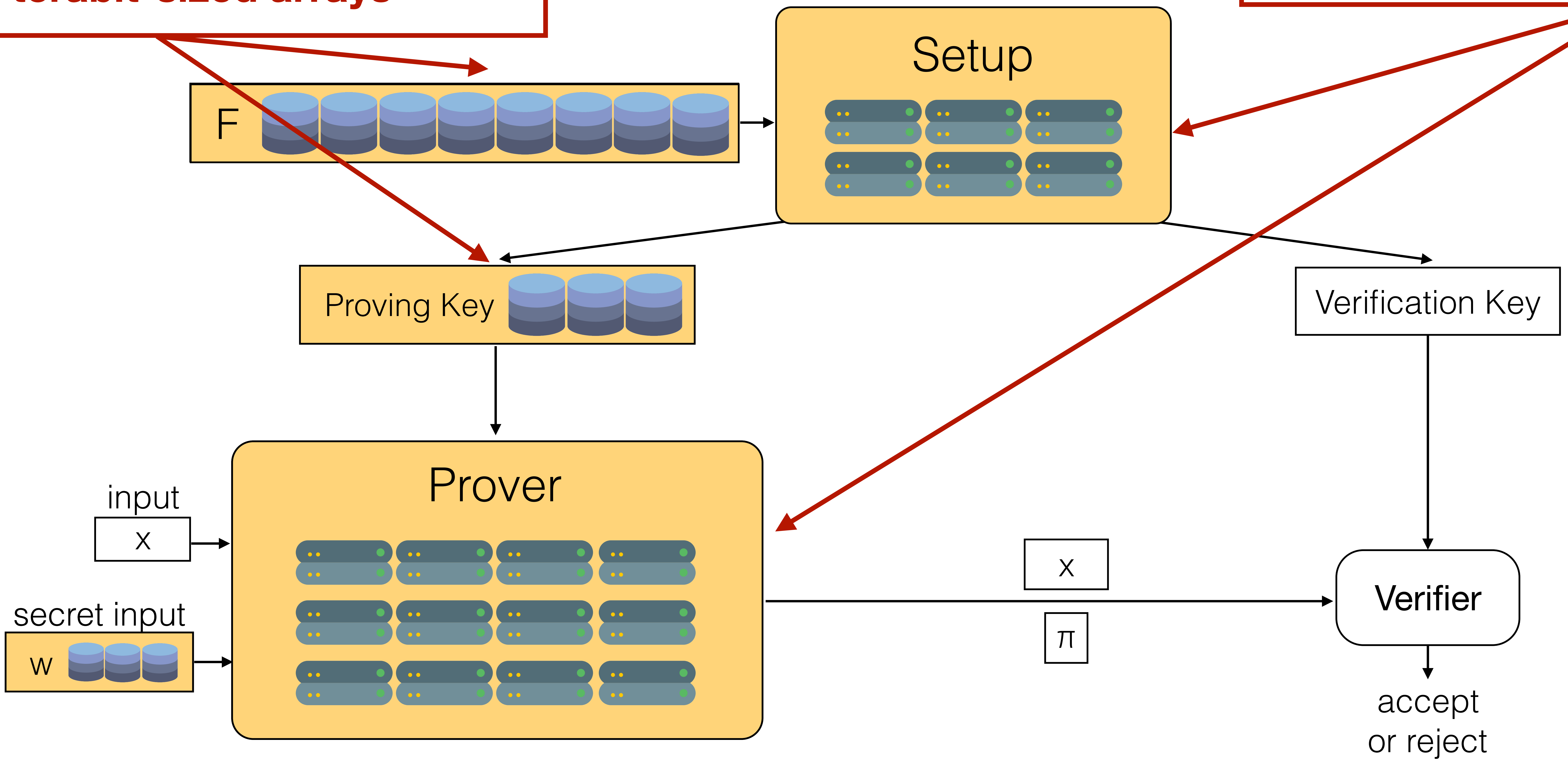

Challenges

2. Representing these polynomials as terabit-sized arrays
1. Multiplying polynomials of degree that are in the billions
F
Setup
3. Accessing large pools of shared memory in complex patterns
Proving Key
Verification Key
input
x
Prover
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Challenges

2. Representing these polynomials as terabit-sized arrays
1. Multiplying polynomials of degree that are in the billions
F
Setup
3. Accessing large pools of shared memory in complex patterns
Proving Key
Verification Key
4. Synchronizing shared state that incurs significant network delays
input
x
Prover
secret input
w
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Verifier
accept or reject

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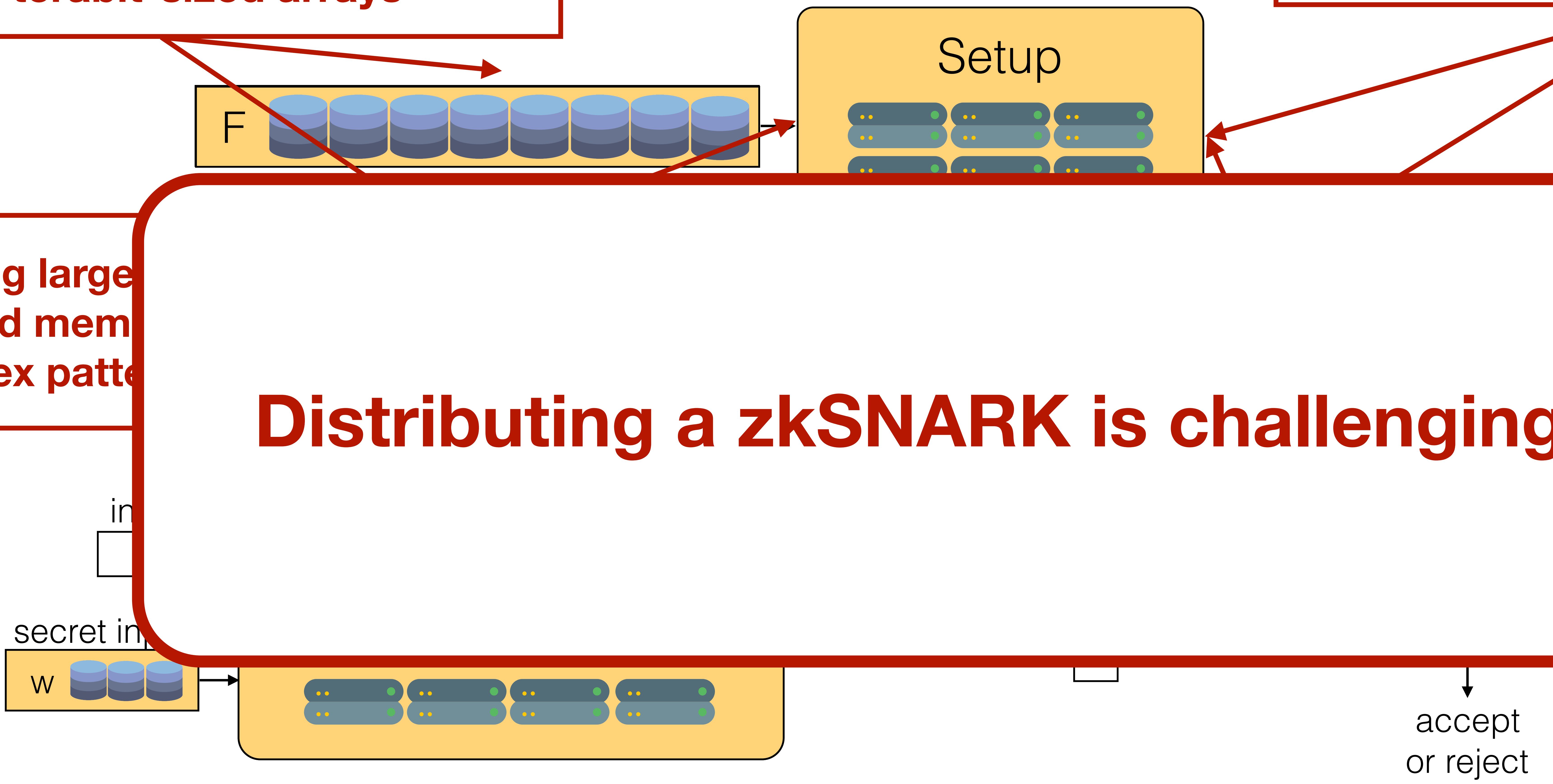

Distributing a zkSNARK is challenging

DIZK Architecture

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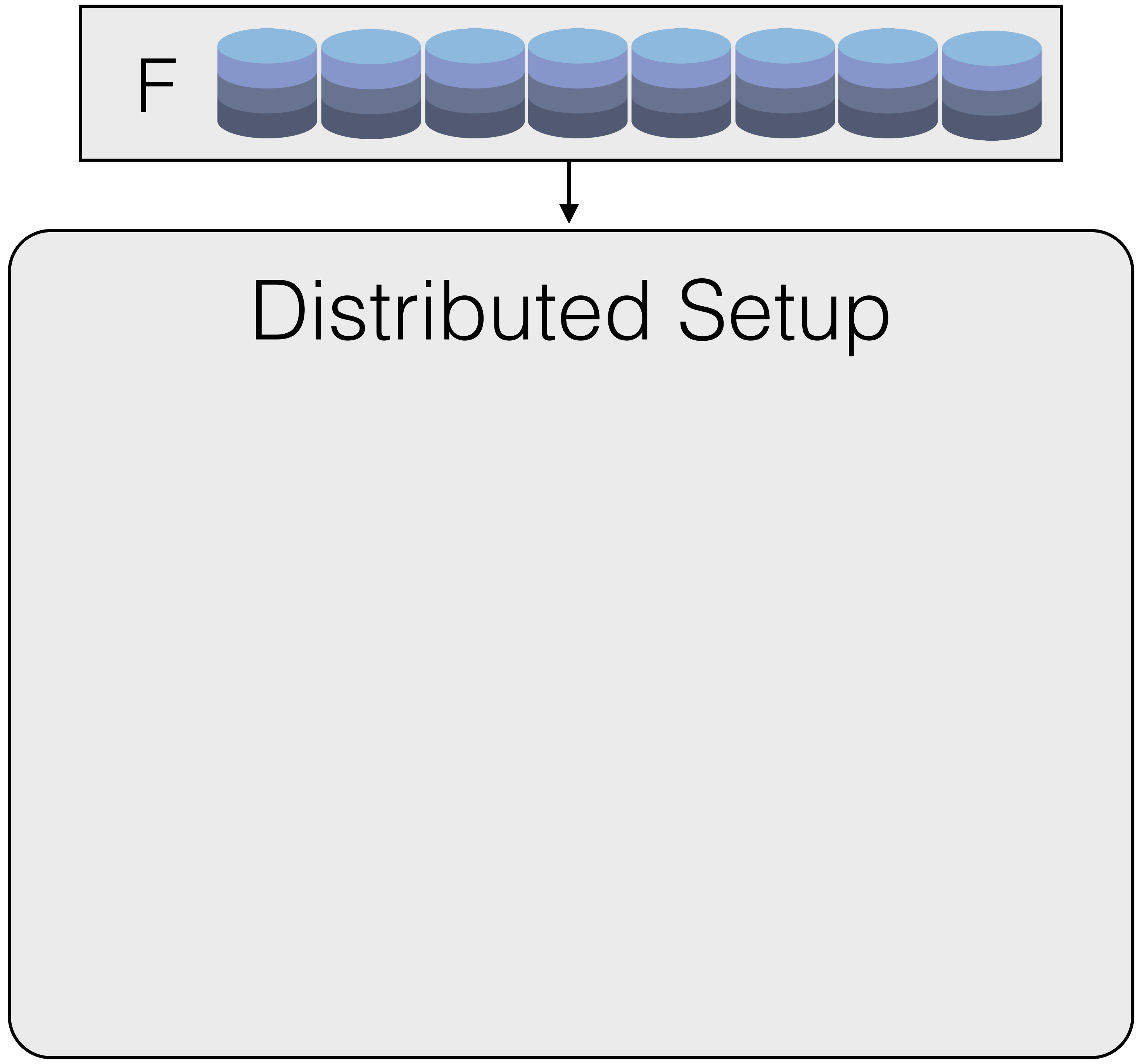
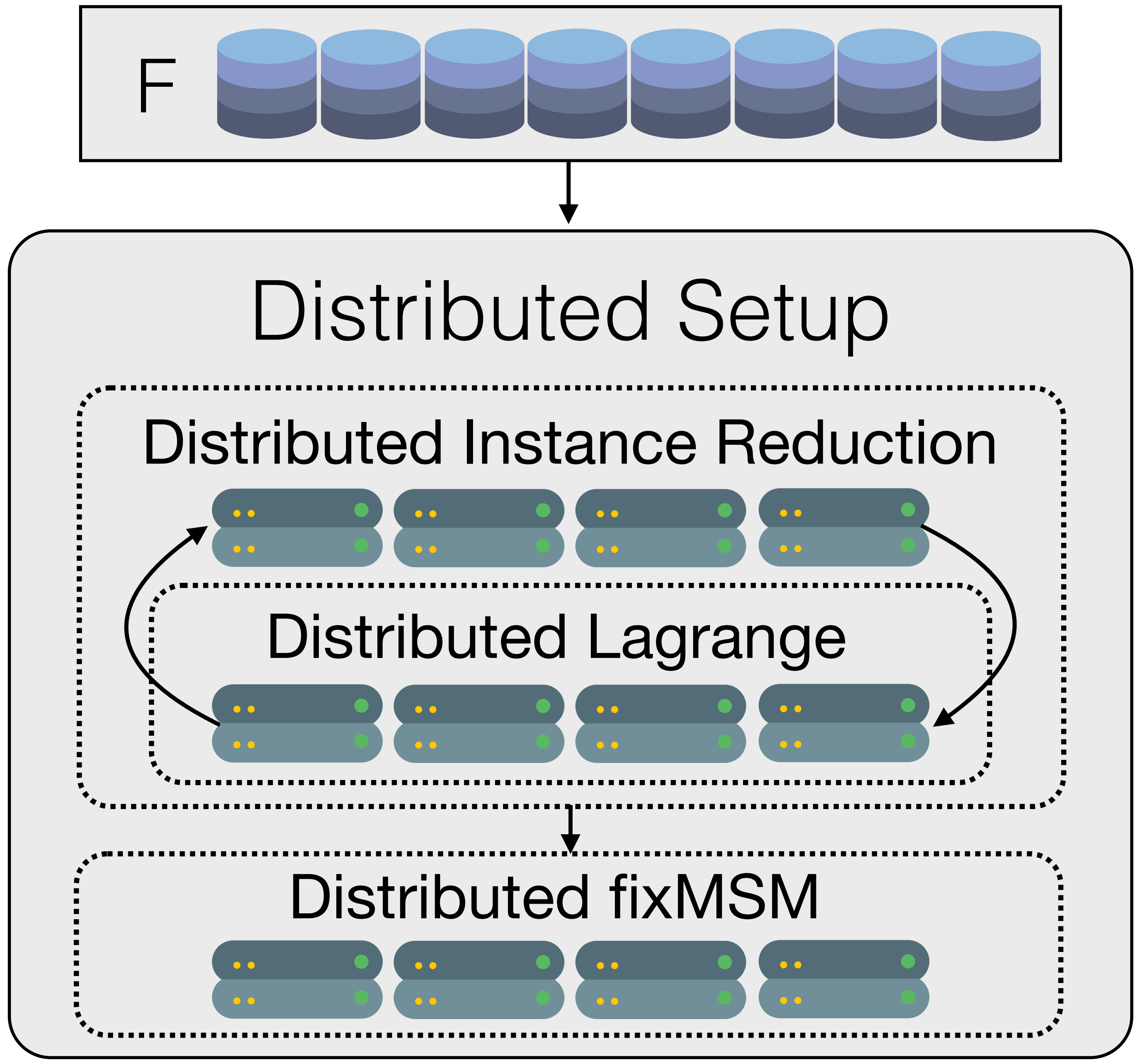


DIZK Architecture



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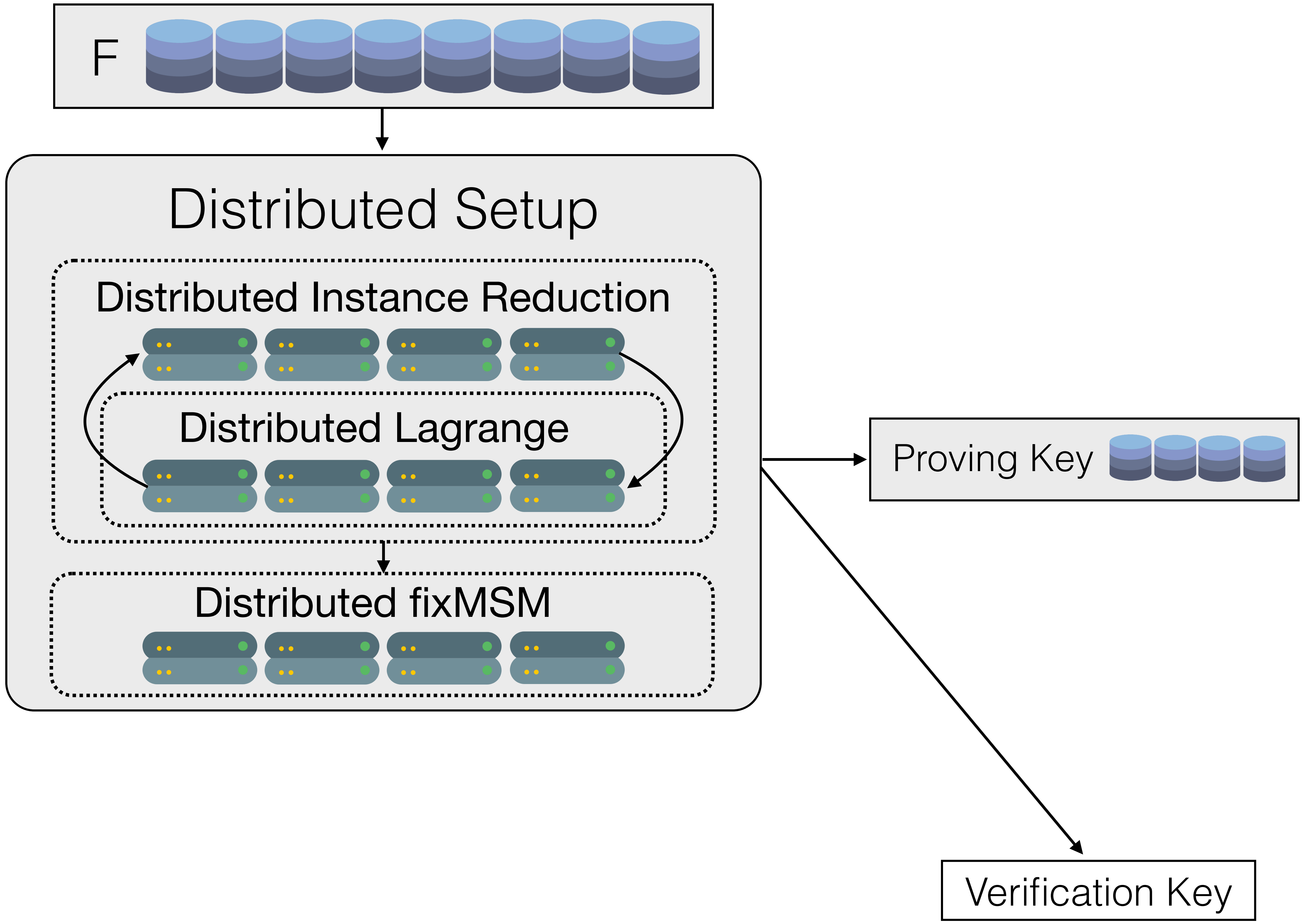

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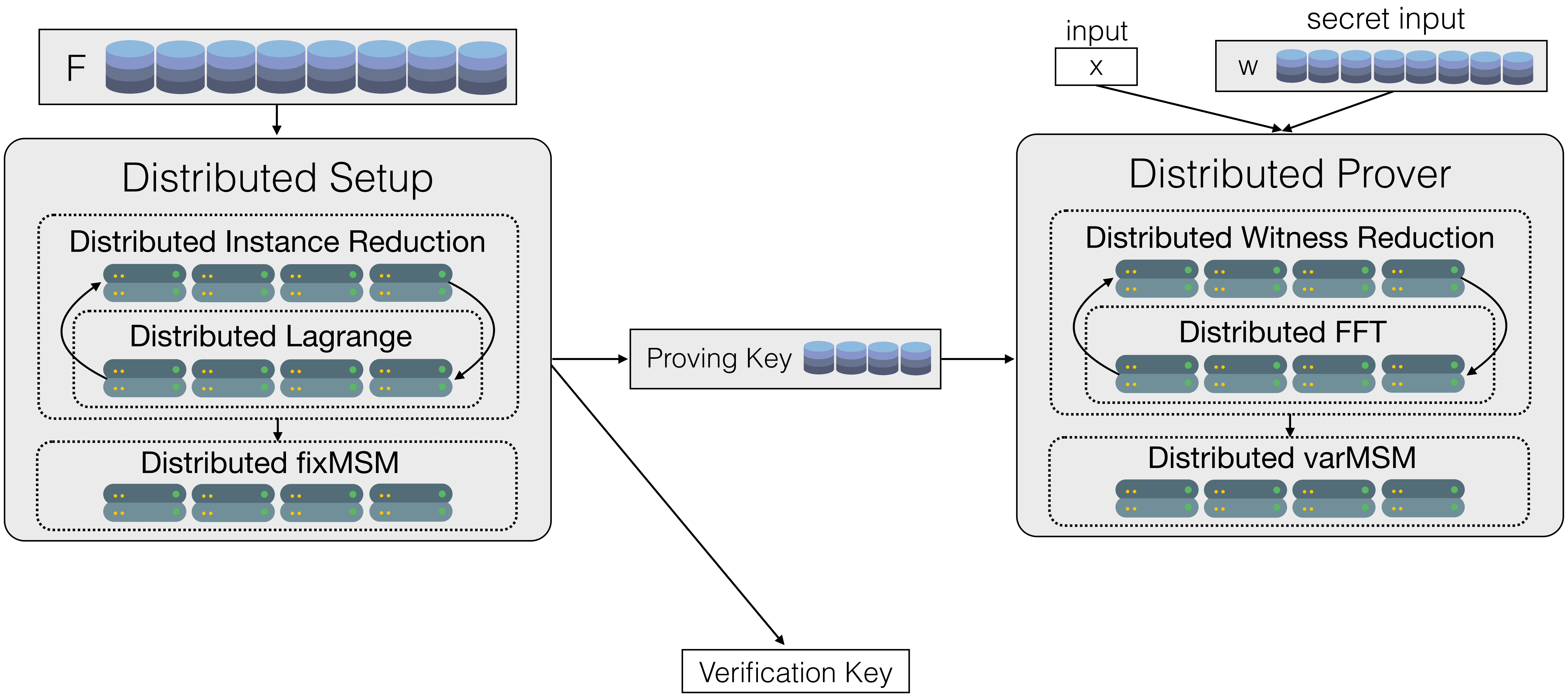

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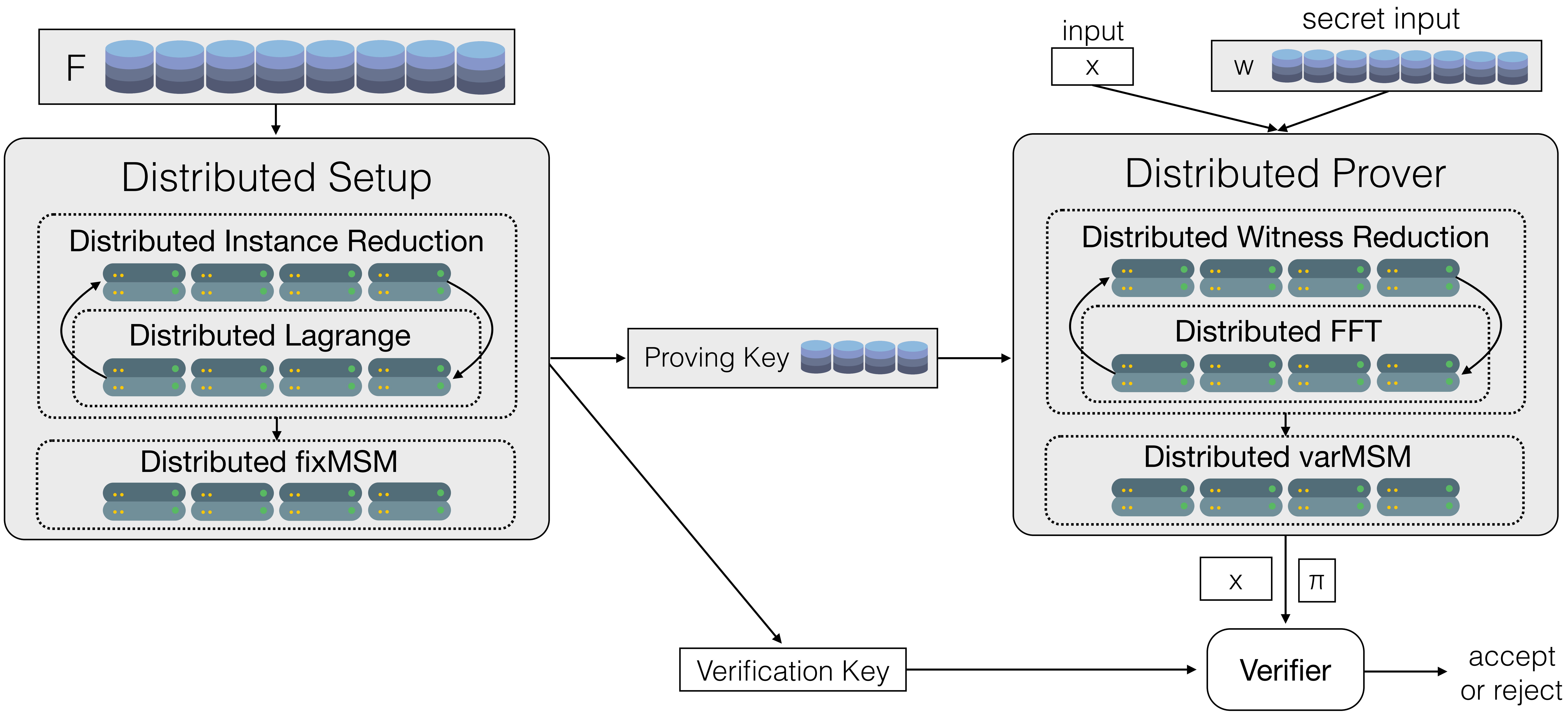

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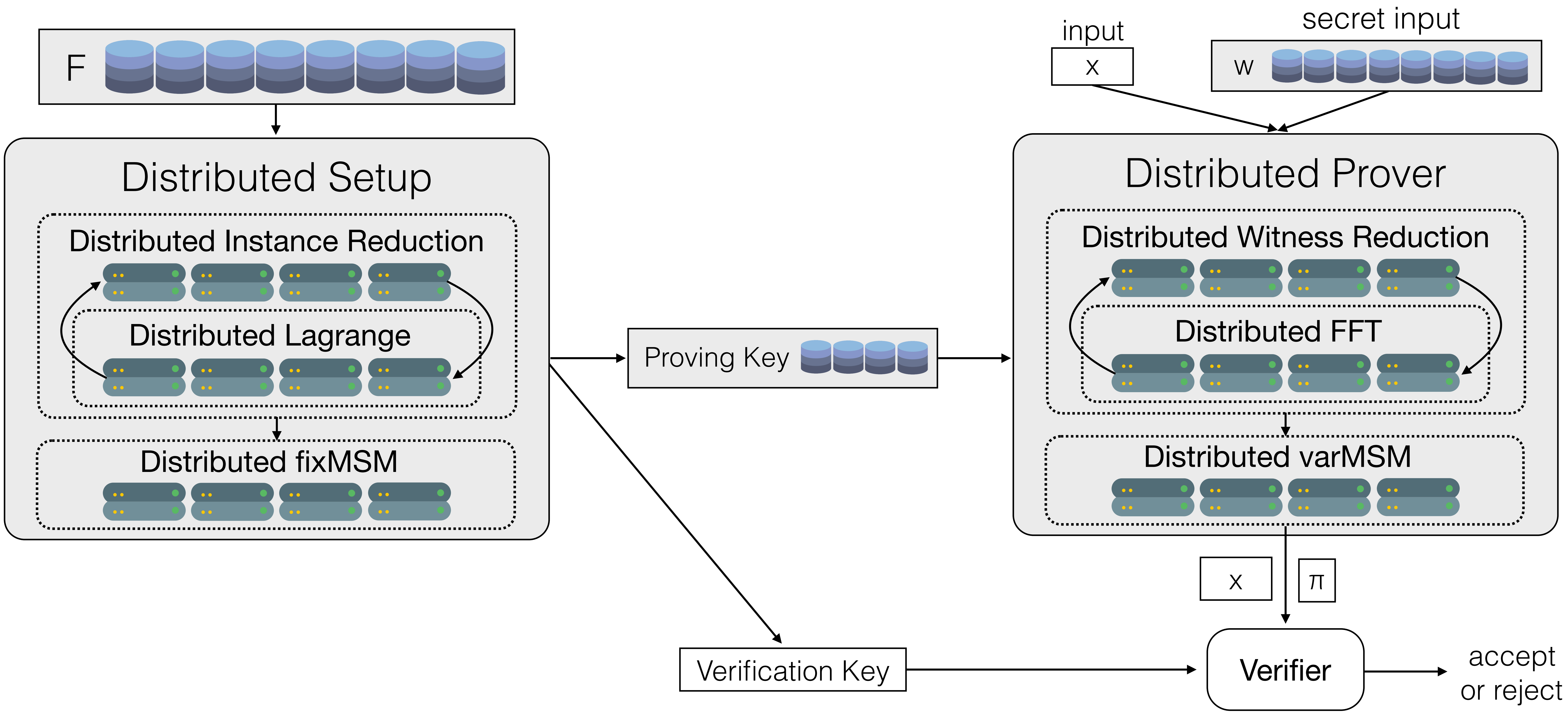

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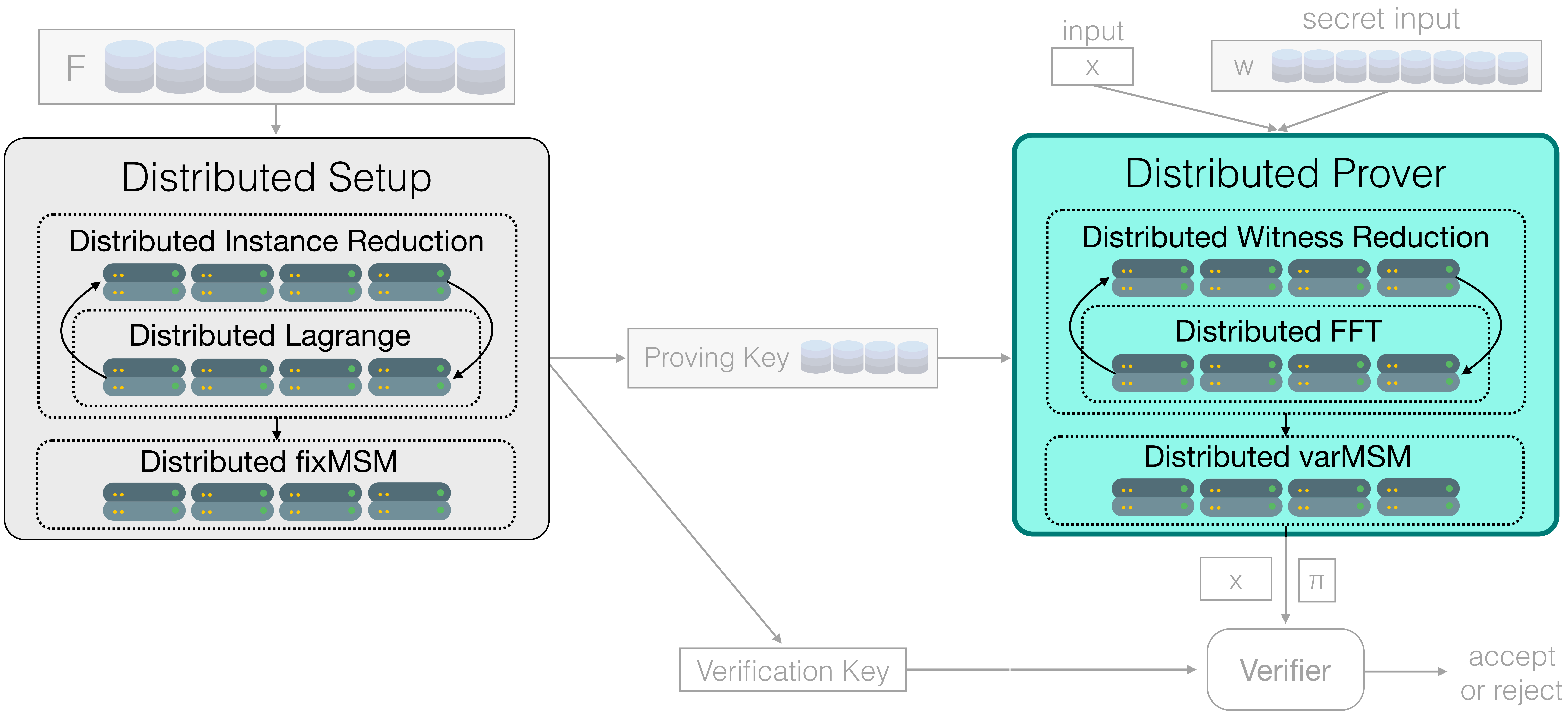

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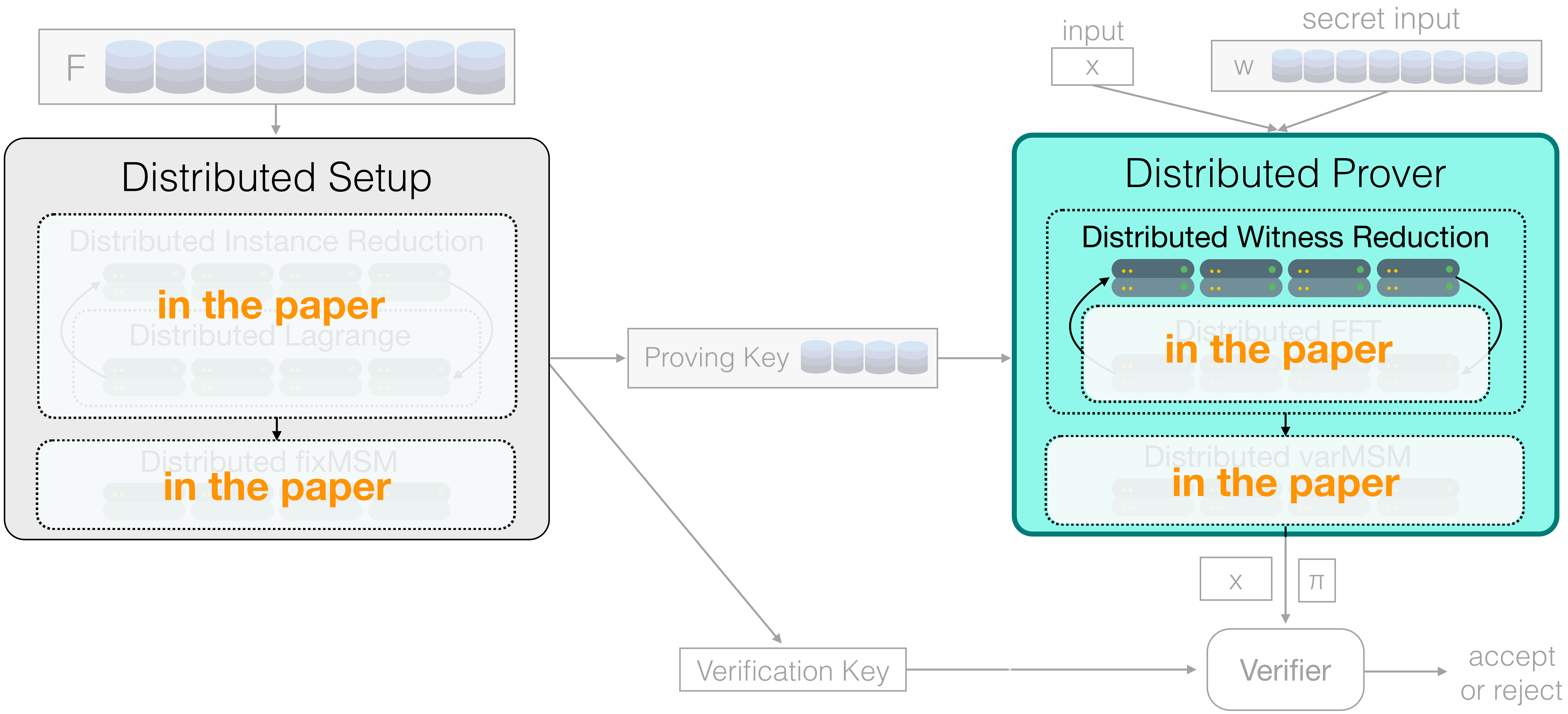

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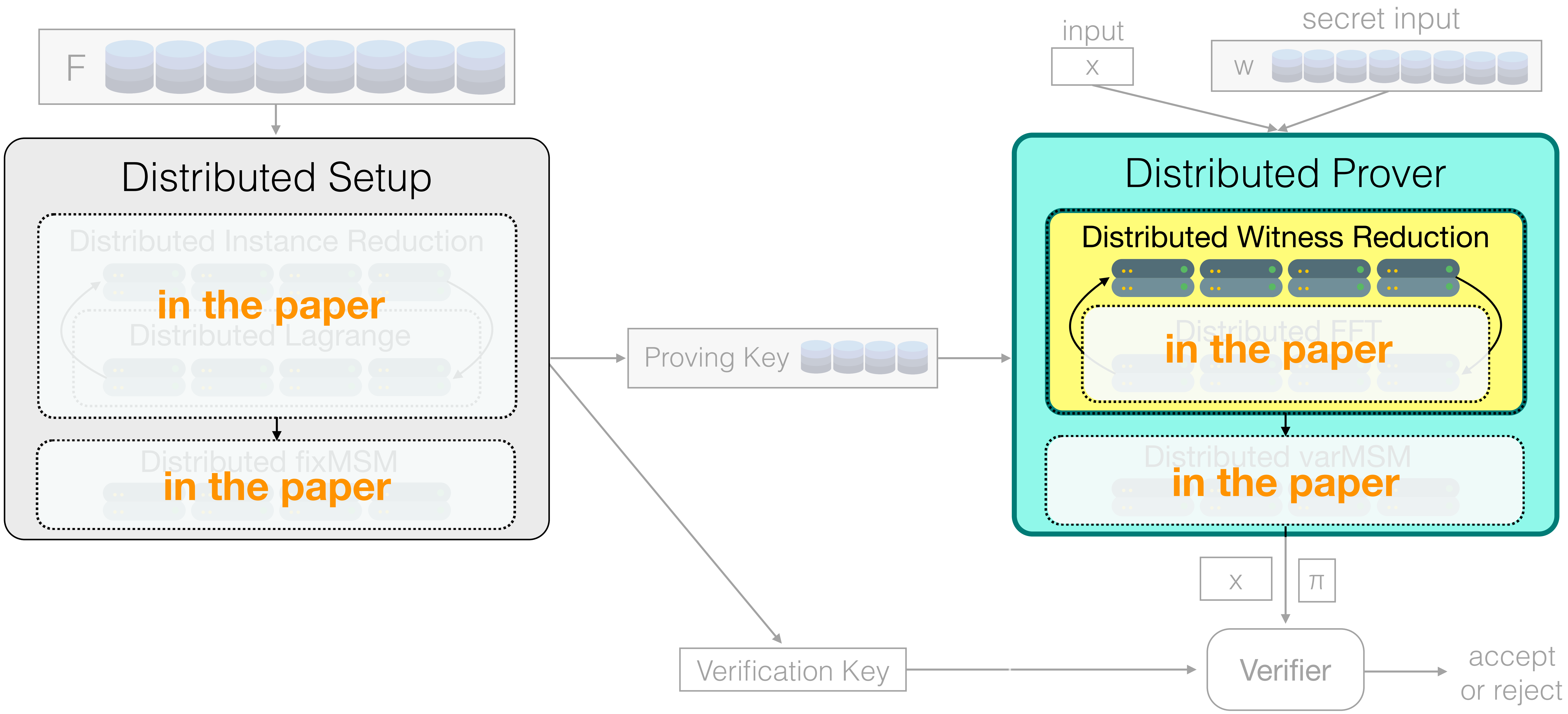

Witness Reduction

[GGPR 13]

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Billion gate **circuit** → Billion degree **polynomial**

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$$\boxed{H(X) = \frac{\left(\sum_{i=0}^{N} A_i(X)\, z_i\right) \cdot \left(\sum_{i=0}^{N} B_i(X)\, z_i\right) - \left(\sum_{i=0}^{N} C_i(X)\, z_i\right)}{Z_D(X)}}$$

Witness Reduction

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Billion gate **circuit** → Billion degree **polynomial**

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matrix $\mathbf{A} = (\mathbf{A}_0, \ldots, \mathbf{A}_N)$

z = vector of N + 1 field elements

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Strawman for $\sum_{i=0}^{N} A_i(X)\ z_i$

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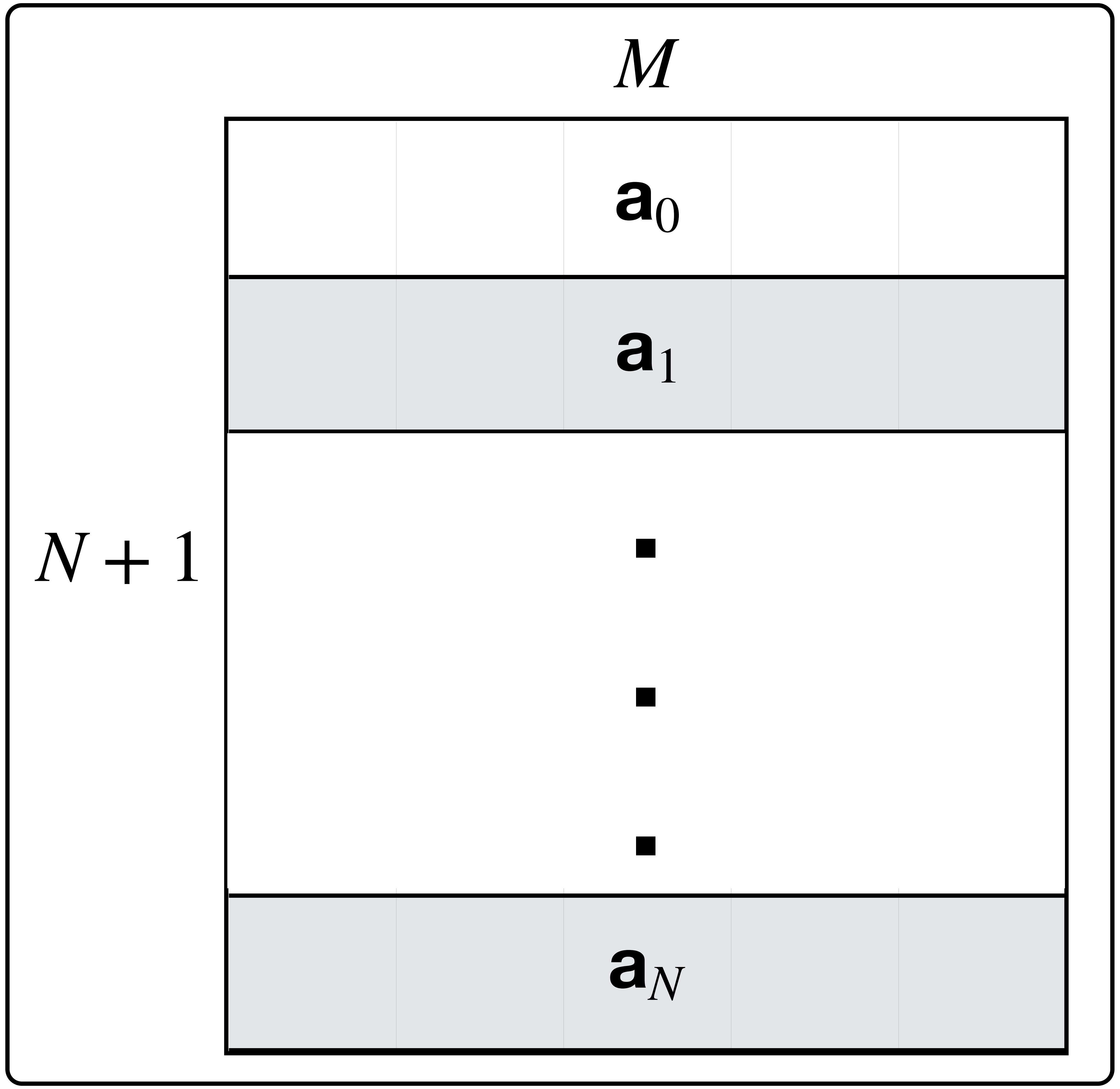

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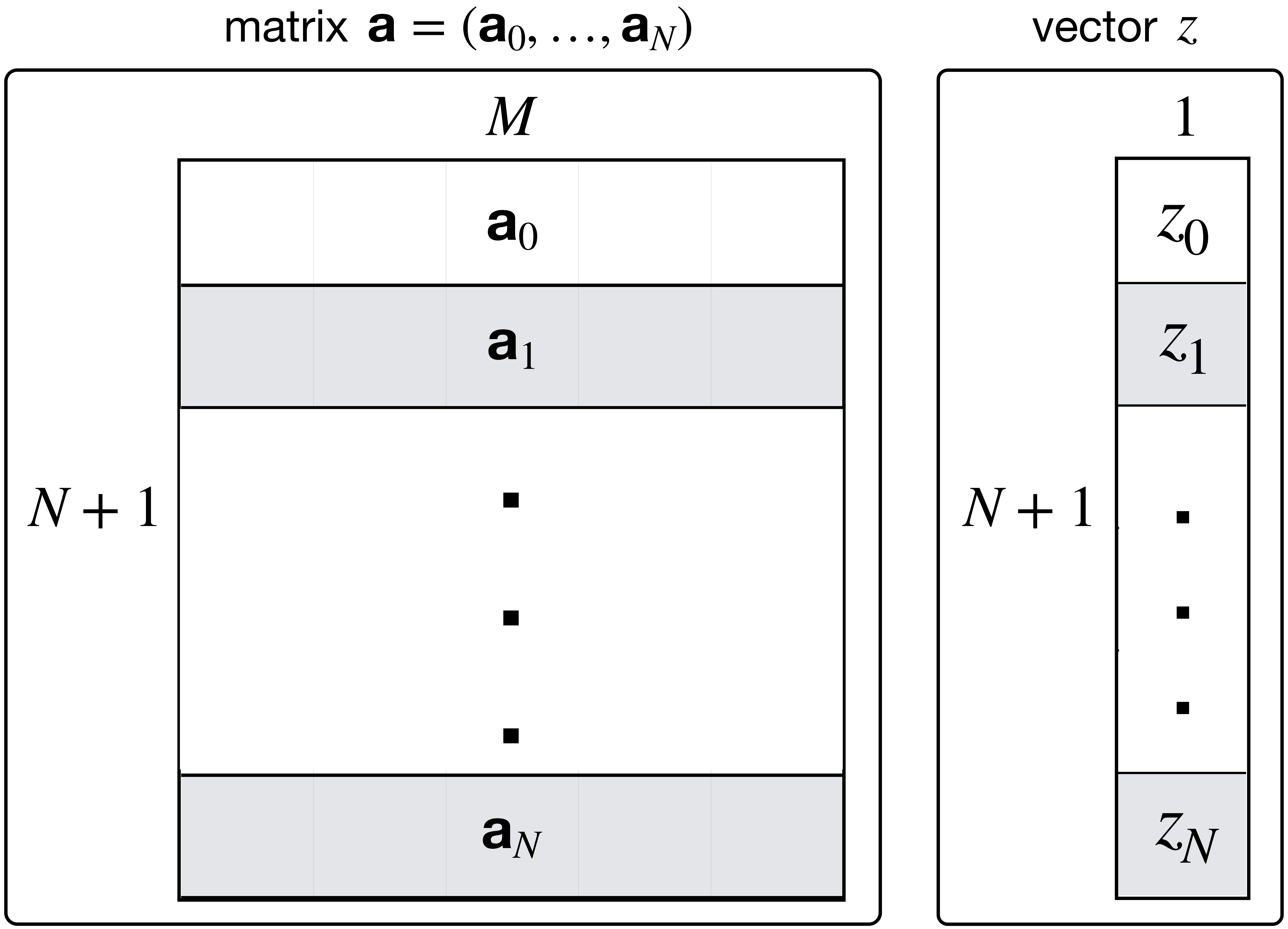

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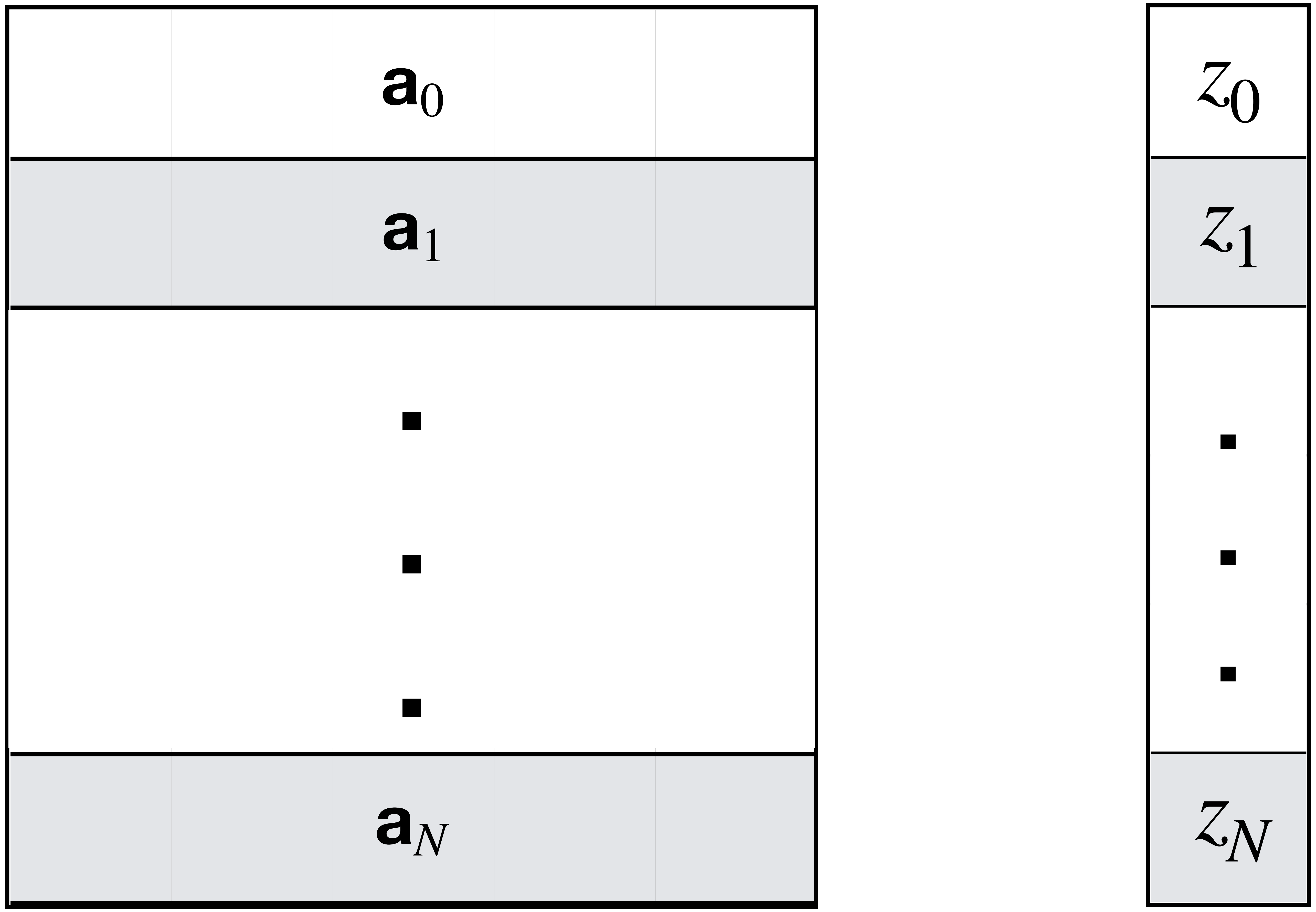

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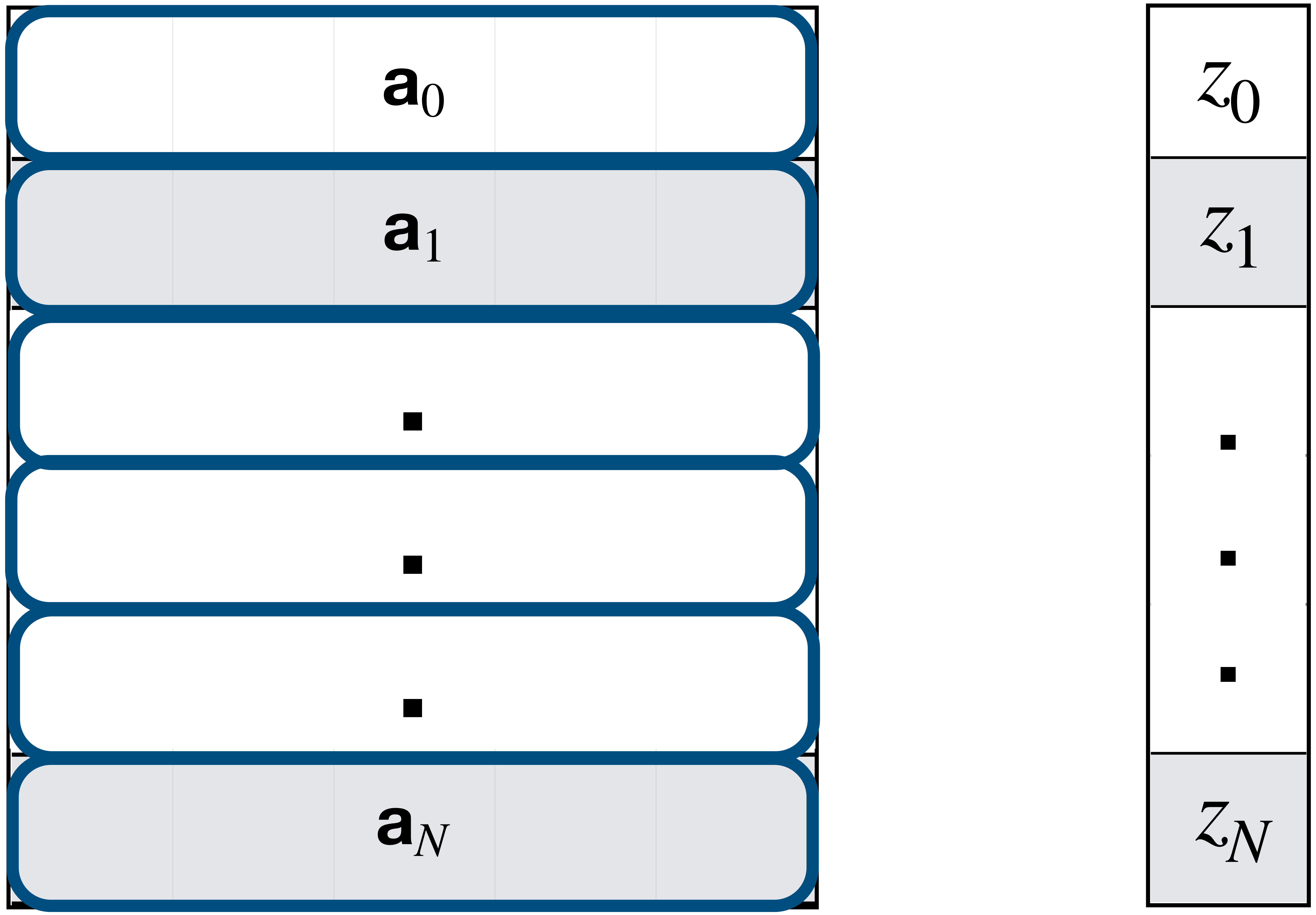

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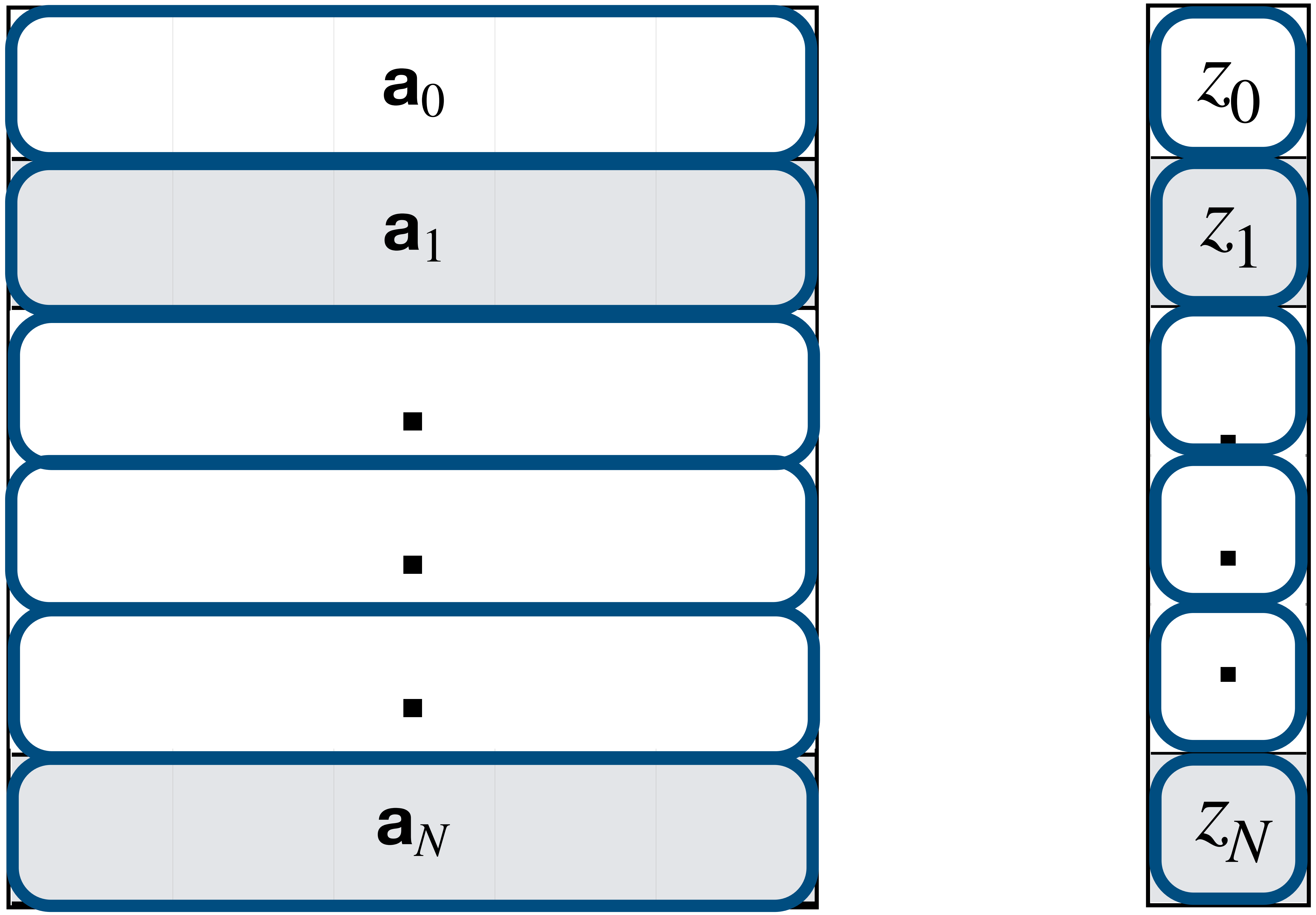

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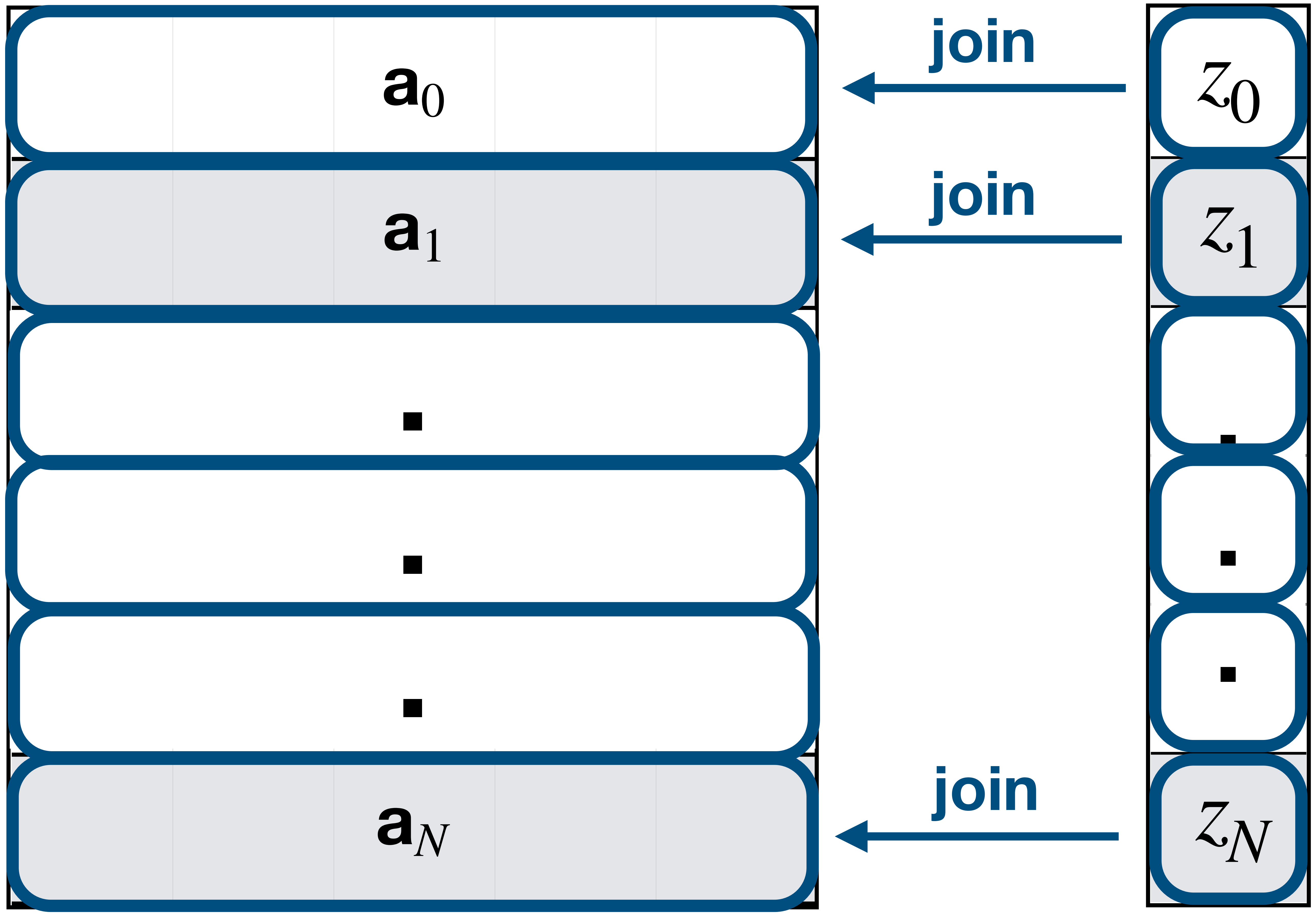

Strawman for $\sum_{i=0}^{N} A_i(X)\ z_i$

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$(\mathbf{a}_i,\ z_i)$ pairs

$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M}, z_0)$
$(\mathbf{a}_{1,0}, z_1)$	$(\mathbf{a}_{1,1}, z_1)$	$(\mathbf{a}_{1,2}, z_1)$	$\cdots$	$(\mathbf{a}_{1,M}, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M}, z_N)$

Strawman for $\sum_{i=0}^{N} A_i(X)\, z_i$

$(991, z_0)$	$(681, z_0)$	$(1978, z_0)$	$\cdots$	$(517, z_0)$
$(0, z_1)$	$(2476, z_1)$	$(0, z_1)$	$\cdots$	$(0, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	$\cdots$	$(0, z_N)$

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Almost sparse

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$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	$\cdots$	$(0, z_N)$

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$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	$\cdots$	$(0, z_N)$

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$(0, z_1)$	$(2476, z_1)$	$(0, z_1)$		$\cdots$		$(0, z_1)$
$\vdots$	$\vdots$	$\vdots$		$\ddots$		$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$		$\cdots$		$(0, z_N)$

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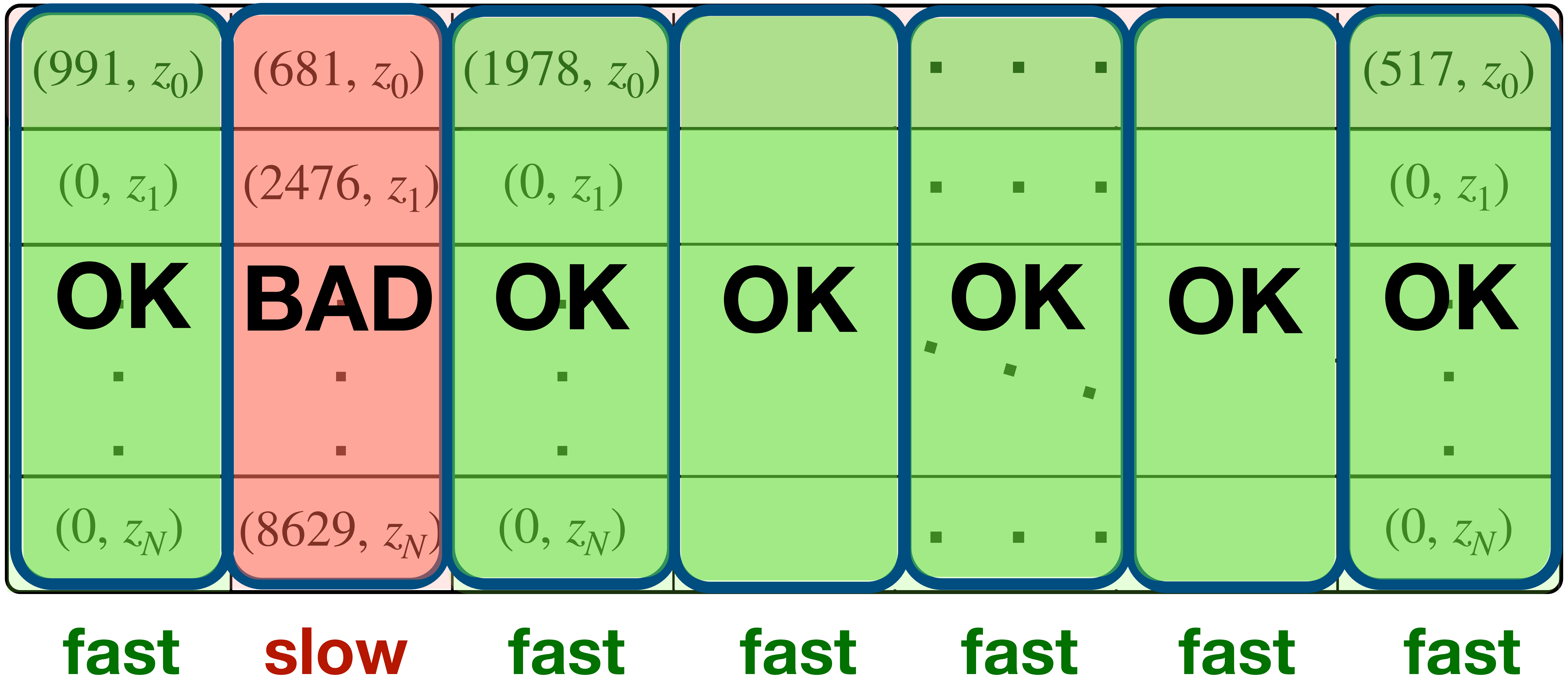

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$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	$\cdots$	$(0, z_N)$

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Almost sparse

$(991, z_0)$	$(681, z_0)$	$(1978, z_0)$	$\cdots$	$(517, z_0)$
$(0, z_1)$	$(2476, z_1)$	$(0, z_1)$	$\cdots$	$(0, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	$\cdots$	$(0, z_N)$

Strawman for $\sum_{i=0}^{N} A_i(X)\, z_i$

Almost sparse

$(991, z_0)$	$(681, z_0)$	$(1978, z_0)$	**BAD** $\cdots$	$(517, z_0)$	**slow**
$(0, z_1)$	$(2476, z_1)$	$(0, z_1)$	**OK** $\cdots$	$(0, z_1)$	**fast**
$\vdots$	$\vdots$	$\vdots$	**OK** $\ddots$	$\vdots$	**fast**
			OK		**fast**
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	**OK** $\cdots$	$(0, z_N)$	**fast**

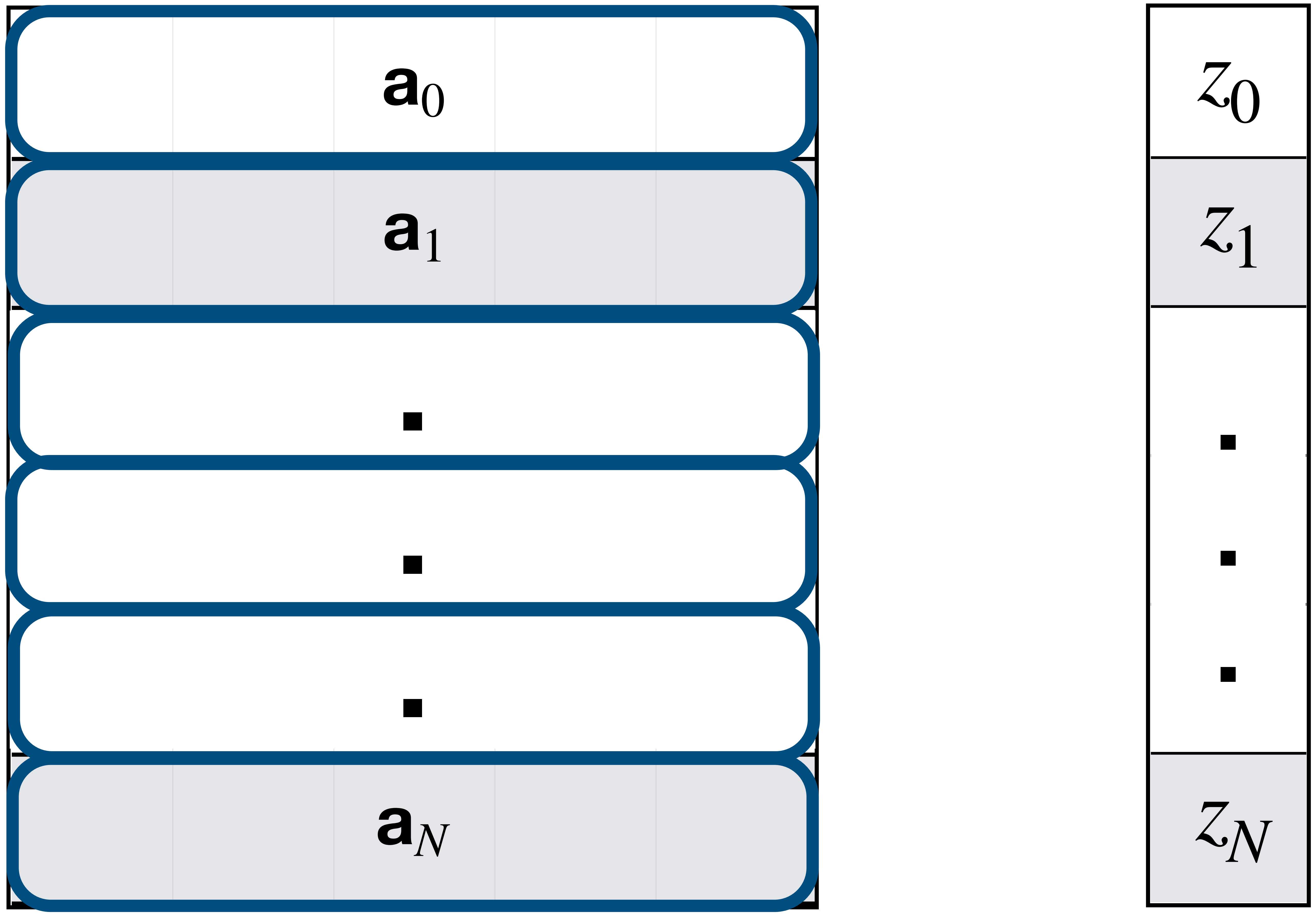
Off-the-shelf Approaches

Off-the-shelf Approaches

Replicate and ***partition*** the data
so that the computation is **distributed evenly**.

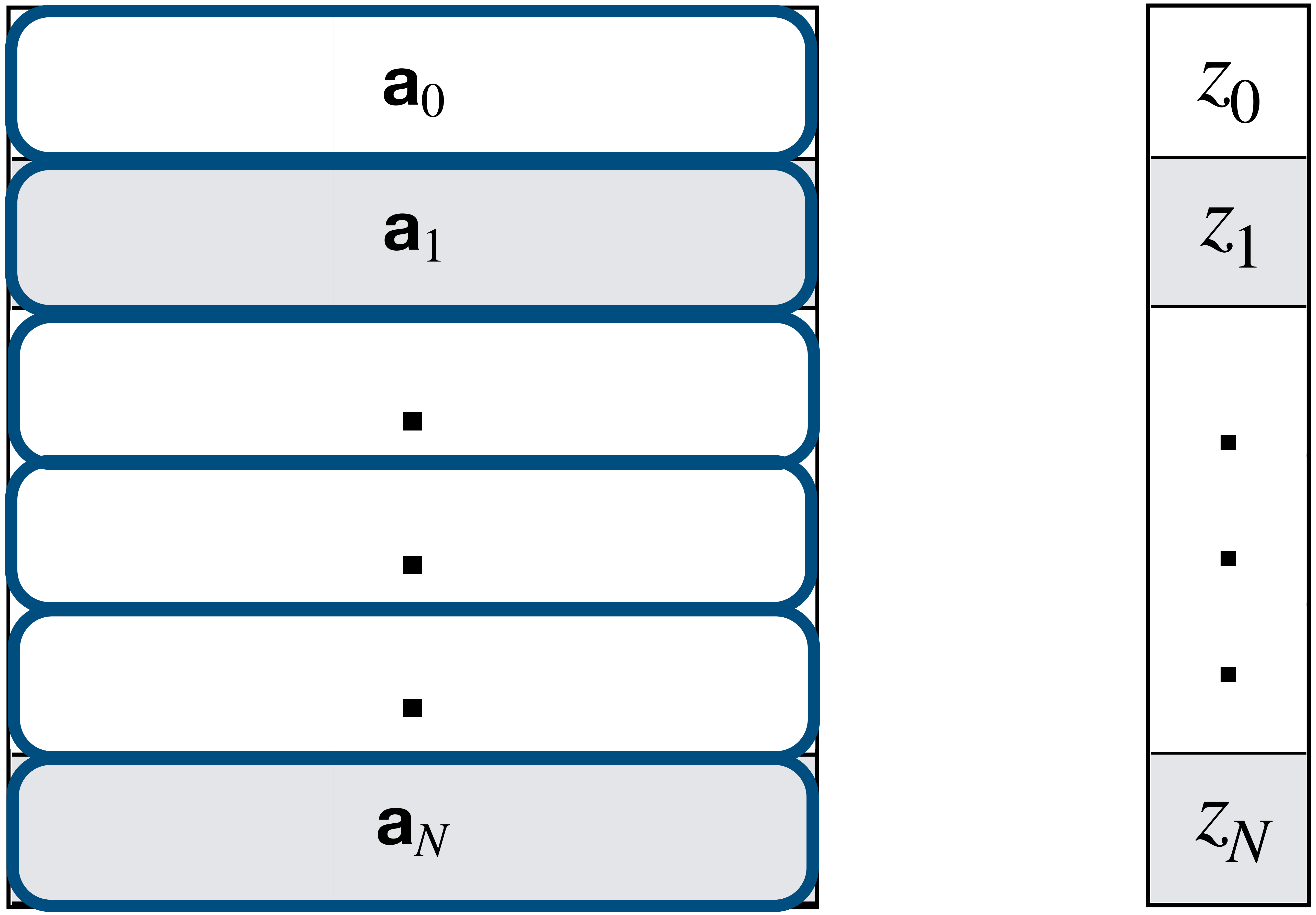
blockjoin

(Common technique to address data skew)



blockjoin

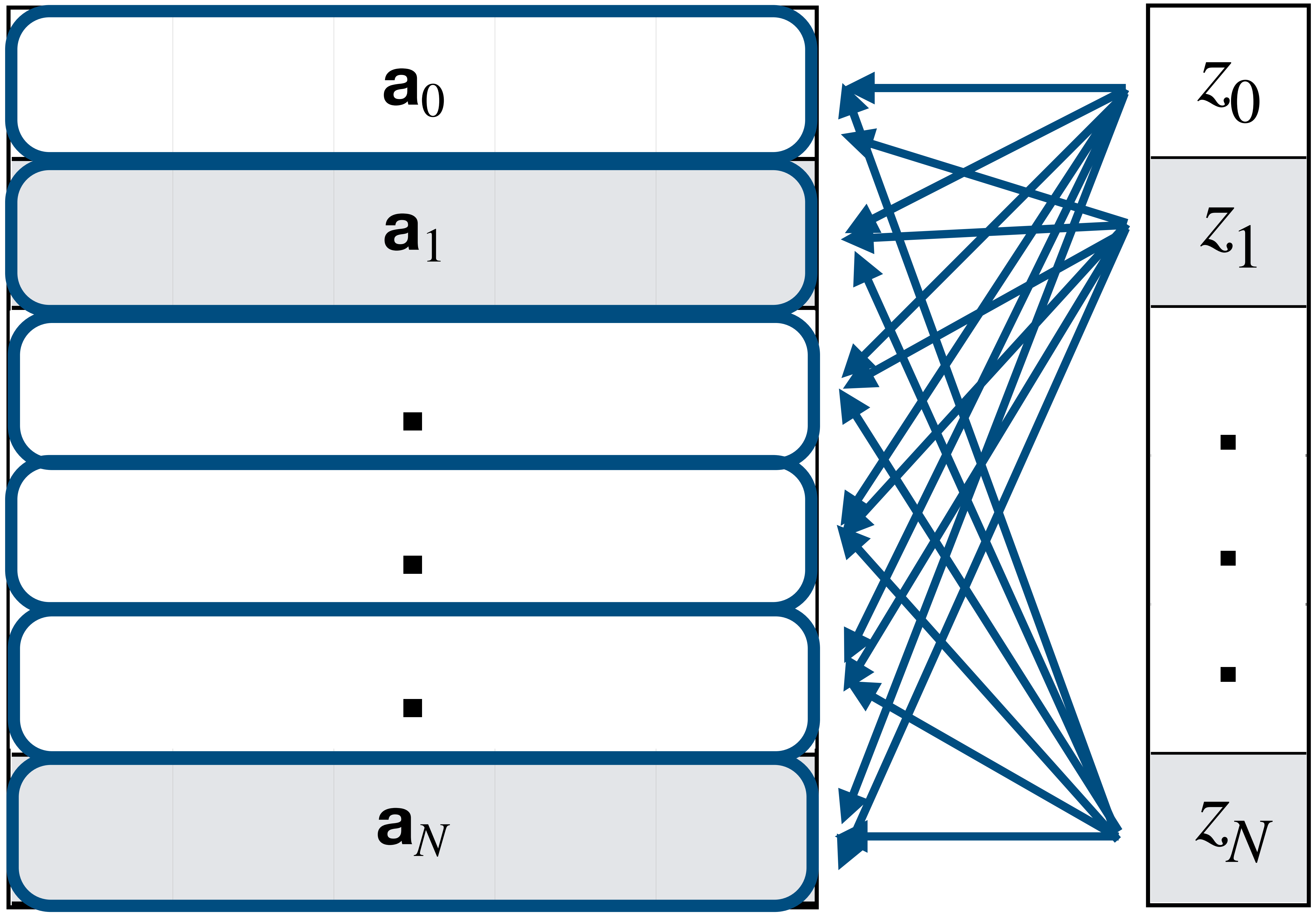
(Common technique to address data skew)



Replicated each entry for *every* machine

blockjoin

(Common technique to address data skew)



Replicated each entry for *every* machine

`blockjoin`

(Common technique to address data skew)

$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$(\mathbf{a}_{0,3}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_0)$	$(\mathbf{a}_{0,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$
$(\mathbf{a}_{0,0}, z_N)$	$(\mathbf{a}_{0,1}, z_N)$	$(\mathbf{a}_{0,2}, z_N)$	$(\mathbf{a}_{0,3}, z_N)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_N)$	$(\mathbf{a}_{0,M}, z_N)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
$(\mathbf{a}_{N,0}, z_0)$	$(\mathbf{a}_{N,1}, z_0)$	$(\mathbf{a}_{N,2}, z_0)$	$(\mathbf{a}_{N,3}, z_0)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$		
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$(\mathbf{a}_{N,3}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_N)$

`blockjoin` (N + 1) * (# partitions) replications

(Common technique to address data skew)

$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$(\mathbf{a}_{0,3}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_0)$	$(\mathbf{a}_{0,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$
$(\mathbf{a}_{0,0}, z_N)$	$(\mathbf{a}_{0,1}, z_N)$	$(\mathbf{a}_{0,2}, z_N)$	$(\mathbf{a}_{0,3}, z_N)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_N)$	$(\mathbf{a}_{0,M}, z_N)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
$(\mathbf{a}_{N,0}, z_0)$	$(\mathbf{a}_{N,1}, z_0)$	$(\mathbf{a}_{N,2}, z_0)$	$(\mathbf{a}_{N,3}, z_0)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$		
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$(\mathbf{a}_{N,3}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_N)$

blockjoin

(Common technique to address data skew)

Billions

(N + 1) * (# partitions) replications

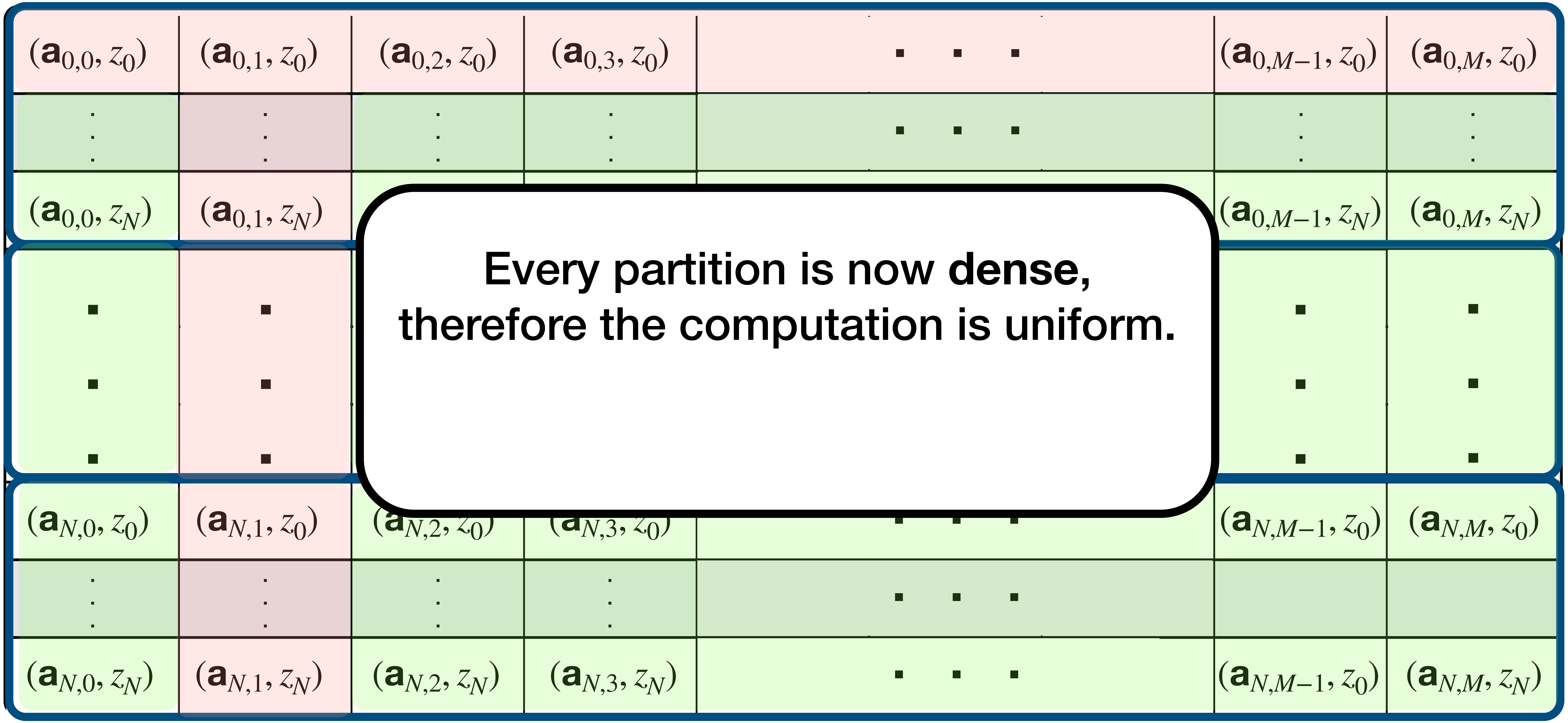
$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$(\mathbf{a}_{0,3}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_0)$	$(\mathbf{a}_{0,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$
$(\mathbf{a}_{0,0}, z_N)$	$(\mathbf{a}_{0,1}, z_N)$	$(\mathbf{a}_{0,2}, z_N)$	$(\mathbf{a}_{0,3}, z_N)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_N)$	$(\mathbf{a}_{0,M}, z_N)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
$(\mathbf{a}_{N,0}, z_0)$	$(\mathbf{a}_{N,1}, z_0)$	$(\mathbf{a}_{N,2}, z_0)$	$(\mathbf{a}_{N,3}, z_0)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$		
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$(\mathbf{a}_{N,3}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_N)$

blockjoin

(Common technique to address data skew)

Billions

(N + 1) * (# partitions) replications



blockjoin

(Common technique to address data skew)

(N + 1) * (# partitions) replications

Billions

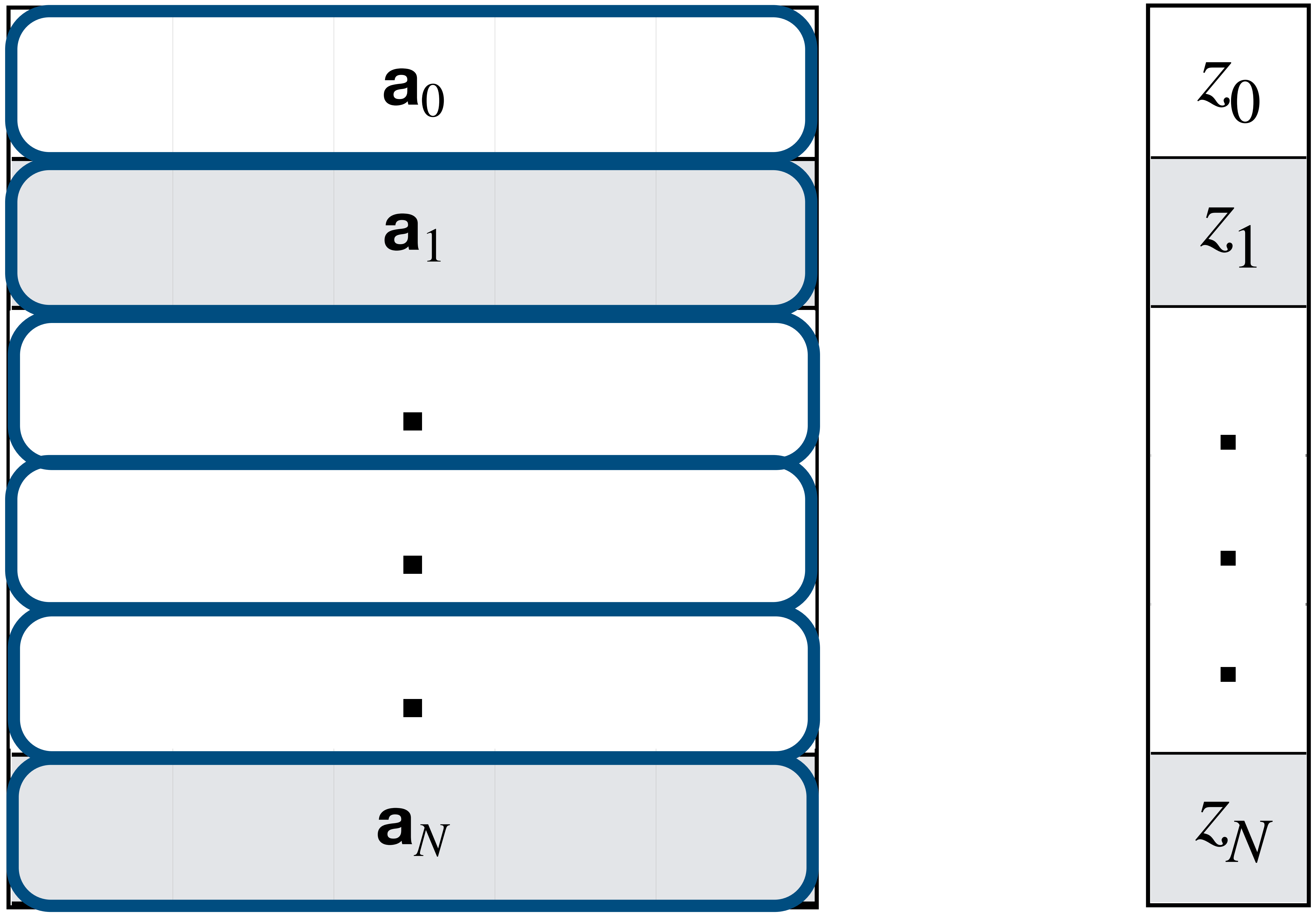
$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$(\mathbf{a}_{0,3}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M-1}, z_0)$	$(\mathbf{a}_{0,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$
$(\mathbf{a}_{0,0}, z_N)$	$(\mathbf{a}_{0,1}, z_N)$				$(\mathbf{a}_{0,M-1}, z_N)$	$(\mathbf{a}_{0,M}, z_N)$
$\vdots$	$\vdots$				$\vdots$	$\vdots$
$(\mathbf{a}_{N,0}, z_0)$	$(\mathbf{a}_{N,1}, z_0)$	$(\mathbf{a}_{N,2}, z_0)$	$(\mathbf{a}_{N,3}, z_0)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_0)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\cdots$		
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$(\mathbf{a}_{N,3}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M-1}, z_0)$	$(\mathbf{a}_{N,M}, z_N)$

Every partition is now **dense**, therefore the computation is uniform.

(However, the table is huge and impractical to compute)

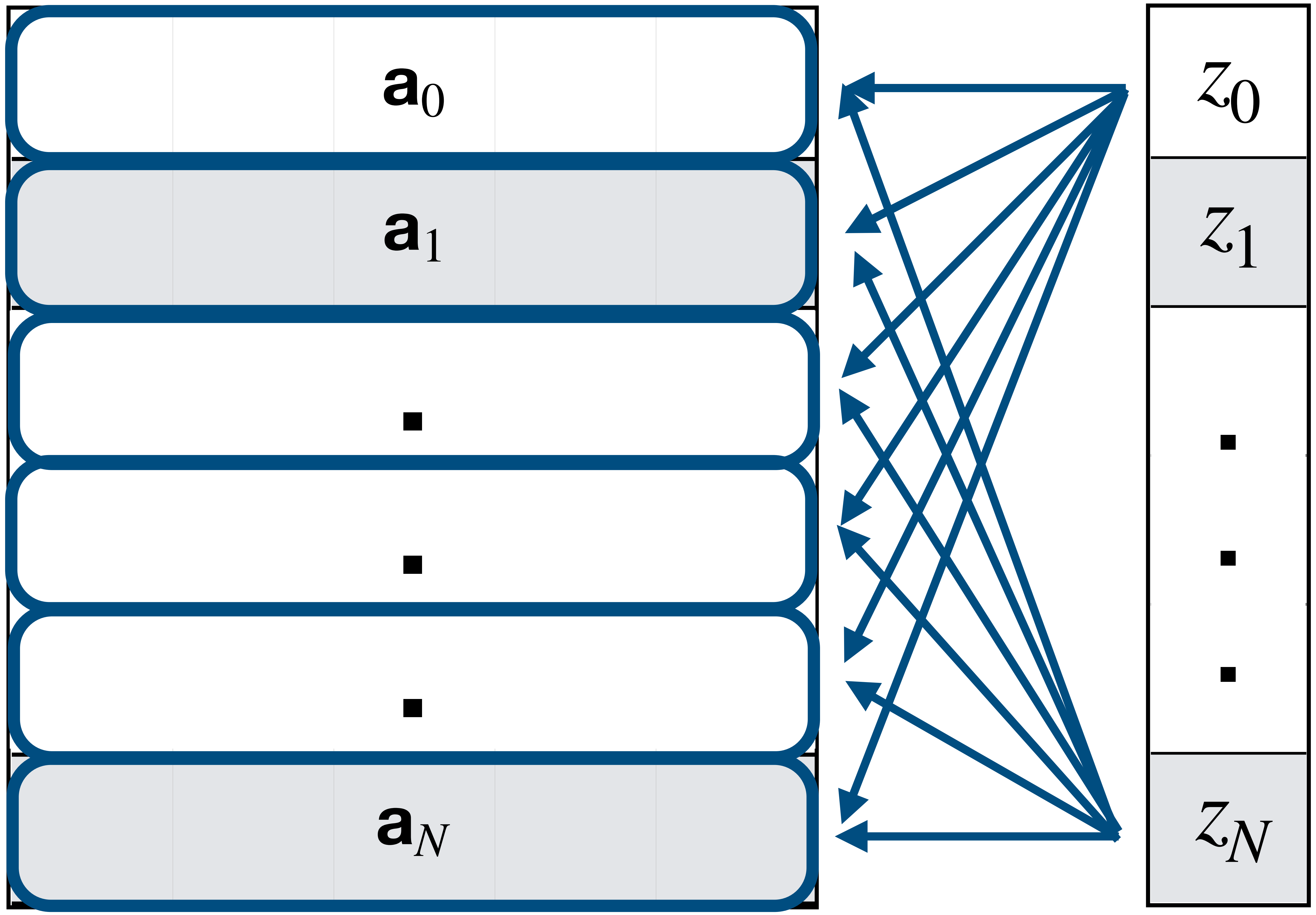
skewjoin

(Another common technique to address data skew. Source: *Tresata*)



skewjoin

(Another common technique to address data skew. Source: *Tresata*)



Compute usage *statistics* and replicate *frequently-used* entries for every machine

skewjoin

(Another common technique to address data skew. Source: *Tresata*)

$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M}, z_0)$
$(\mathbf{a}_{1,0}, z_1)$	$(\mathbf{a}_{1,1}, z_1)$	$(\mathbf{a}_{1,2}, z_1)$	$\cdots$	$(\mathbf{a}_{1,M}, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M}, z_N)$

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(Another common technique to address data skew. Source: *Tresata*)

$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M}, z_0)$
$(\mathbf{a}_{1,0}, z_1)$	$(\mathbf{a}_{1,1}, z_1)$	$(\mathbf{a}_{1,2}, z_1)$	$\cdots$	$(\mathbf{a}_{1,M}, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M}, z_N)$

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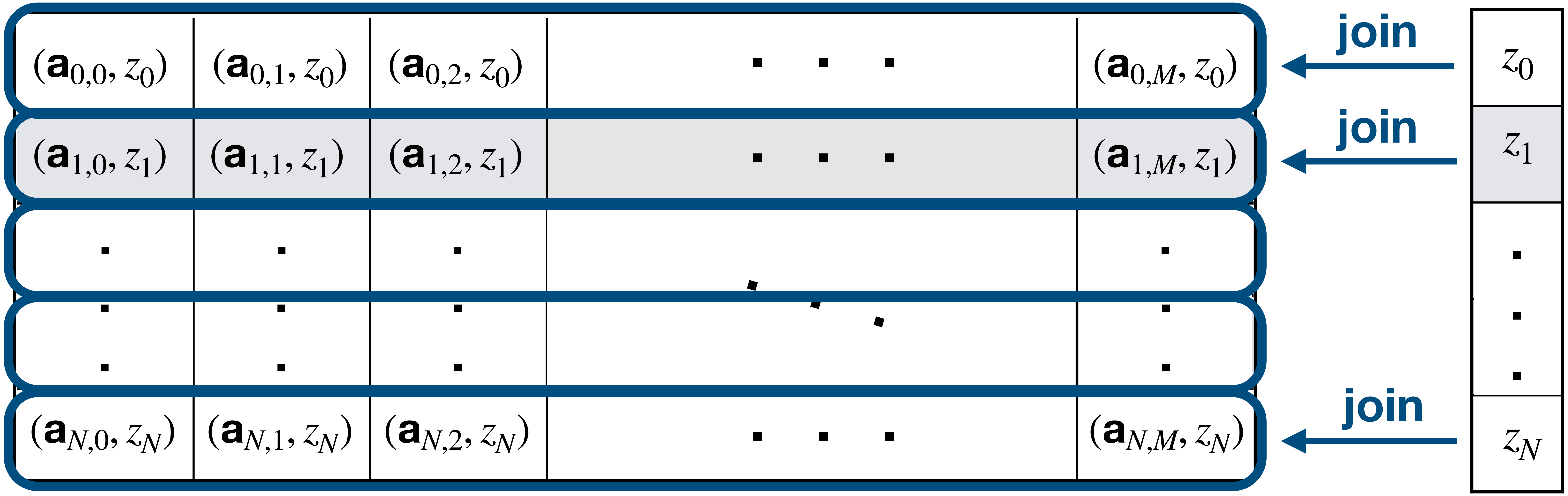
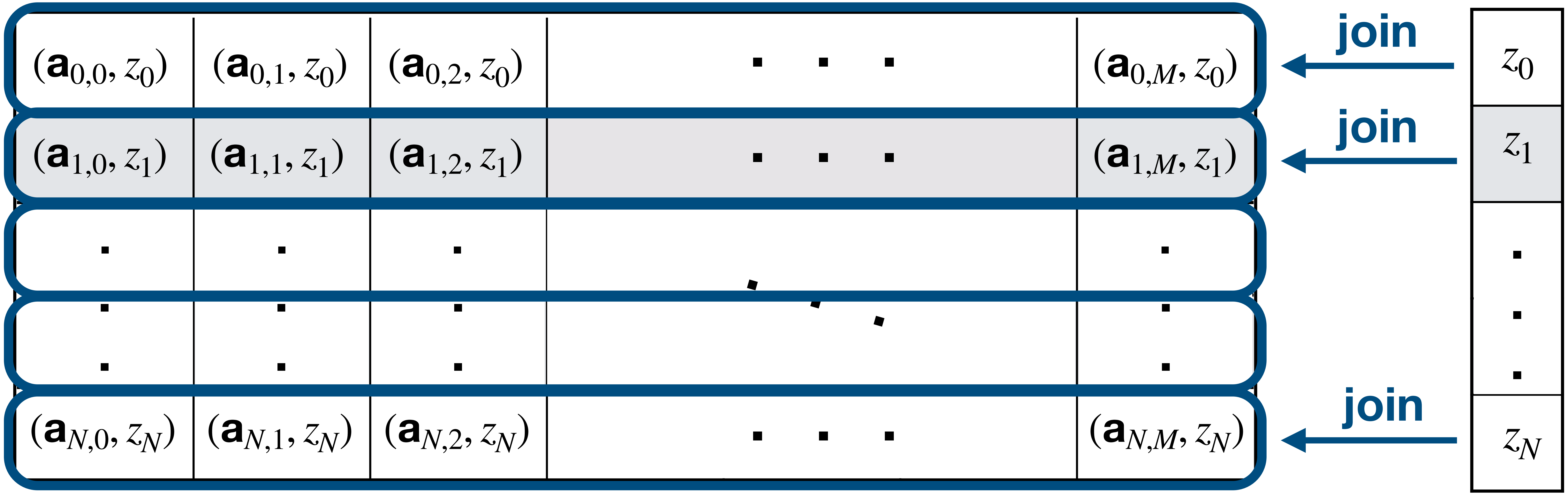


`skewjoin` == Strawman

(Another common technique to address data skew. Source: *Tresata*)



skewjoin

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$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$	$\cdots$	$(\mathbf{a}_{0,M}, z_0)$
$(\mathbf{a}_{1,0}, z_1)$	$(\mathbf{a}_{1,1}, z_1)$	$(\mathbf{a}_{1,2}, z_1)$	$\cdots$	$(\mathbf{a}_{1,M}, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$	$\cdots$	$(\mathbf{a}_{N,M}, z_N)$

`skewjoin`

(Another common technique to address data skew. Source: *Tresata*)

$(\mathbf{a}_{0,0}, z_0)$	$(\mathbf{a}_{0,1}, z_0)$	$(\mathbf{a}_{0,2}, z_0)$		$\cdots$		$(\mathbf{a}_{0,M}, z_0)$
$(\mathbf{a}_{1,0}, z_1)$	$(\mathbf{a}_{1,1}, z_1)$	$(\mathbf{a}_{1,2}, z_1)$		$\cdots$		$(\mathbf{a}_{1,M}, z_1)$
$\vdots$	$\vdots$	$\vdots$		$\ddots$		$\vdots$
$(\mathbf{a}_{N,0}, z_N)$	$(\mathbf{a}_{N,1}, z_N)$	$(\mathbf{a}_{N,2}, z_N)$		$\cdots$		$(\mathbf{a}_{N,M}, z_N)$

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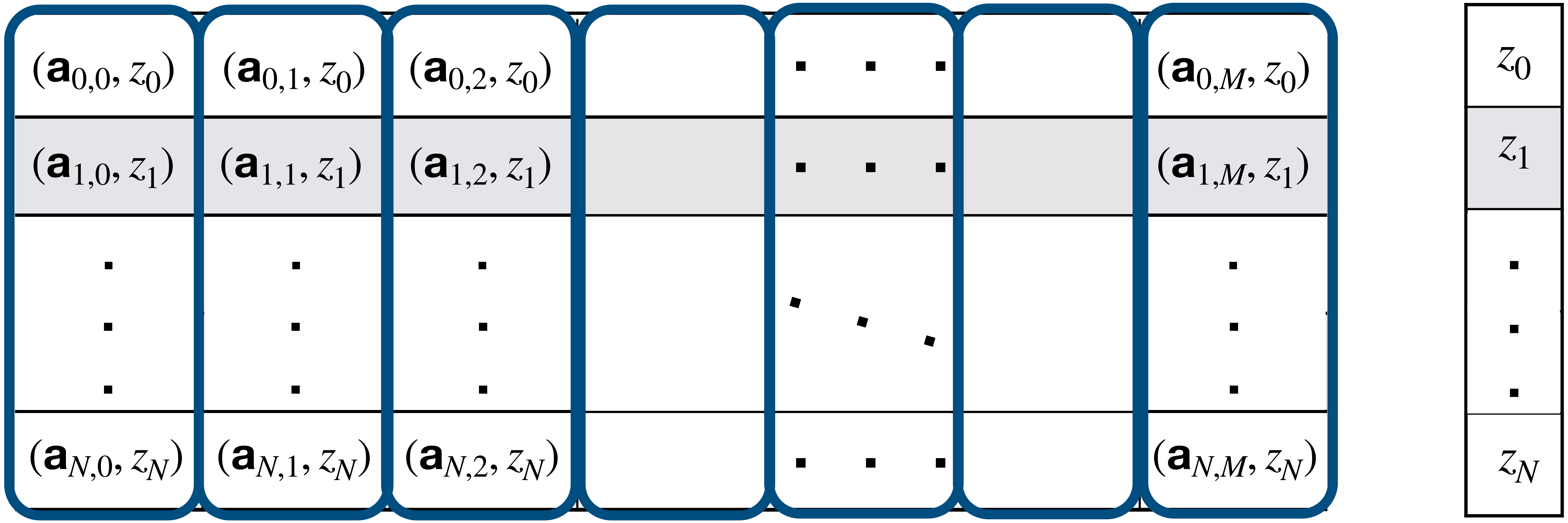

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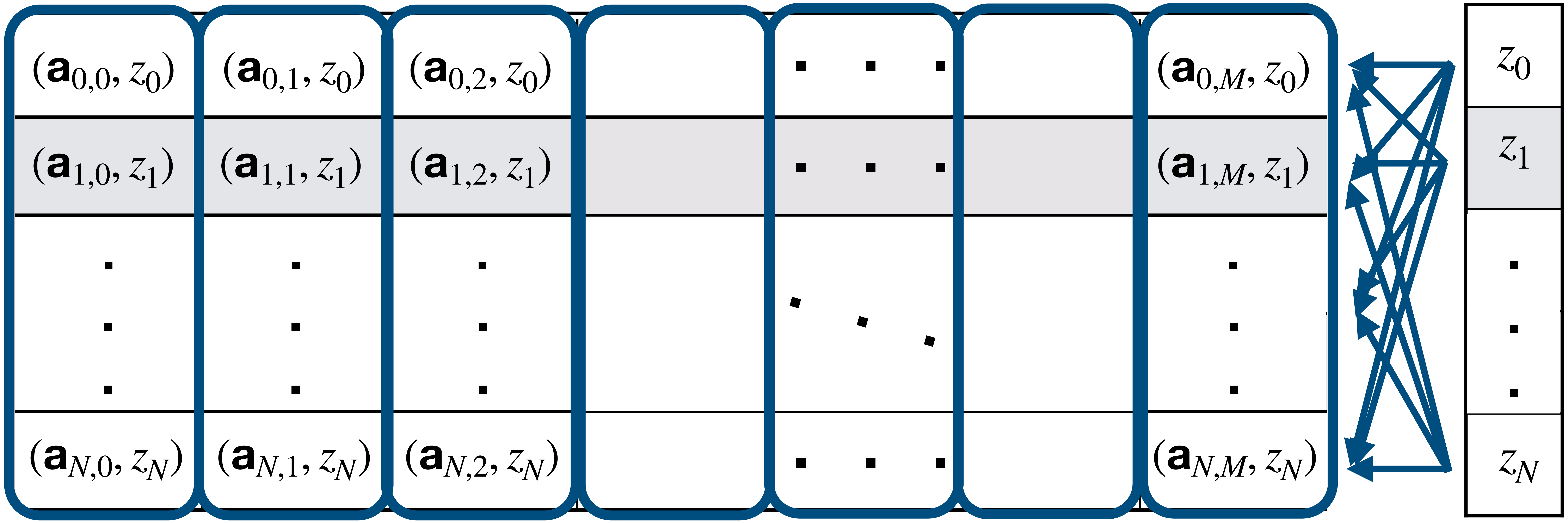
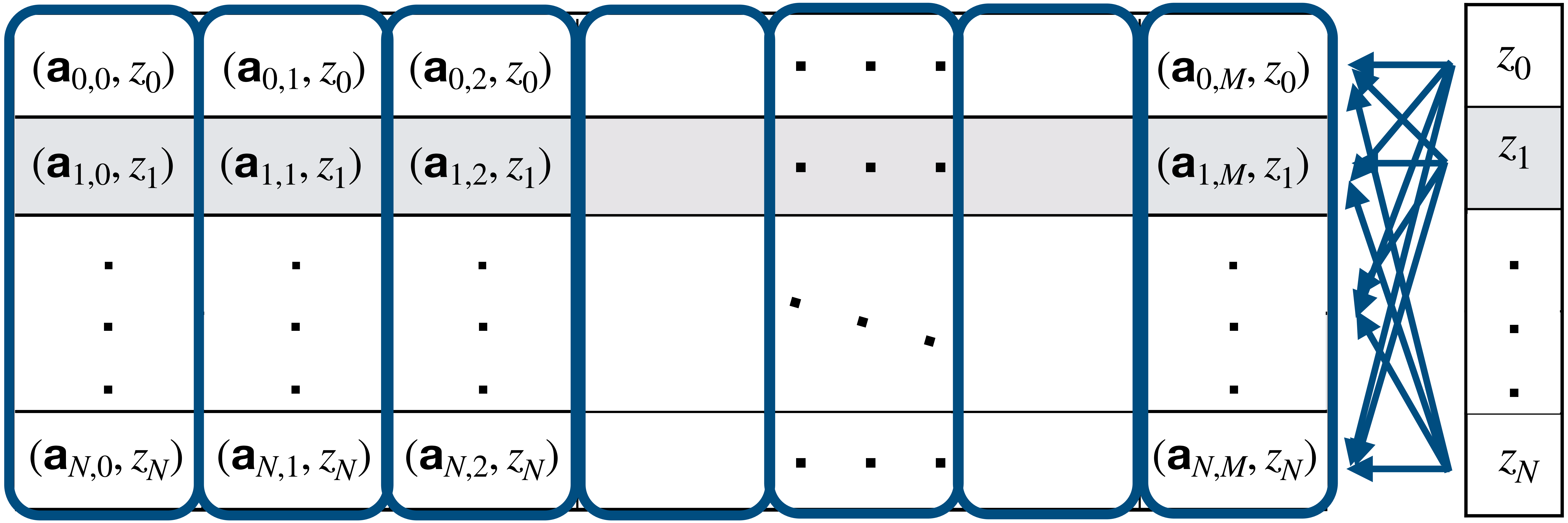


`skewjoin` == `blockjoin`

(Another common technique to address data skew. Source: *Tresata*)



Tailored Approach

Tailored Approach

Isolate and ***transform*** the data
so that the computation is **distributed evenly.**

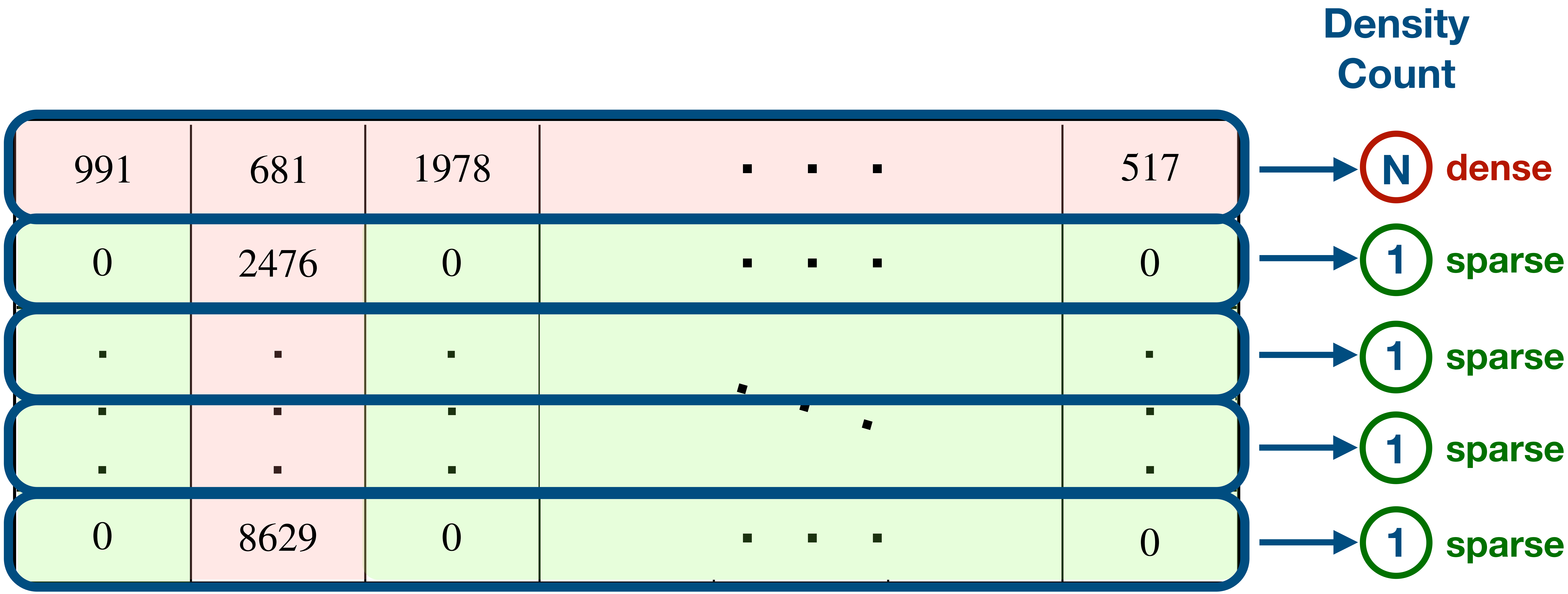
Tailored Approach — Part 1

Identify Dense Vectors

991	681	1978	. . .	517
0	2476	0	. . .	0
⋮	⋮	⋮	⋱	⋮
0	8629	0	. . .	0

Tailored Approach — Part 1

Identify Dense Vectors



Tailored Approach — Part 2

Employ a Hybrid Solution

Density Count

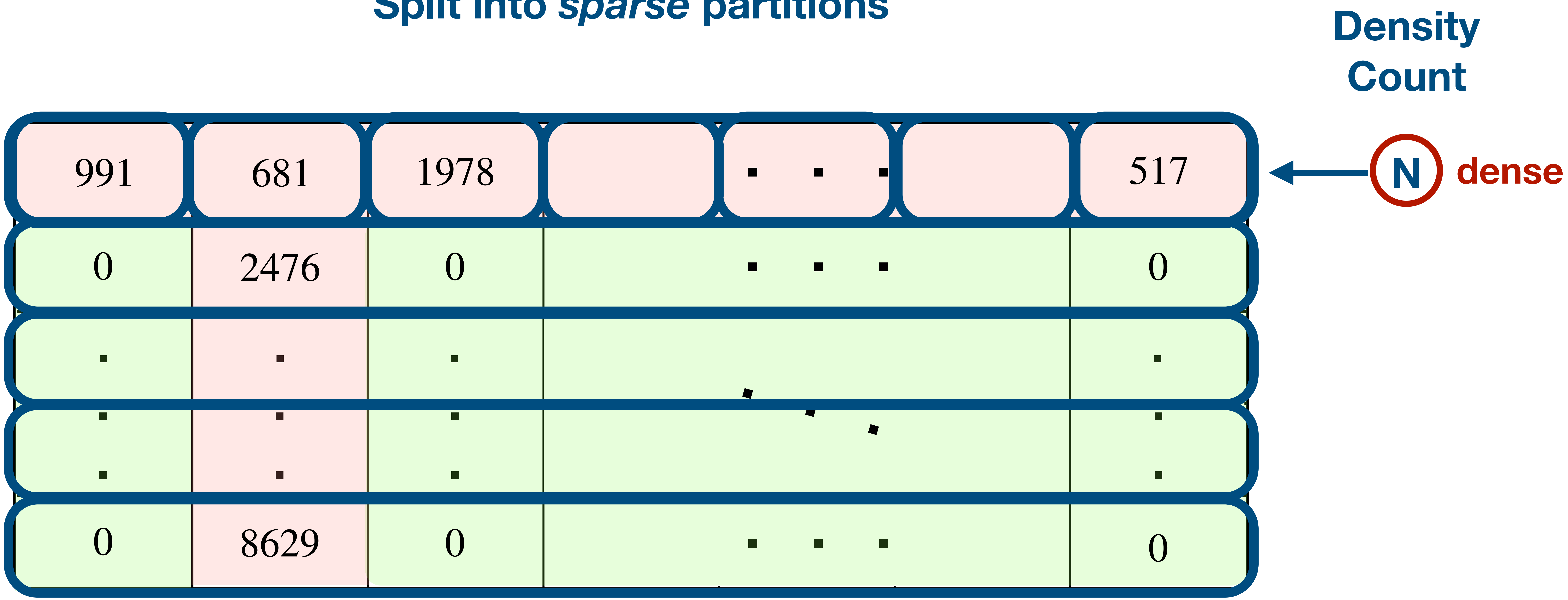
991	681	1978	. . .	517
0	2476	0	. . .	0
⋮	⋮	⋮	⋱	⋮
0	8629	0	. . .	0

N dense

Tailored Approach — Part 2

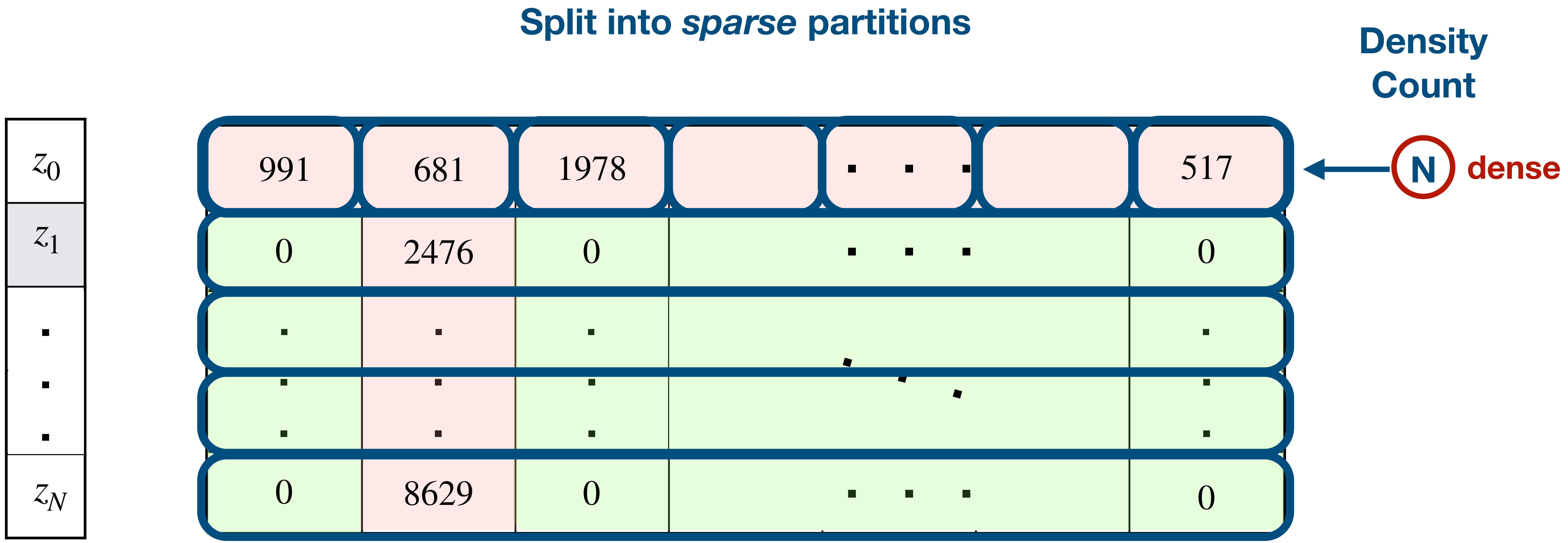
Employ a Hybrid Solution

Split into *sparse* partitions



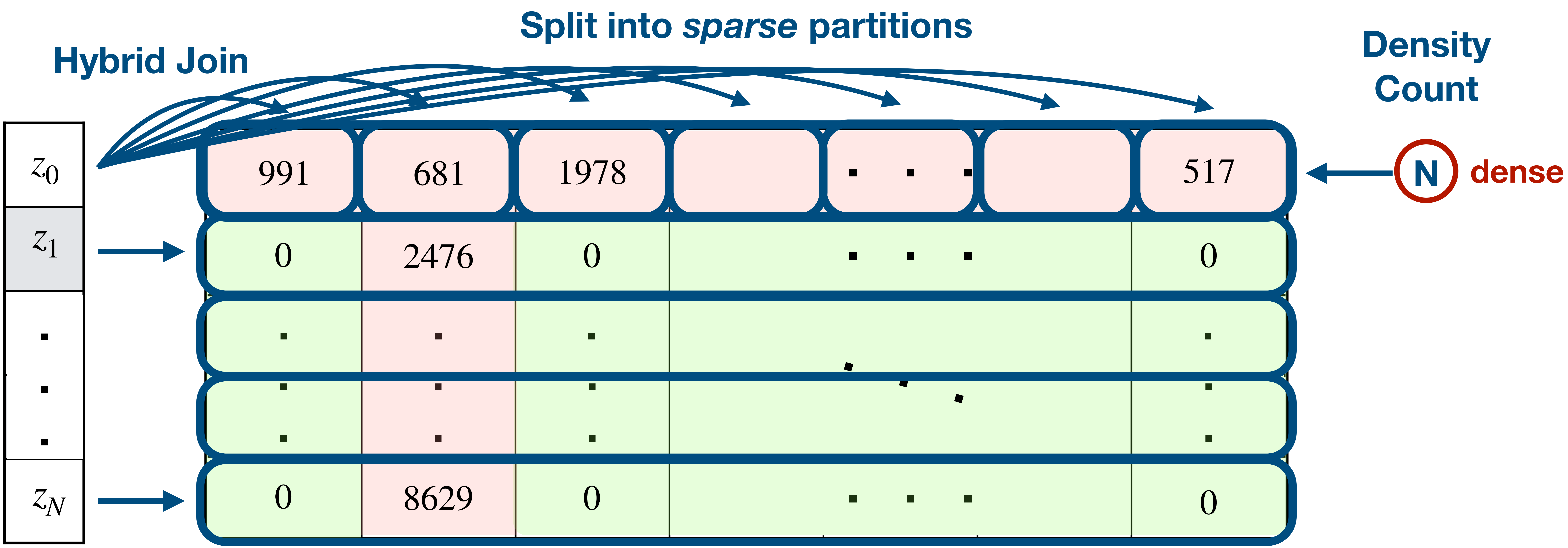
Tailored Approach — Part 2

Employ a Hybrid Solution



Tailored Approach — Part 2

Employ a Hybrid Solution



Tailored Approach — Part 2

Employ a Hybrid Solution

Each partition has just 1 nonzero computation

$(991, z_0)$	$(681, z_0)$	$(1978, z_0)$	$\cdots$	$(517, z_0)$
$(0, z_1)$	$(2476, z_1)$	$(0, z_1)$	$\cdots$	$(0, z_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$	$\cdots$	$(0, z_N)$

Tailored Approach — Part 2

Employ a Hybrid Solution

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$(0, z_1)$	$(2476, z_1)$	$(0, z_1)$		$\cdots$		$(0, z_1)$
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$(0, z_N)$	$(8629, z_N)$	$(0, z_N)$		$\cdots$		$(0, z_N)$

Tailored Approach — Part 2

Employ a Hybrid Solution

Each partition has just 1 nonzero computation

$991 \cdot z_0$	$681 \cdot z_0$	$1978 \cdot z_0$	$\cdots$	$\cdots$	$\cdots$	$517 \cdot z_0$
0	$2476 \cdot z_1$	0		$\cdots$		0
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
0	$8629 \cdot z_N$	0		$\cdots$		0

Implementation

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- Cluster-computing framework on **Apache Spark**

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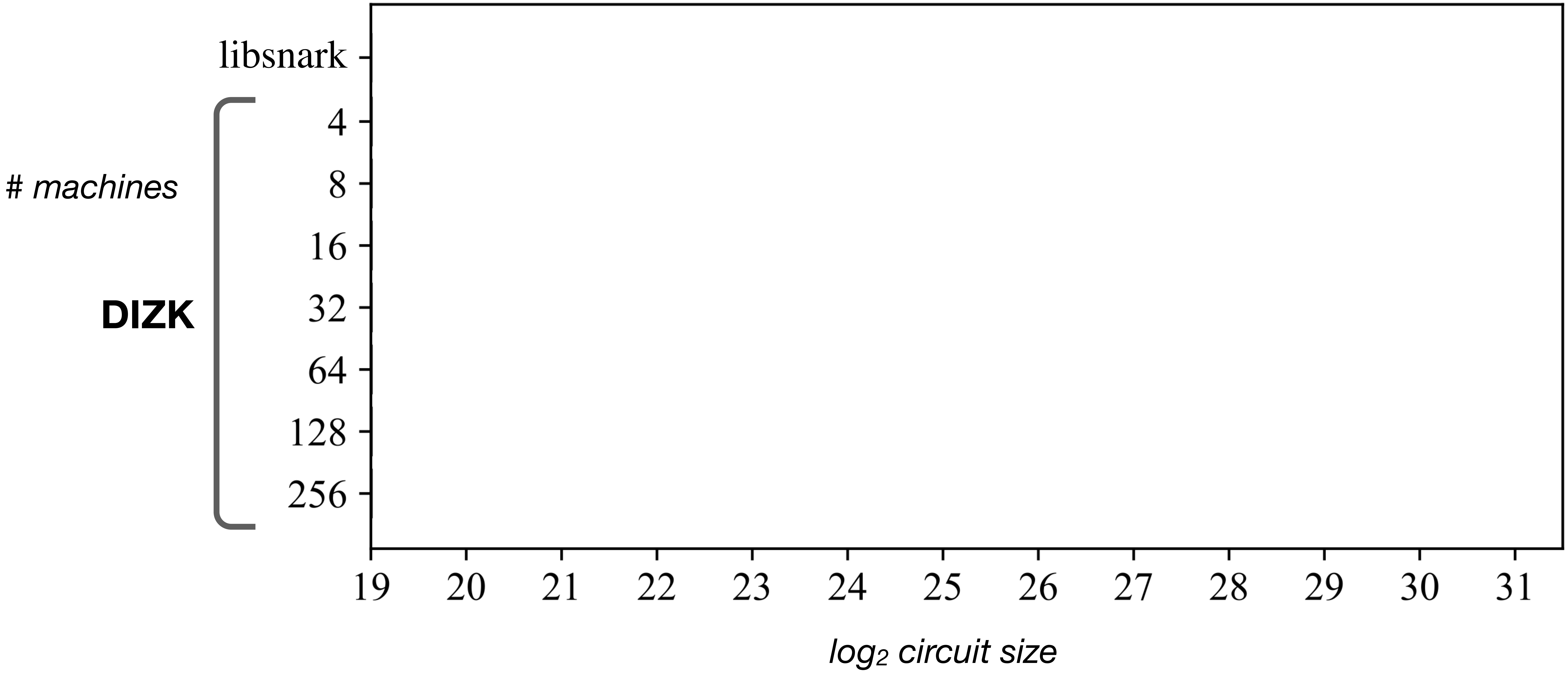
- System written in **Java** (~10k lines of code)

Implementation

- Cluster-computing framework on **Apache Spark**
- System written in **Java** (~10k lines of code)
- Experiments on **Amazon EC2**:
    - r3.8xlarge instances (32 vCPUs, 244 GiB of memory)

Largest Supported Circuit Size



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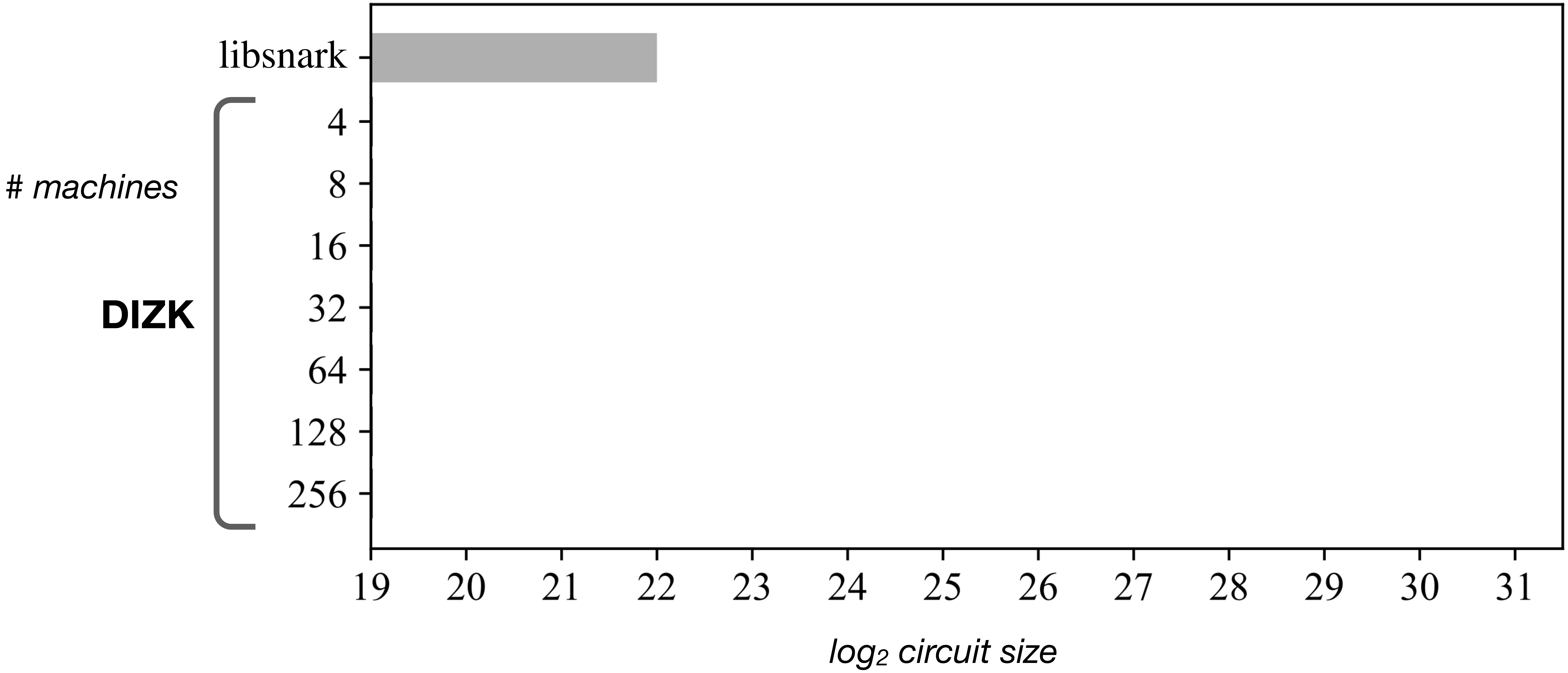

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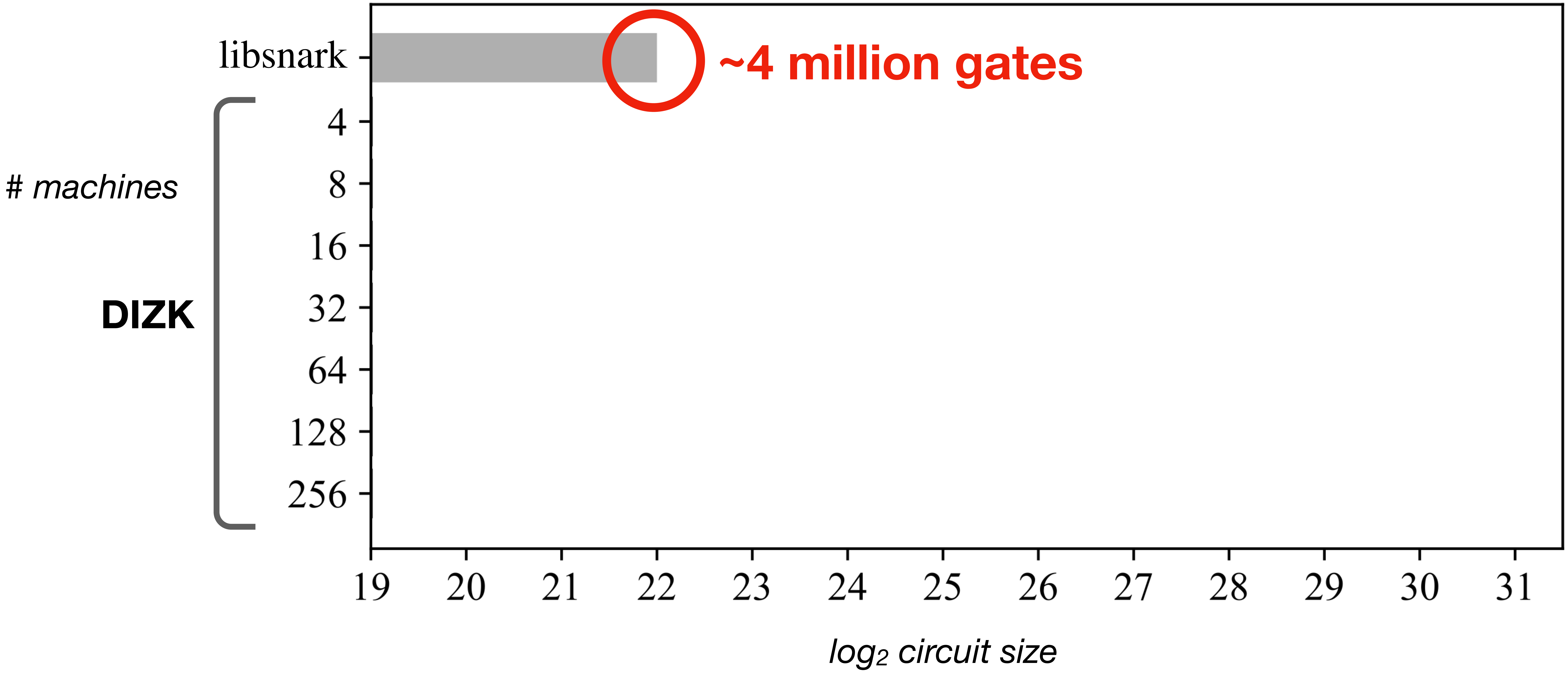

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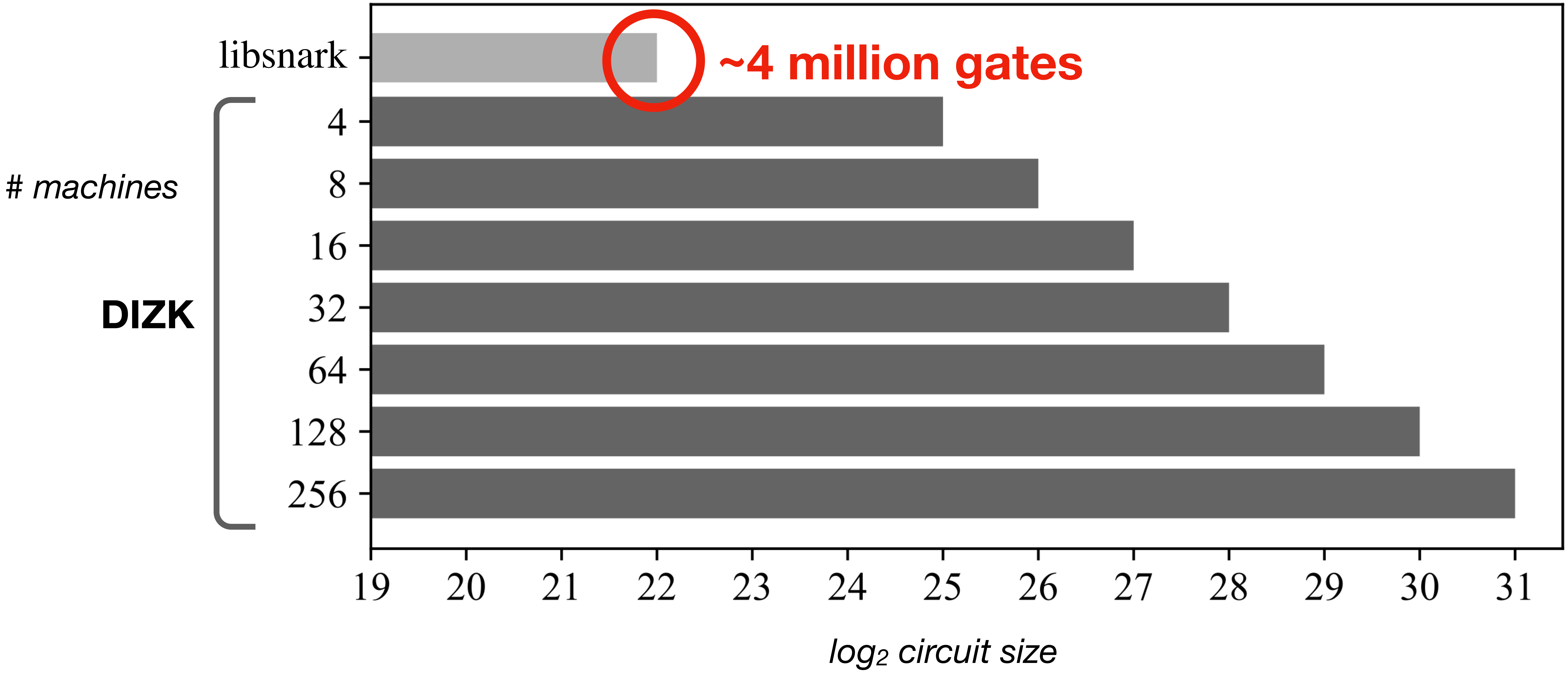

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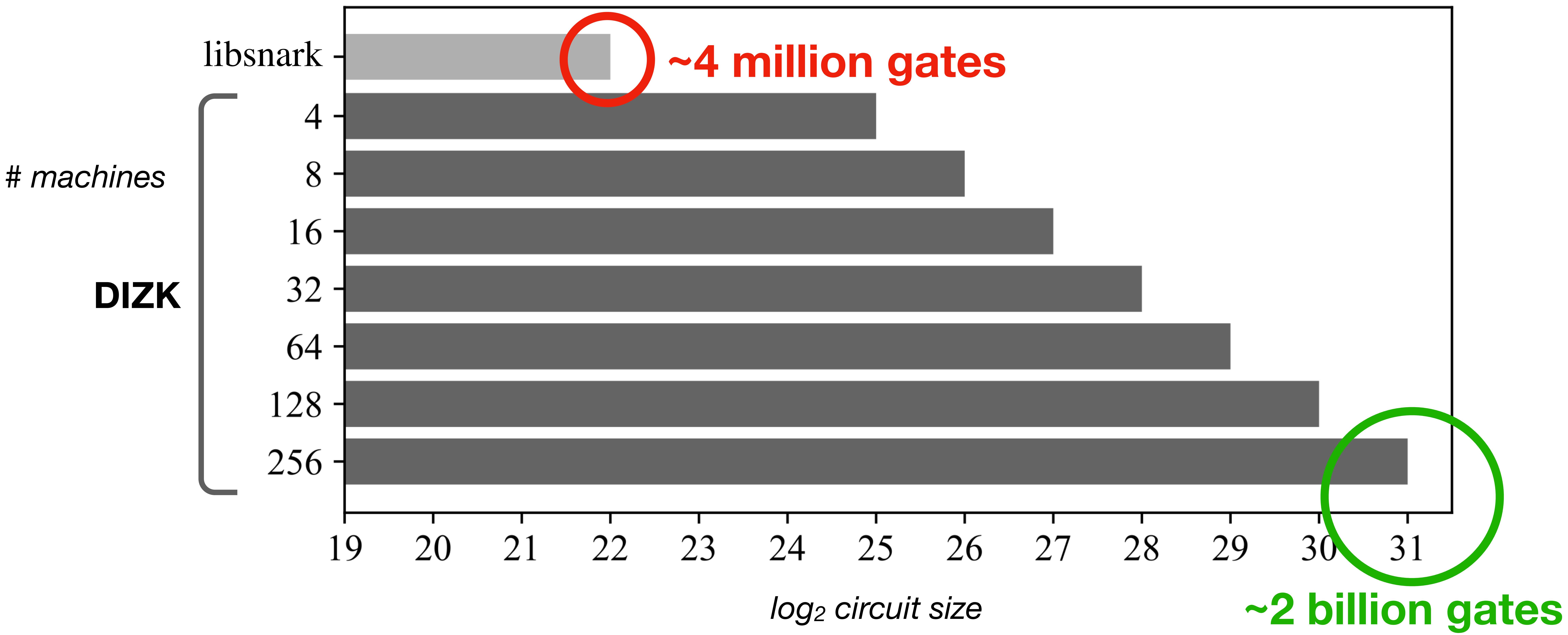

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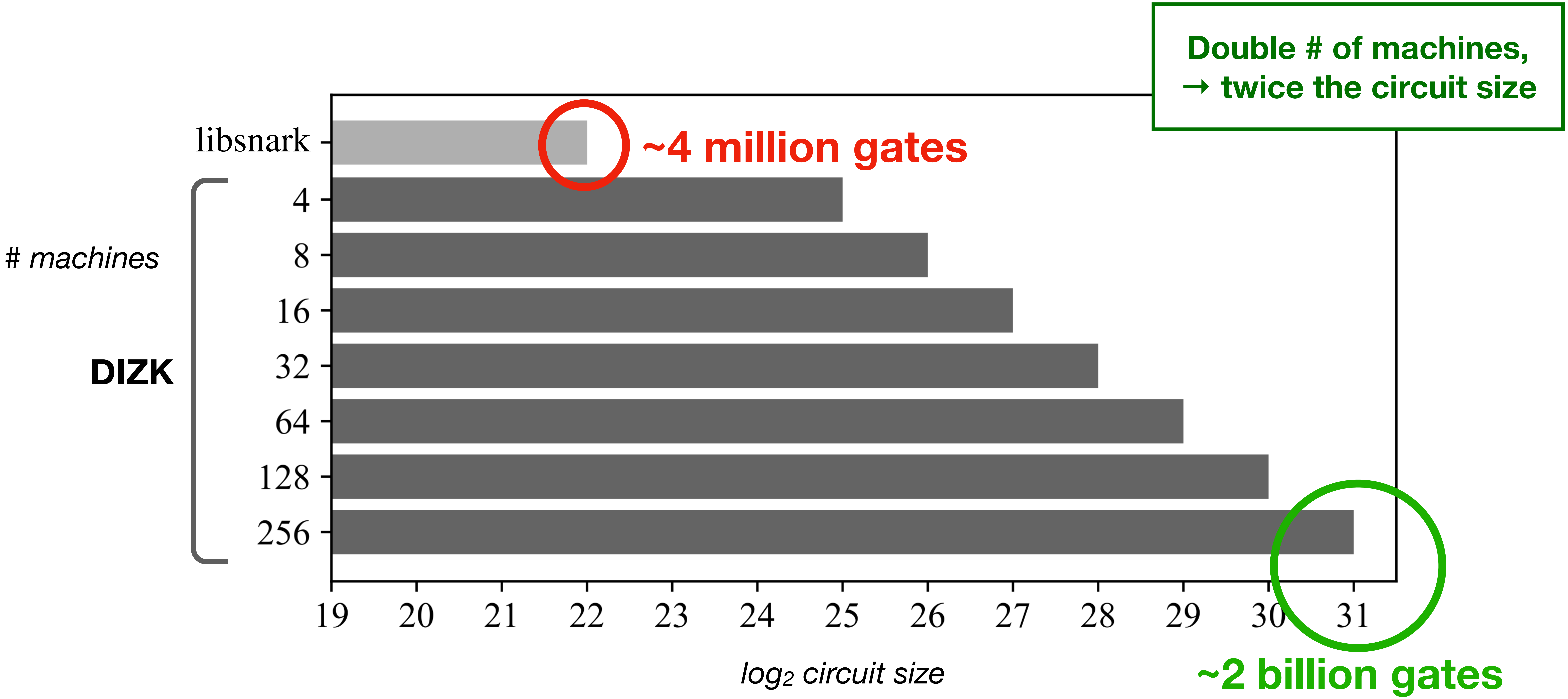
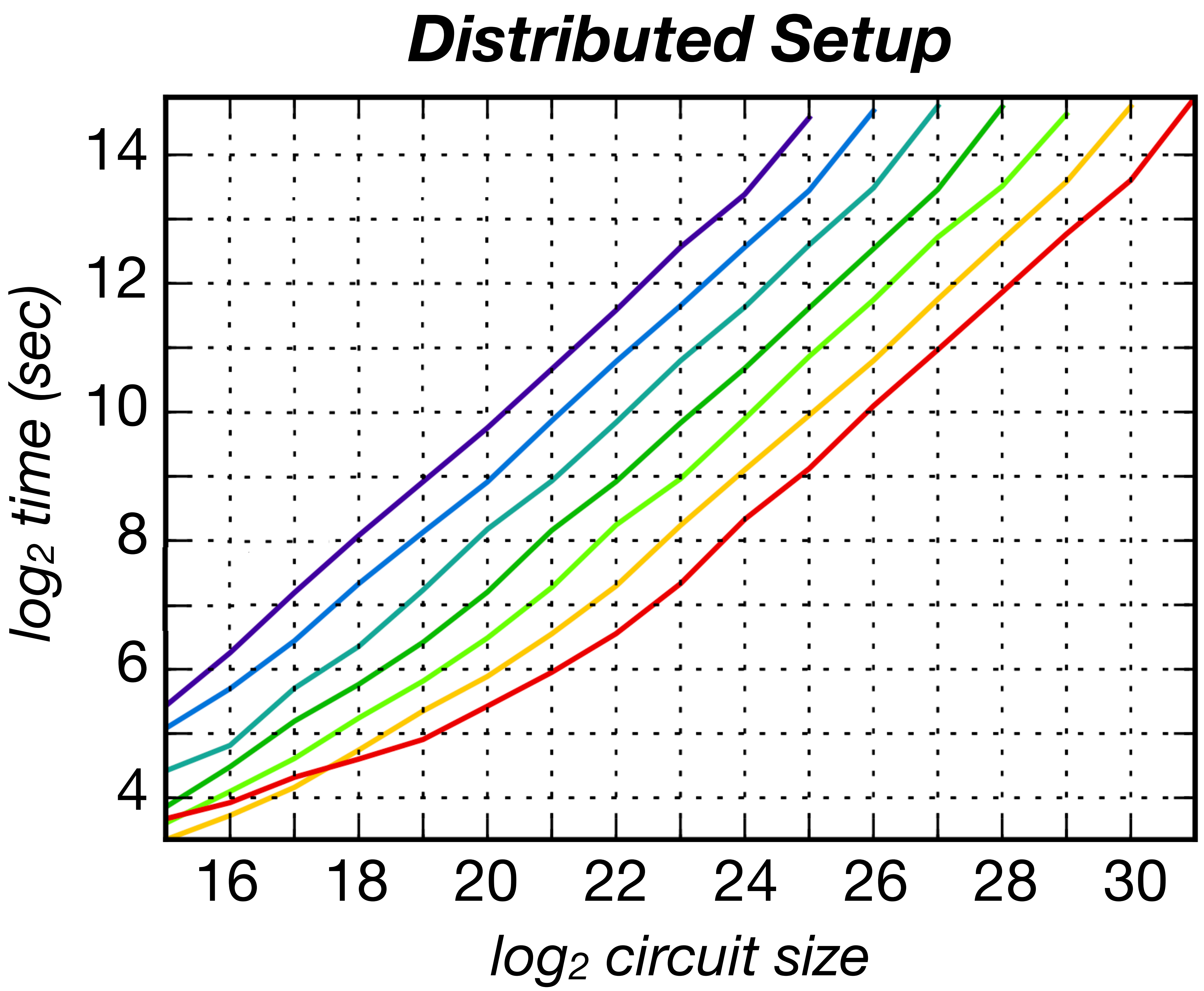
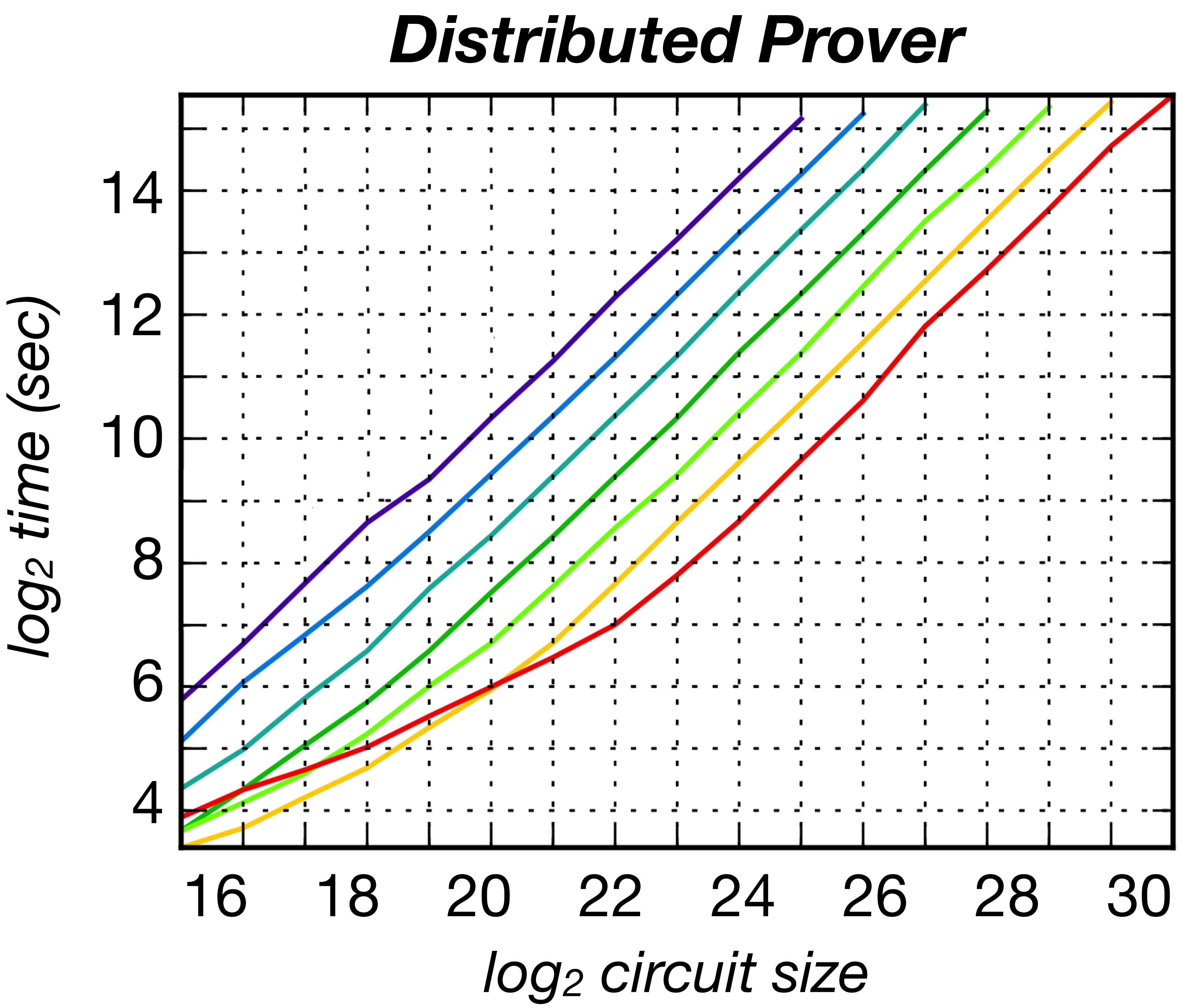
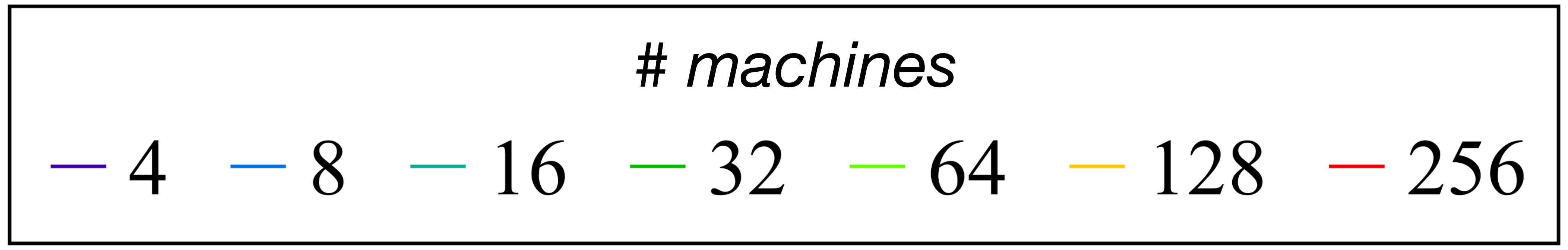


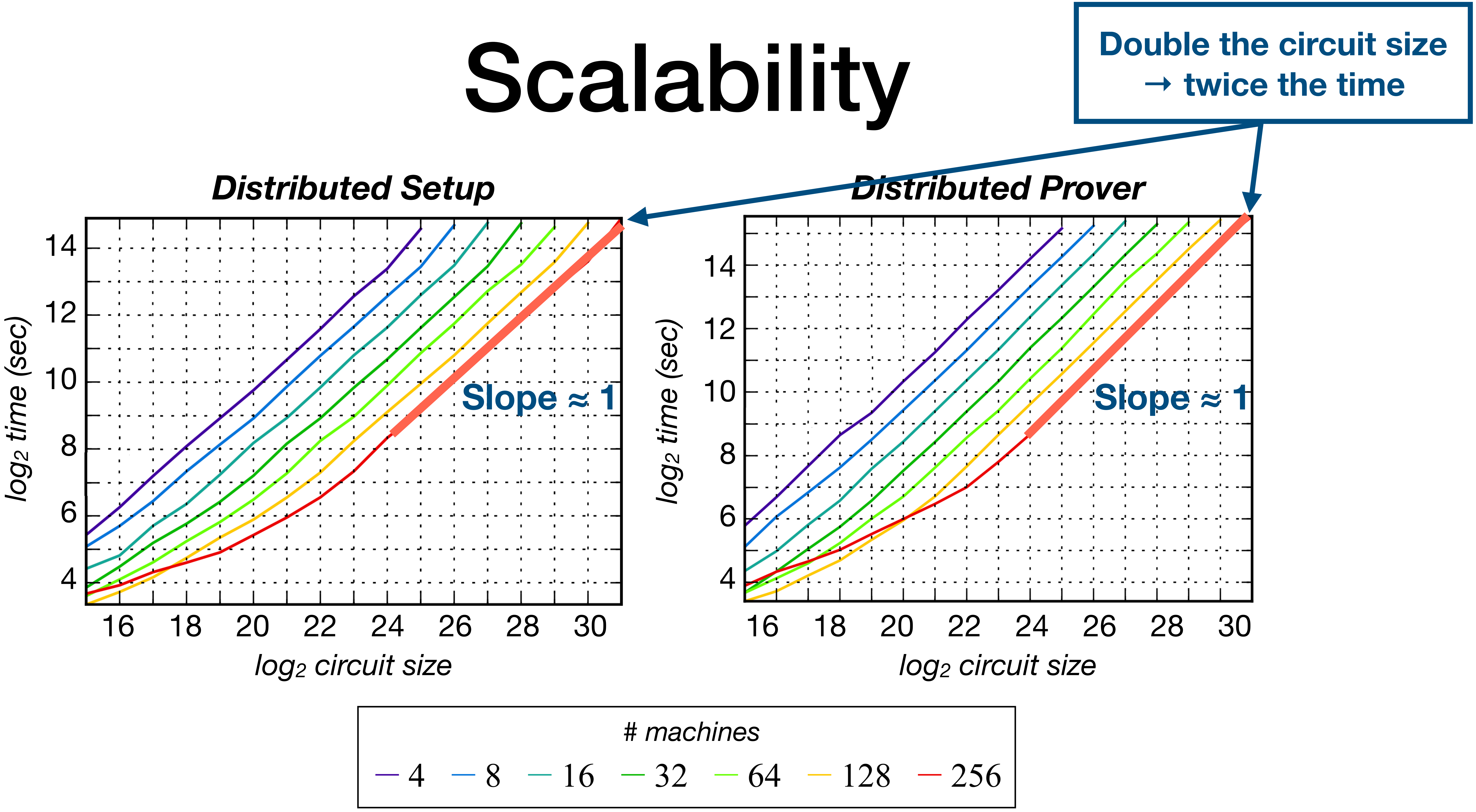
Scalability



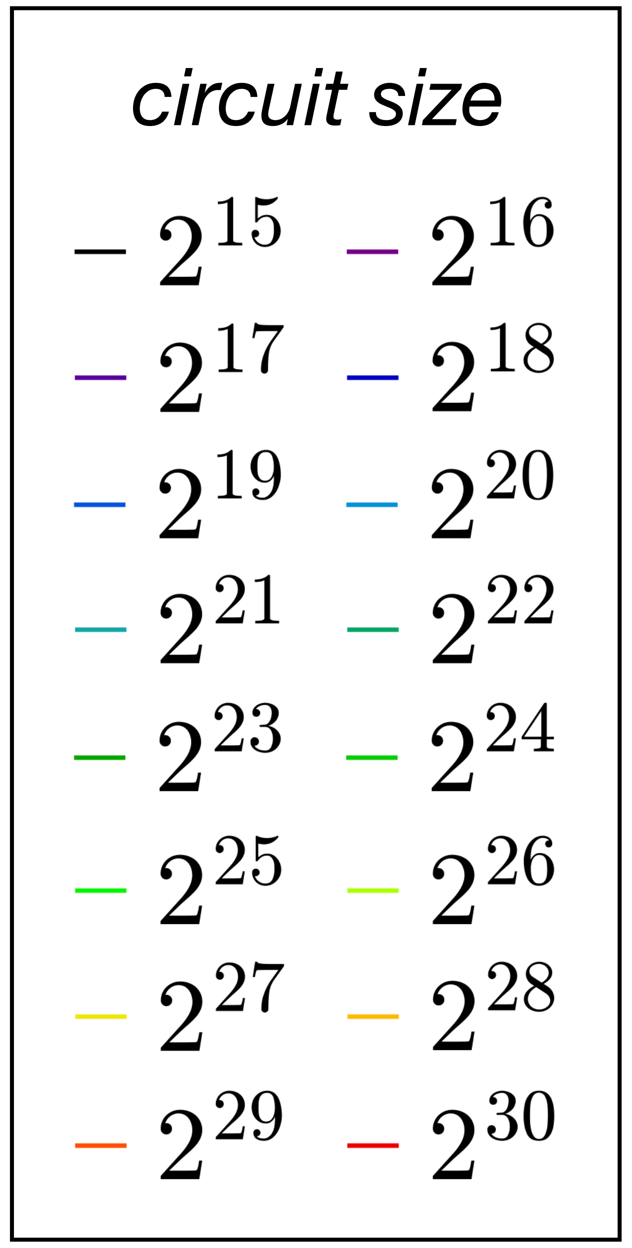


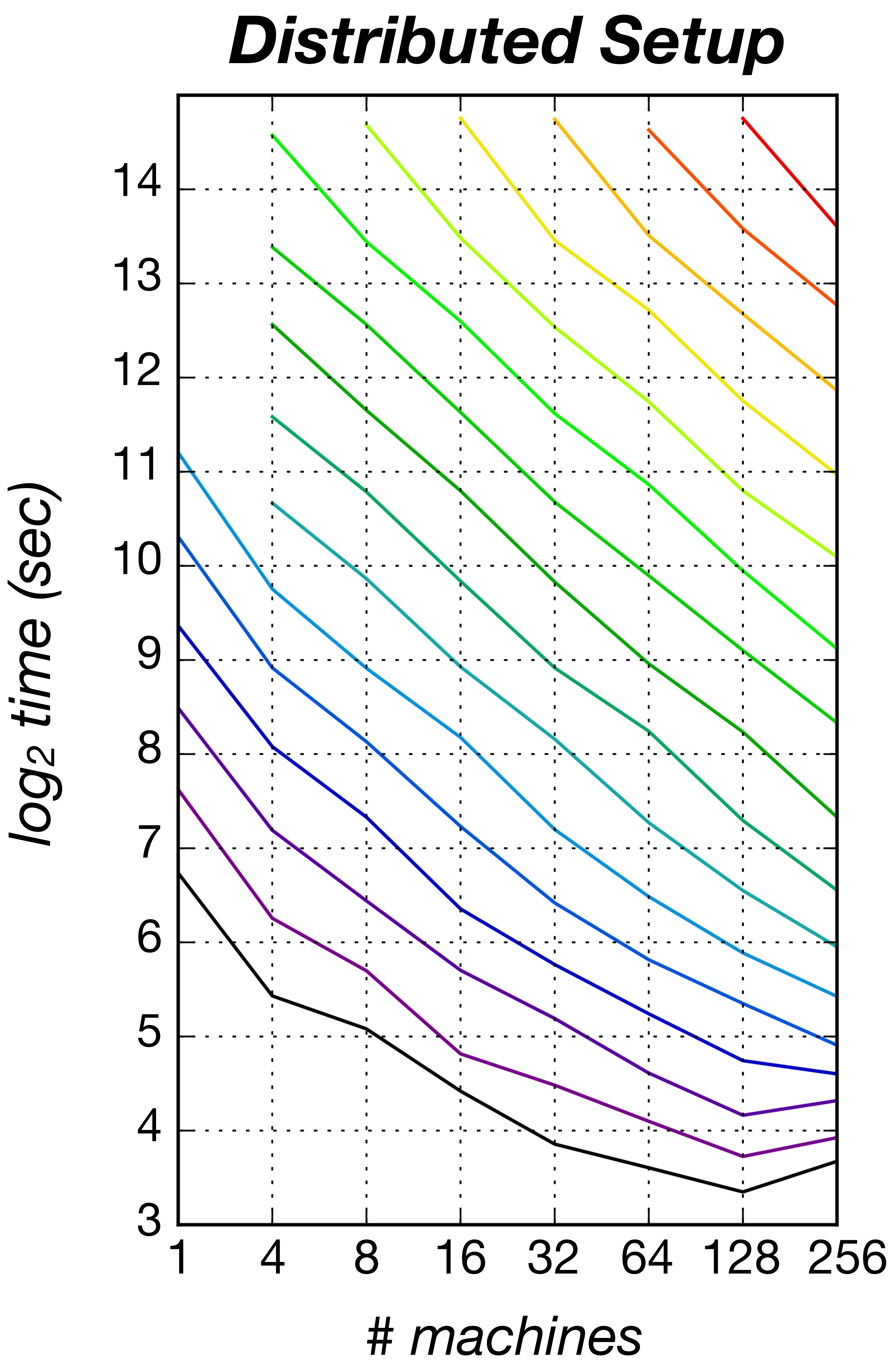


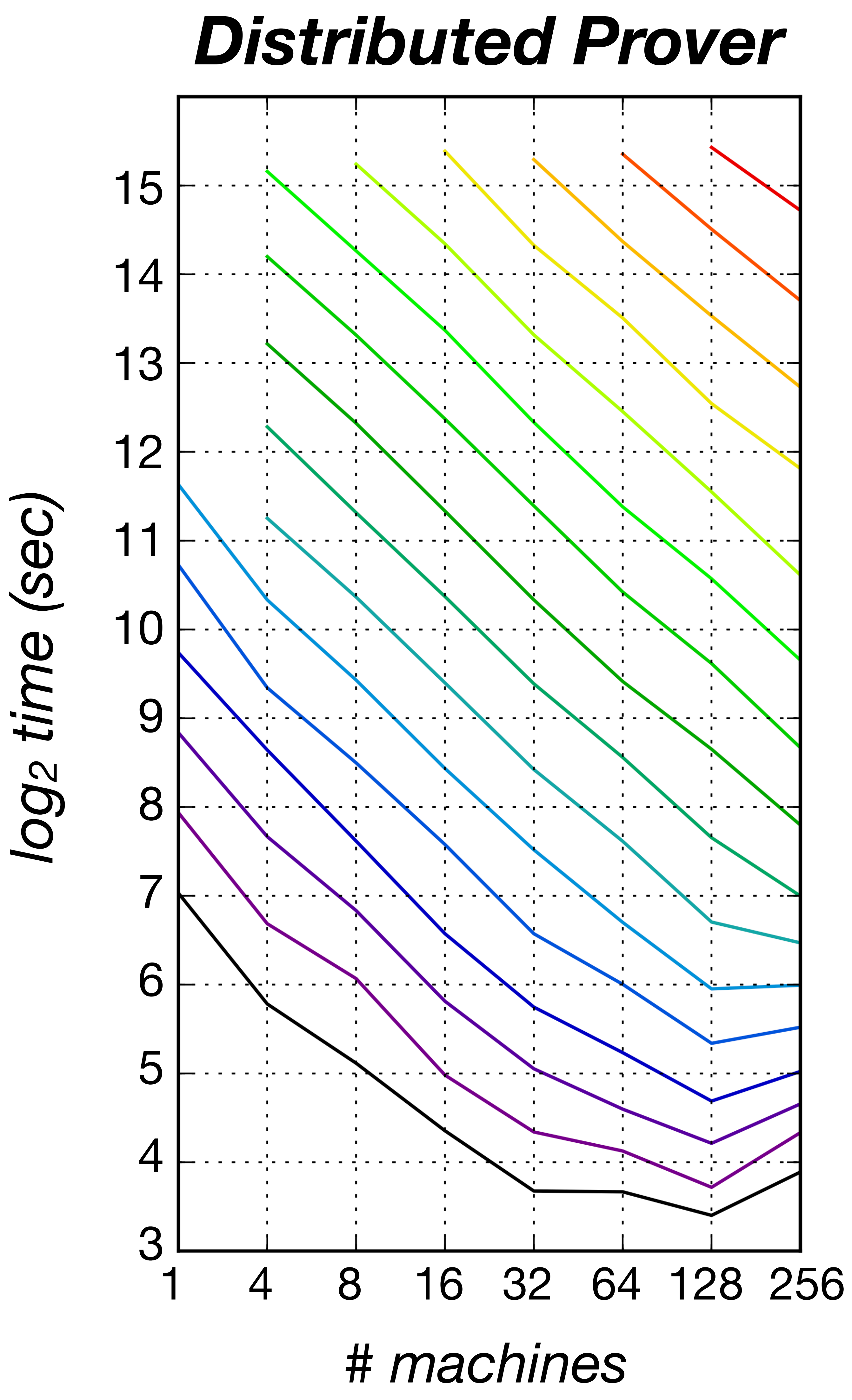
Scalability



Parallelism

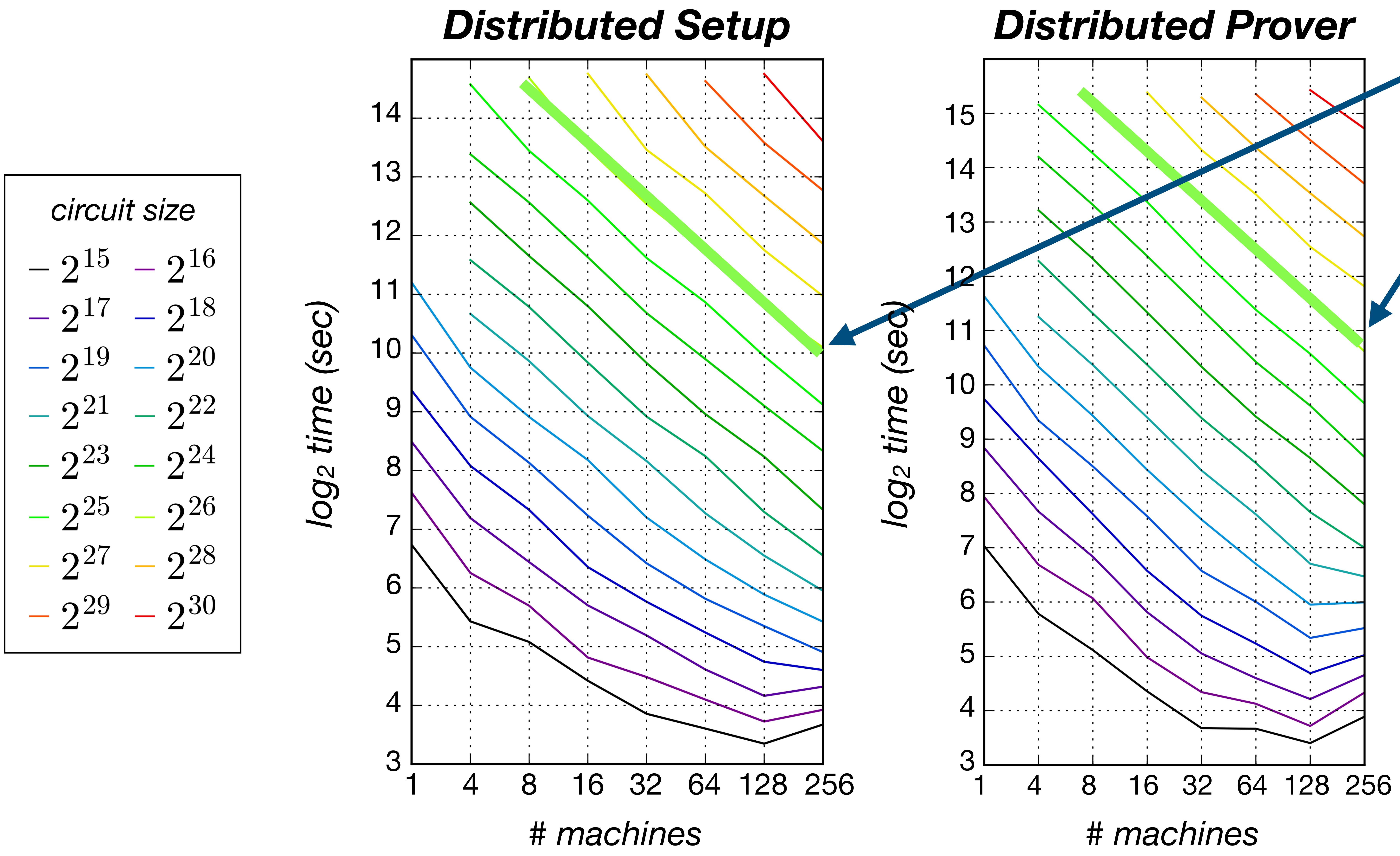






Parallelism

Double # of machines → twice as fast



Conclusion

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	Prior zkSNARKs	DIZK
Maximum circuit size	**Millions of gates**	**Billions of gates**
Cost per gate	**1ms**	**10μs**

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Maximum circuit size	**Millions of gates**	**Billions of gates**
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- Full Paper on Crypto ePrint (**`https://eprint.iacr.org/2018/691`**)
- DIZK (**`dizk.org`**, open-source, MIT License)

Open Questions

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Even Larger Circuits

What techniques will get us to **trillions of gates**, if any?
(Now, we would need ~100,000 machines in the best case scenario, i.e. too many)

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Other Succinct ZKPs

How efficiently can **other succinct ZKPs** be distributed?
(STARKs, Bulletproofs, …)

Our techniques are likely an excellent starting point.