vSQL: Verifying Arbitrary SQL Queries over Dynamic Outsourced Databases

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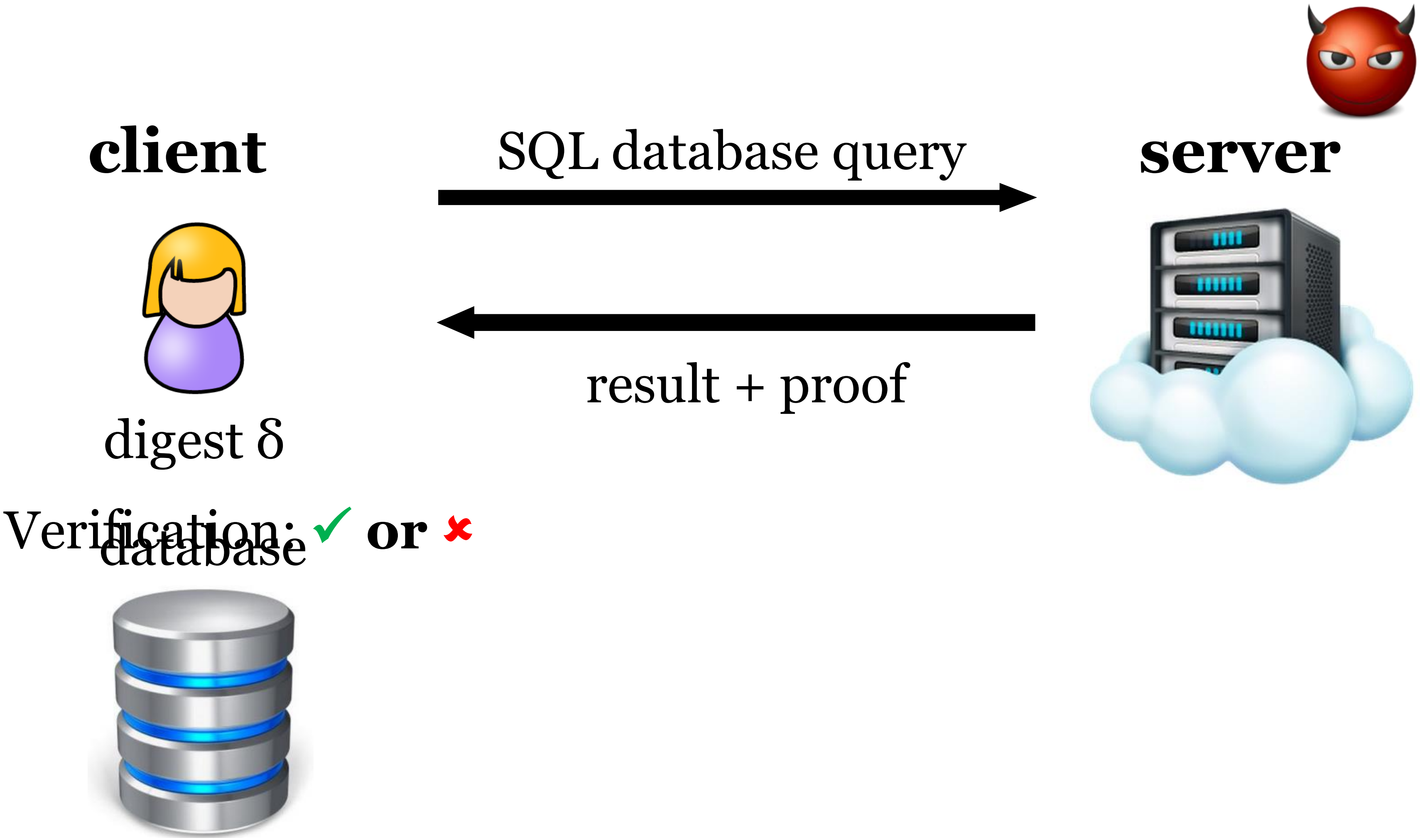
Verifiable Databases



client

SQL database query

server

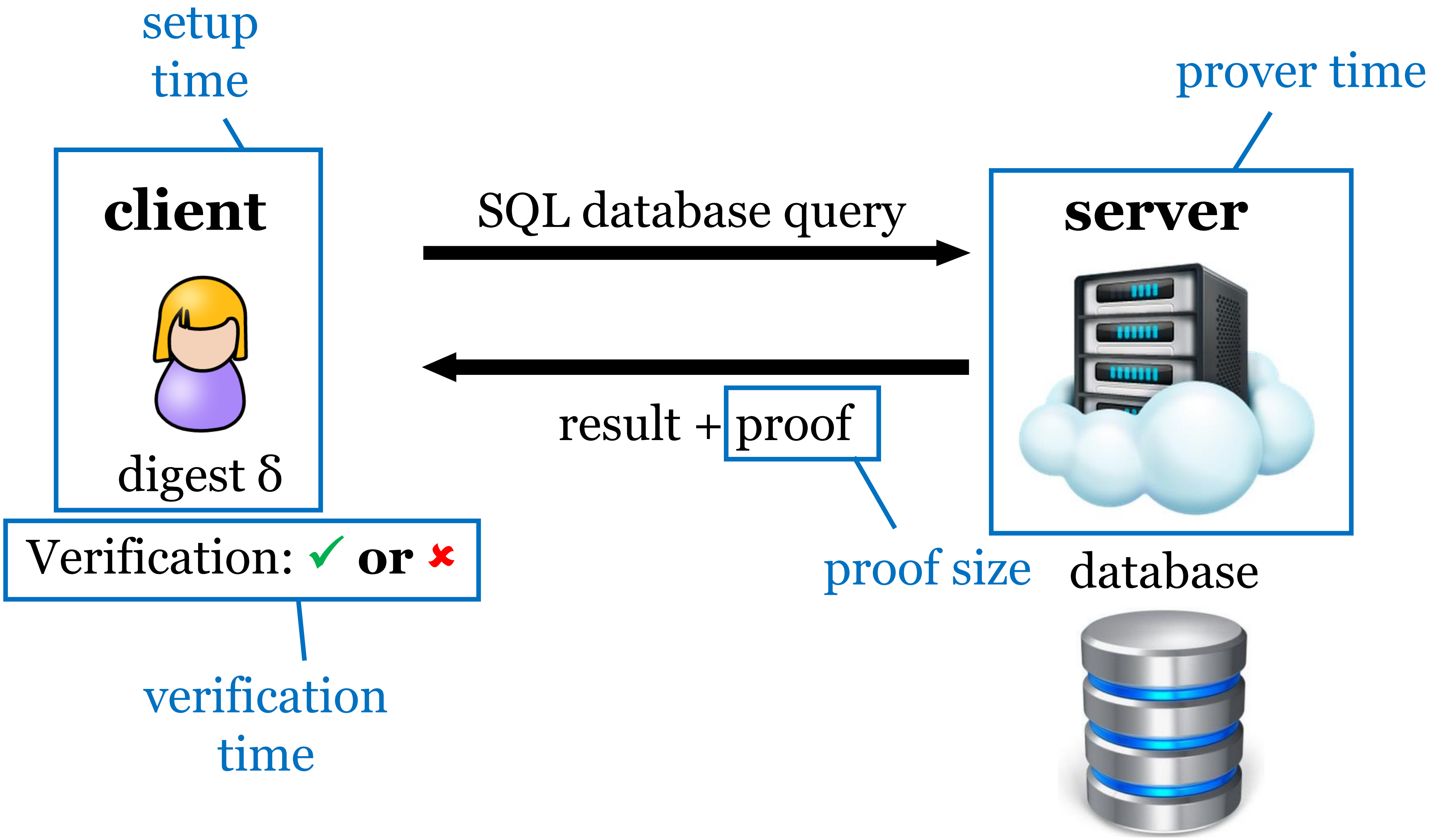
result + proof

digest δ

Verification: ✓ **or** ✘

database

Efficiency Measures of Verifiable Databases



setup time

client

digest δ

Verification: ✓ **or** ✗

verification time

SQL database query

result + proof

proof size

prover time

server

database

Prior Work in Verifiable Databases

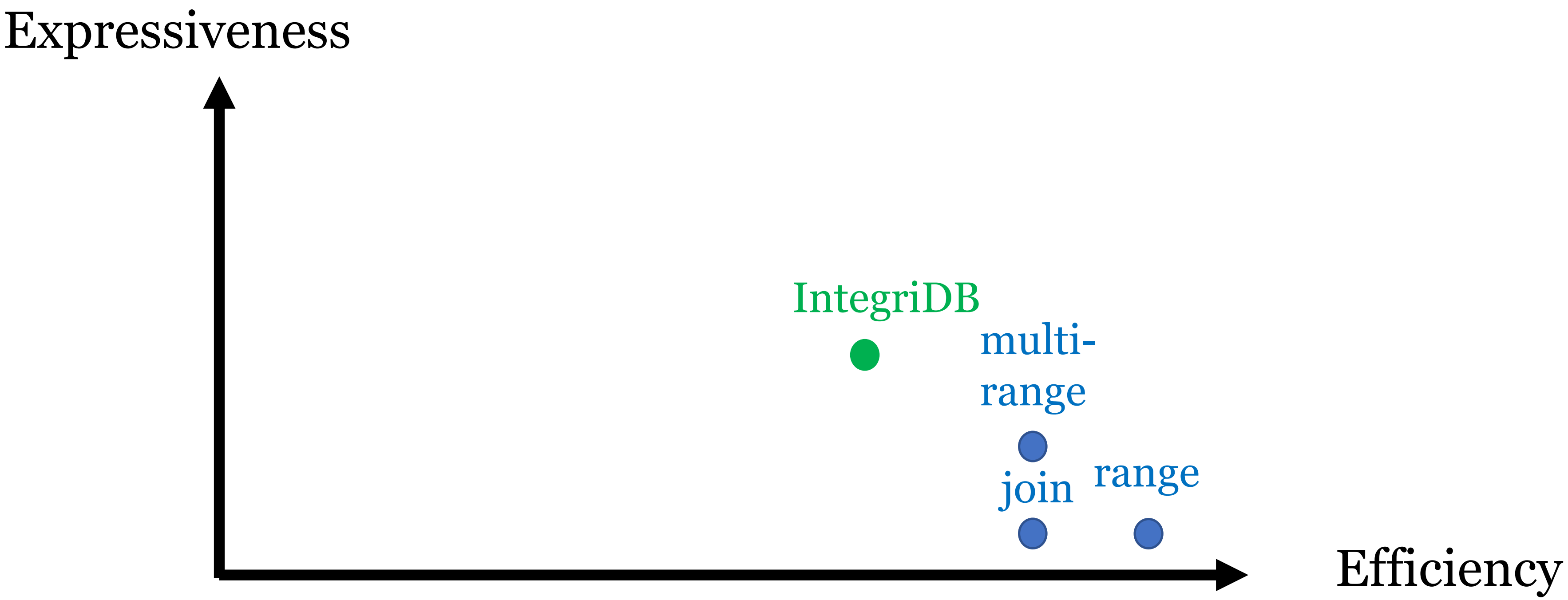
1. Customized Approach (E.g., ADS [Tamassia03])

- Range [LHKR06, MNT06, ...], multi-range [PPT14, ...], join[PJRT05, ...]

✓ Efficient

× Only support limited operations

- IntegriDB [ZKP15]



Prior Work in Verifiable Databases

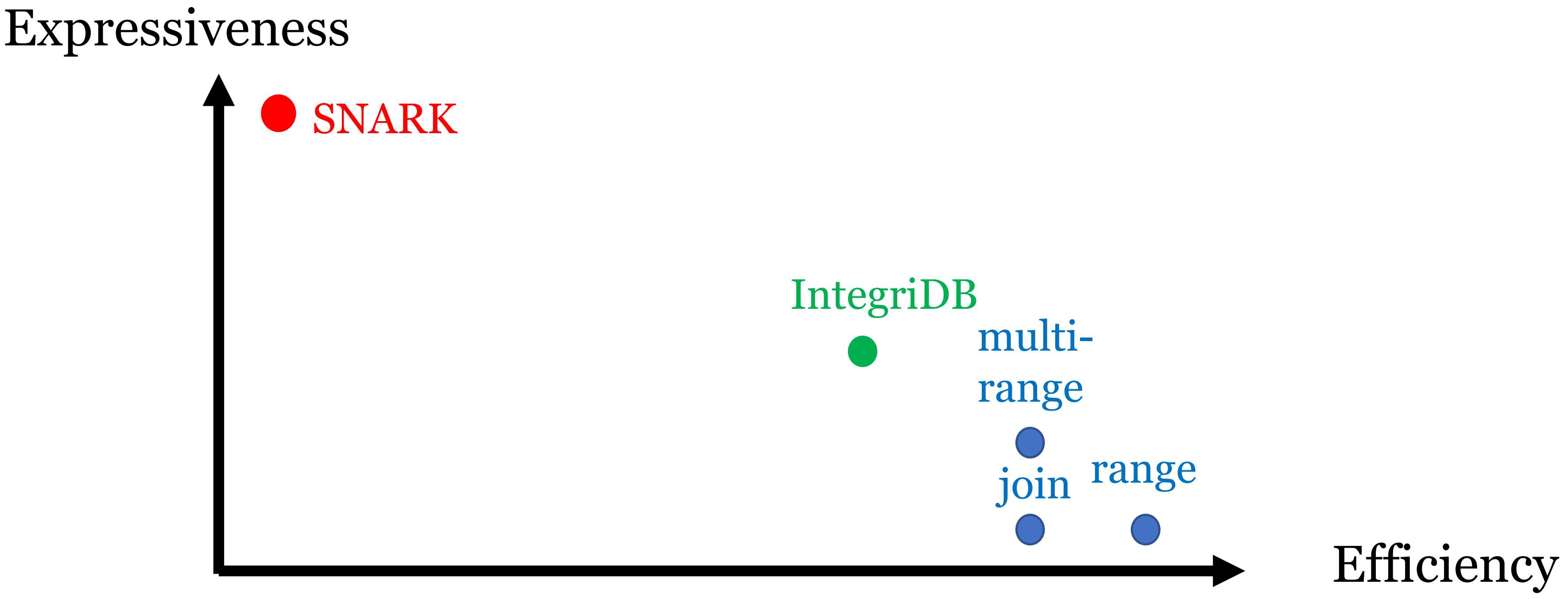
2. Generic Approach (E.g., SNARK [PHGR13, BCGTV13, BFRS+13, …] & PCP [Kilian92, Micali94, ….])

✓ Supports all functions that can be modeled as arithmetic circuits

✓ Constant proof size, fast verification time

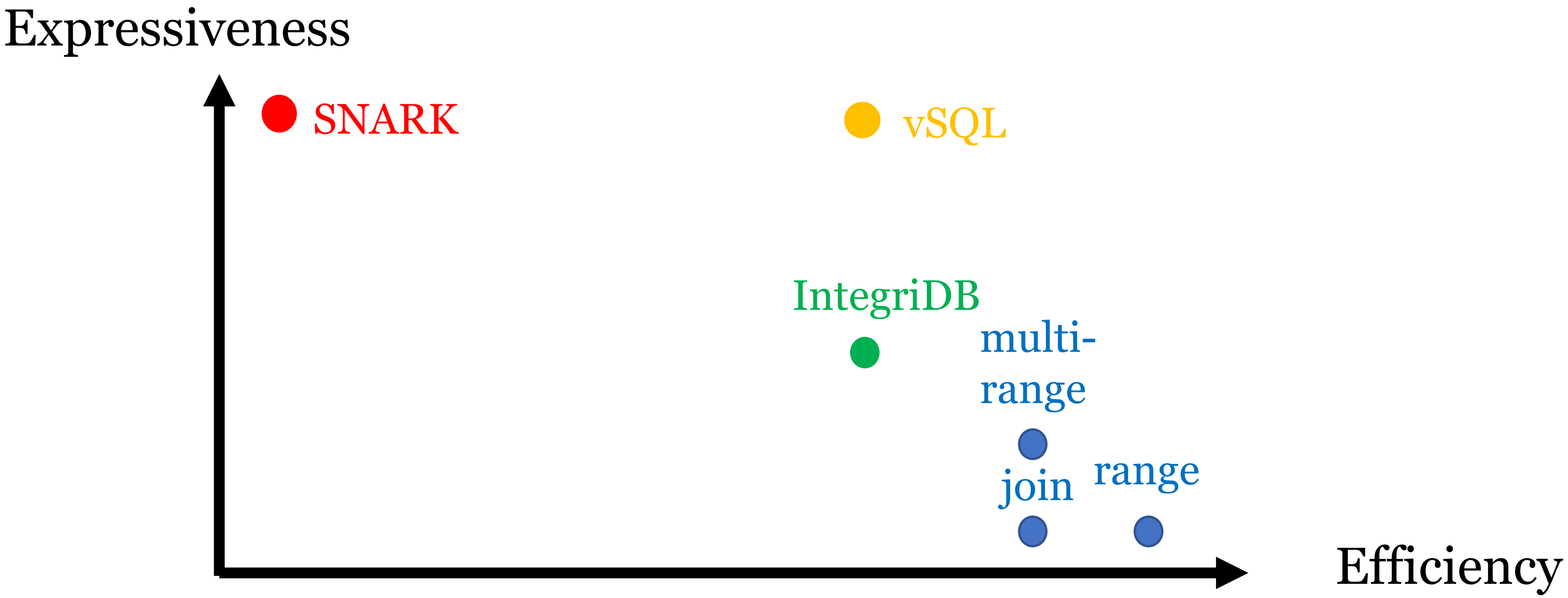
× Large setup time & prover time

× Function specific setup



Our Contribution: vSQL

- Supports arbitrary SQL queries
- Comparable prover time to IntegriDB, faster setup time
- Up to 2 orders of magnitude faster than SNARKs
- No function specific setup



Example

```
SELECT SUM (l_extendedprice * (1 - l_discount)) AS revenue FROM lineitem, part
WHERE
( p_partkey = l_partkey
AND p_brand = ‘Brand#41’
AND p_container IN (‘SM CASE’, ‘SM BOX’, ‘SM PACK’, ‘SM PKG’)
AND l_quantity >= 7 AND l_quantity <= 7 + 10
AND p_size BETWEEN 1 AND 5
AND l_shipmode IN (‘AIR’, ‘AIR REG’)
AND l_shipinstruct = ‘DELIVER IN PERSON’ )
OR
( p_partkey = l_partkey
AND p_brand = ‘Brand#14’
AND p_container IN (‘MED BAG’, ‘MED BOX’,‘MED PKG’, ‘MED PACK’)
AND l_quantity >= 14 AND l_quantity <= 14 + 10
AND p_size BETWEEN 1 AND 10
AND l_shipmode IN (‘AIR’, ‘AIR REG’)
AND l_shipinstruct = ‘DELIVER IN PERSON’ )
OR
( p_partkey = l_partkey
AND p_brand = ‘Brand#23’
AND p_container IN (‘LG CASE’, ‘LG BOX’, ‘LG PACK’, ‘LG PKG’)
AND l_quantity >= 25 AND l_quantity <= 25 + 10
AND p_size BETWEEN 1 AND 15
AND l_shipmode IN (‘AIR’, ‘AIR REG’)
AND l_shipinstruct = ‘DELIVER IN PERSON’ );
```

Query #19 of the TPC-H benchmark
http://www.tpc.org/tpch

Our Construction

Interactive Proof (IP)[GKR08, CMT12, …]

Example

```
SELECT  SUM (l_extendedprice * (1 - l_discount))  AS  revenue  FROM  lineitem, part
WHERE
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```
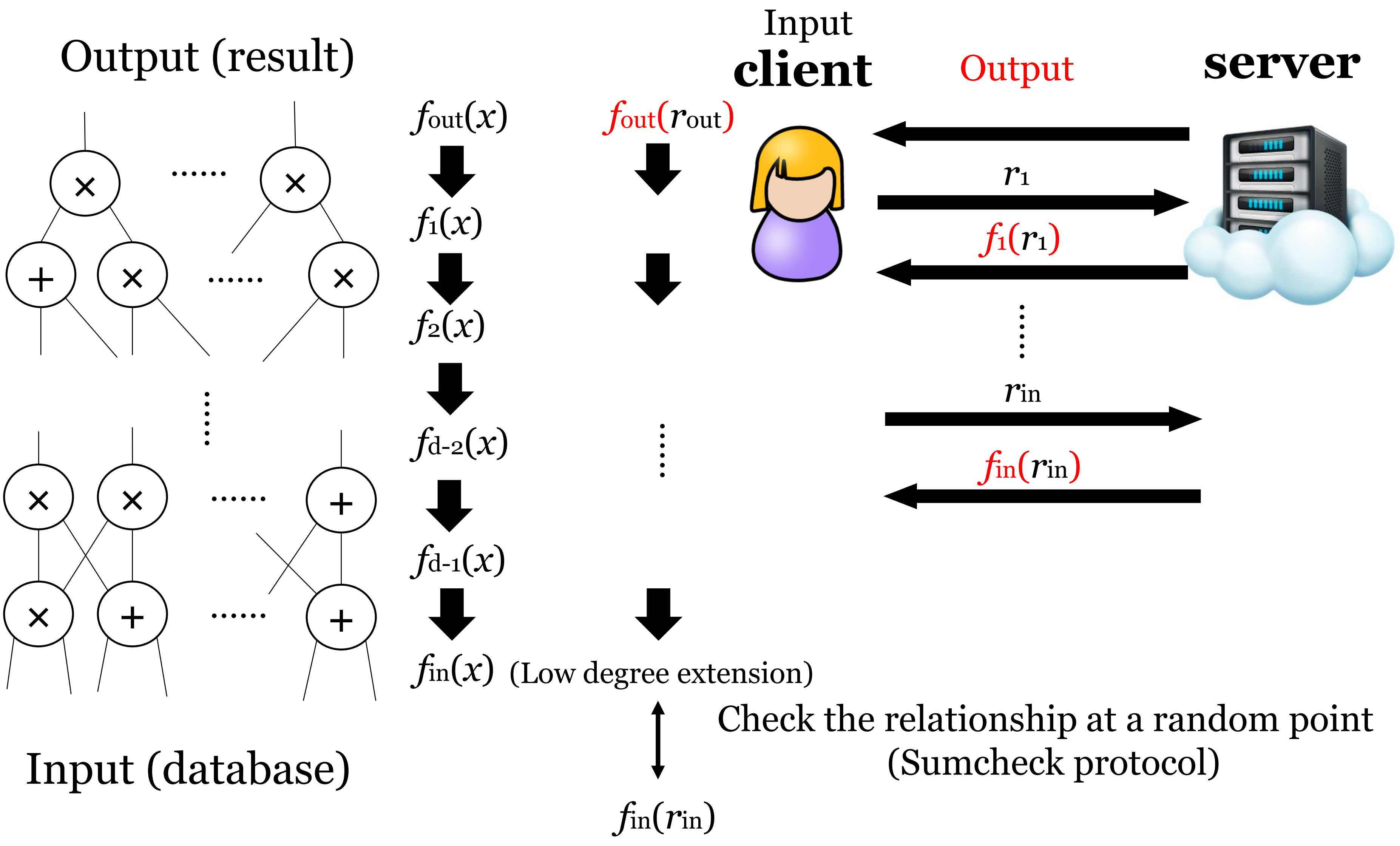

Interactive Proof (IP)[GKR08, CMT12, ...]



Output (result)

$f_{out}(x)$

$f_1(x)$

$f_2(x)$

$f_{d-2}(x)$

$f_{d-1}(x)$

$f_{in}(x)$ (Low degree extension)

Input (database)

$f_{out}(r_{out})$

Input

client

Output

server

r_1

$f_1(r_1)$

r_{in}

$f_{in}(r_{in})$

Check the relationship at a random point
(Sumcheck protocol)

$f_{in}(r_{in})$

Using IP for Verifiable Databases

✓ No setup time

✓ Fast prover time (no crypto operations)

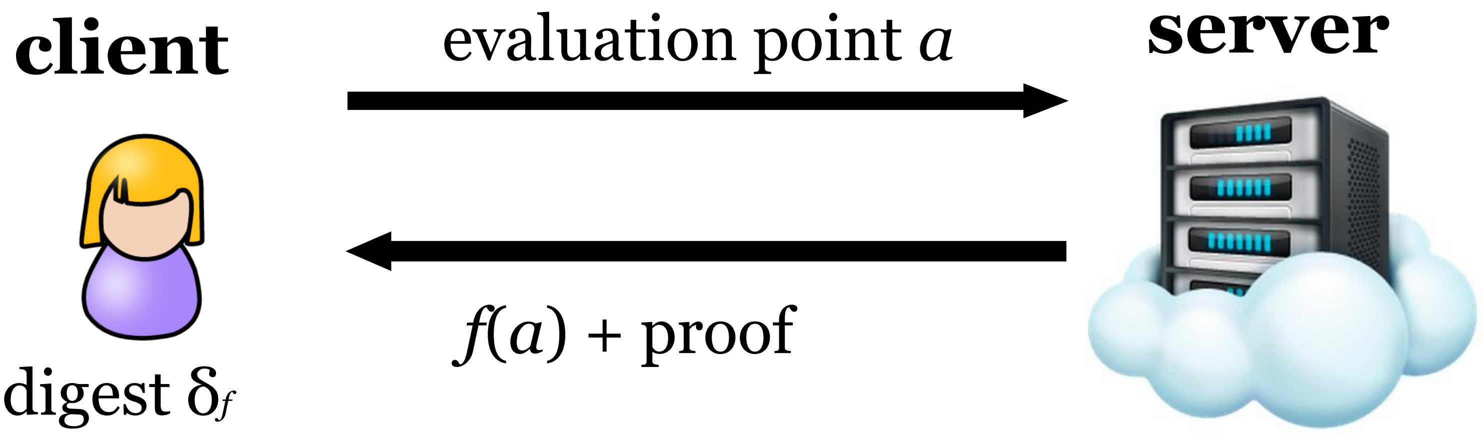
× Storage of the database locally

(Last step: evaluate a polynomial defined by the input at a random point)

Delegating Database to the Server

- Our solution: Verifiable Polynomial Delegation (VPD)

[KZG10, PST13]



client

evaluation point a

server

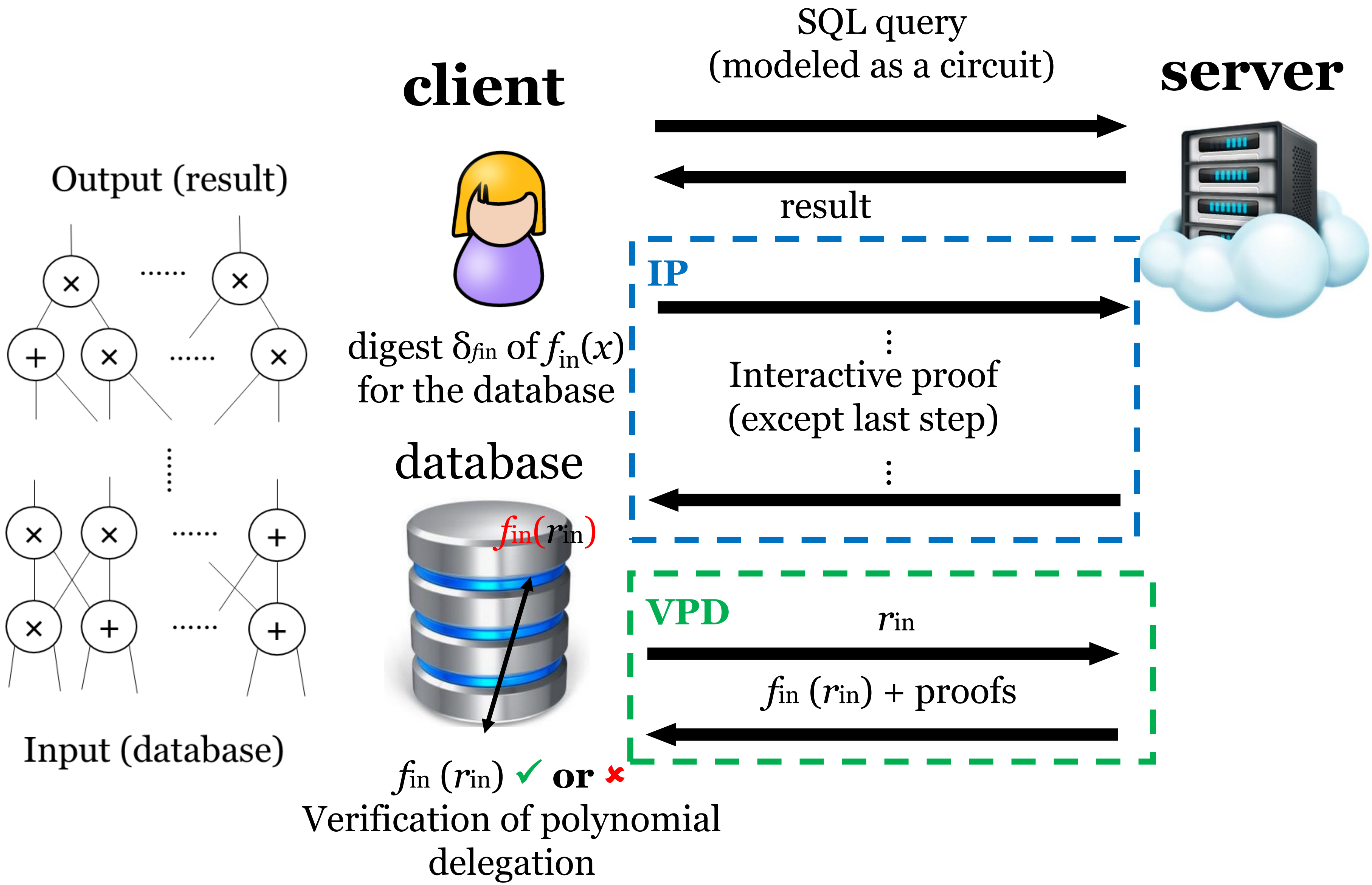
$f(a)$ + proof

digest δ_f (32Bytes)

Verification: ✓ **or** ✘

$f(x)$

vSQL protocol



Output (result)

Input (database)

client

digest $\delta_{f_{in}}$ of $f_{in}(x)$ for the database

database

$f_{in}(r_{in})$

SQL query (modeled as a circuit)

server

result

IP

Interactive proof (except last step)

VPD

r_{in}

$f_{in}(r_{in})$ + proofs

$f_{in}(r_{in})$ ✓ **or** ✗

Verification of polynomial delegation

Using IP for Verifiable Databases

✓ No setup time

✓ Fast prover time (no crypto operations)

× ~~Storage of the database locally~~

~~(Last step: evaluate a polynomial defined by the input at a random point)~~

Verifying Computations in NP

- Some functions are hard to compute using arithmetic circuits

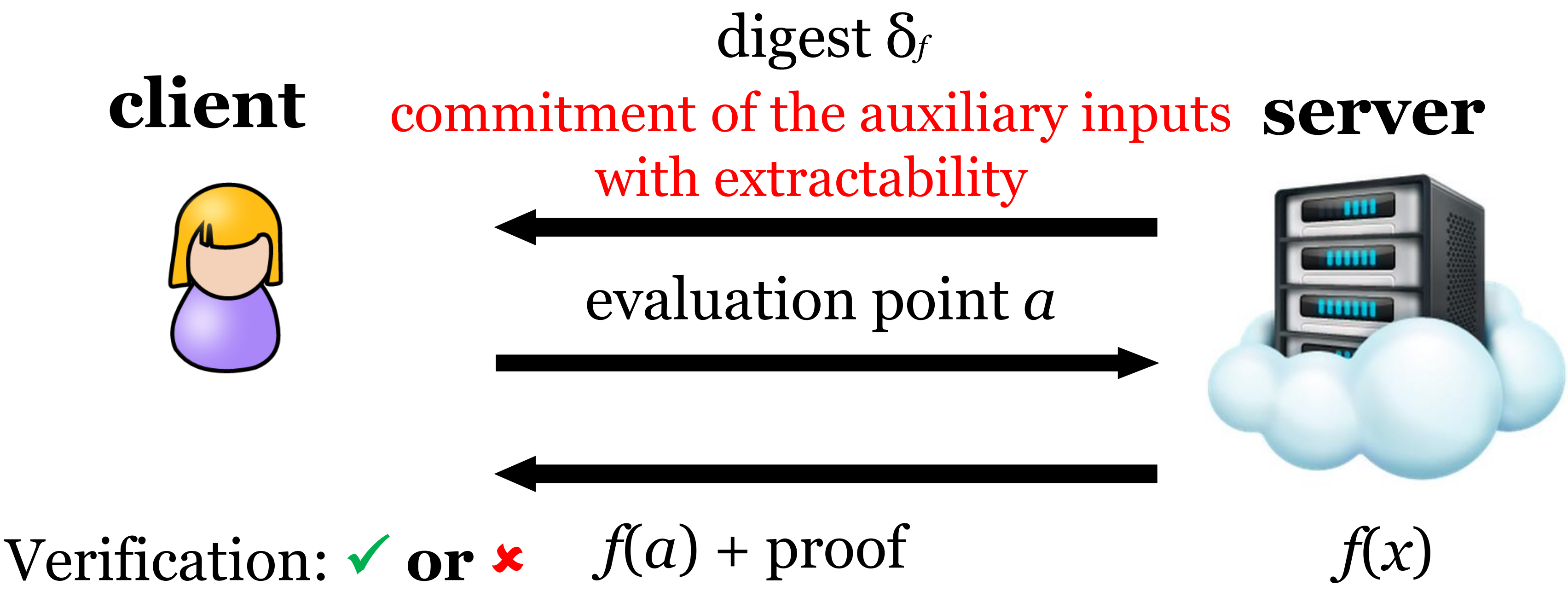
  E.g., Integer division $a \div b$

- They are easy to verify with inputs from the server: $a = q \times b + r$

- Interactive Proof does not support auxiliary input

Verifying Computations in NP

- Our solution: Extractable Verifiable Polynomial Delegation (VPD)



client

server

digest δ_f

commitment of the auxiliary inputs with extractability

evaluation point a

$f(a)$ + proof

$f(x)$

Verification: ✓ **or** ✘

Result: extending IP (GKR, CMT etc.) to NP computations without using FHE [CKLR11, ...]

vSQL

✓ Setup only for the database, not for queries

✓ Faster prover time

(crypto operations is only linear to the database size, does not depend on the circuit size)

✓ Supports auxiliary inputs

✓ Expressive SQL updates (details in the paper)

Experimental Results

Comparison with Prior Work

Queries and database: TPC-H benchmark
Database size: 6 million rows × 13 columns (2.8GB) in the largest table.

Query #19		**IntegriDB**	**SNARK**	**vSQL**
	Setup	7 hours	100 hours*	0.4 hour
	Prover	1.8 hours	54 hours*	1.3 hours
	Verification	232 ms	6 ms	148 ms
	Communication	184 KB	0.3 KB	28 KB

Follow-up:
4× faster!

Update

Query #15: create a new table on the fly by range and sum

Old table: 2.8GB new table: 1.7MB

Prover	**Verification**	**Communication**
0.5 hour	85ms	85.7KB

Summary of vSQL

- vSQL: Verifiable Polynomial Delegation + Interactive Proof
  - ➢Comparable efficiency, better expressiveness compared to customized VC
  - ➢Up to 2 orders of magnitude faster compared to SNARKs
  - ➢Setup only for database, no query dependent setup

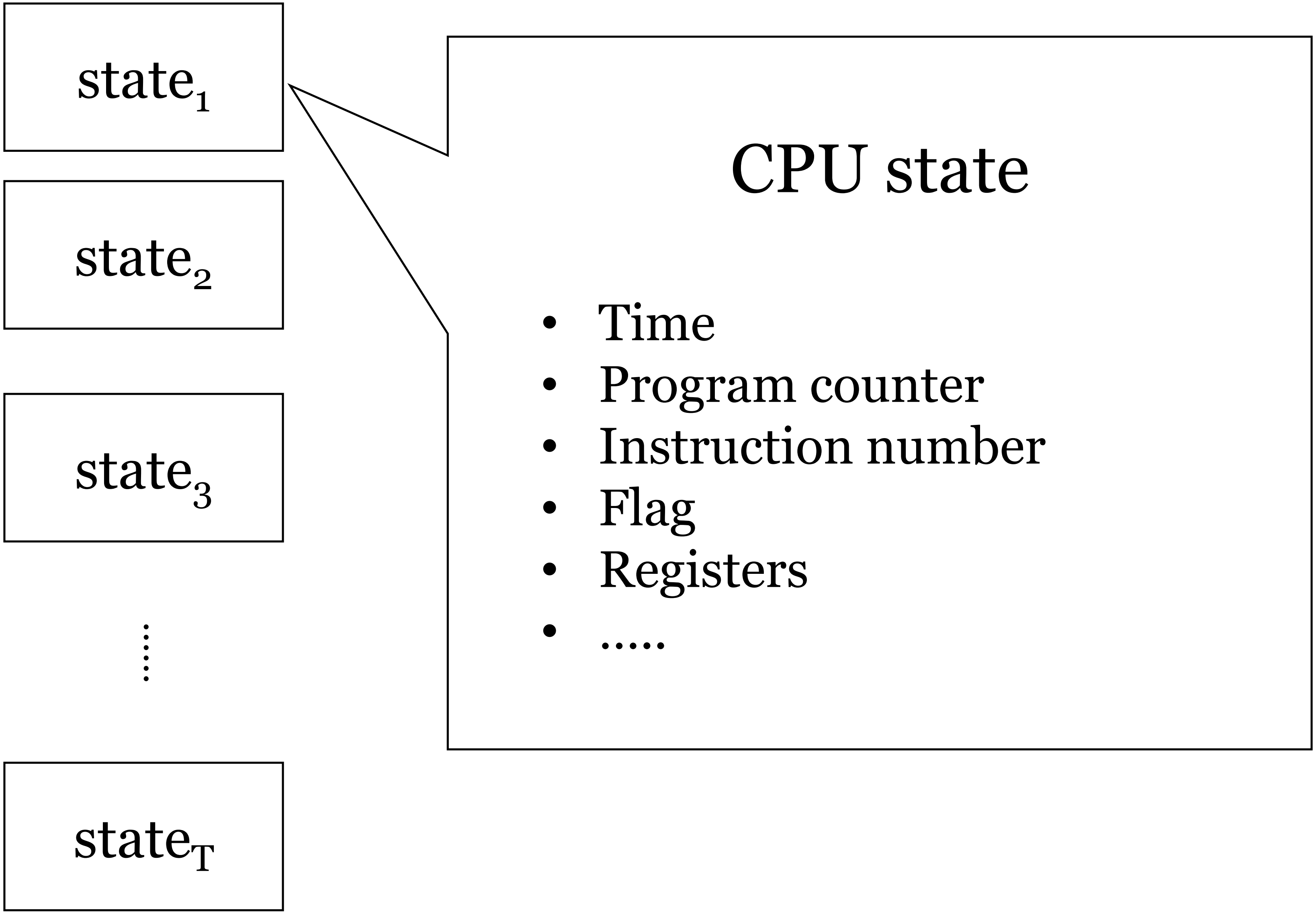
One Preprocessing to Rule Them All: Verifiable Computation with Circuit-Independent Preprocessing and Applications to Verifiable RAM Programs

- Interactive argument for NP, with function independent preprocessing
- Apply to verifiable RAM computations
- Theorem: Prover time linear in #of CPU steps T

  vs. quasi-linear using SNARKs [BCTV14]
- 8× faster prover time, 120× smaller memory consumption, up to 2 million CPU steps

RAM to Circuit Reduction [BCTV14]

By time:



state_1

state_2

state_3

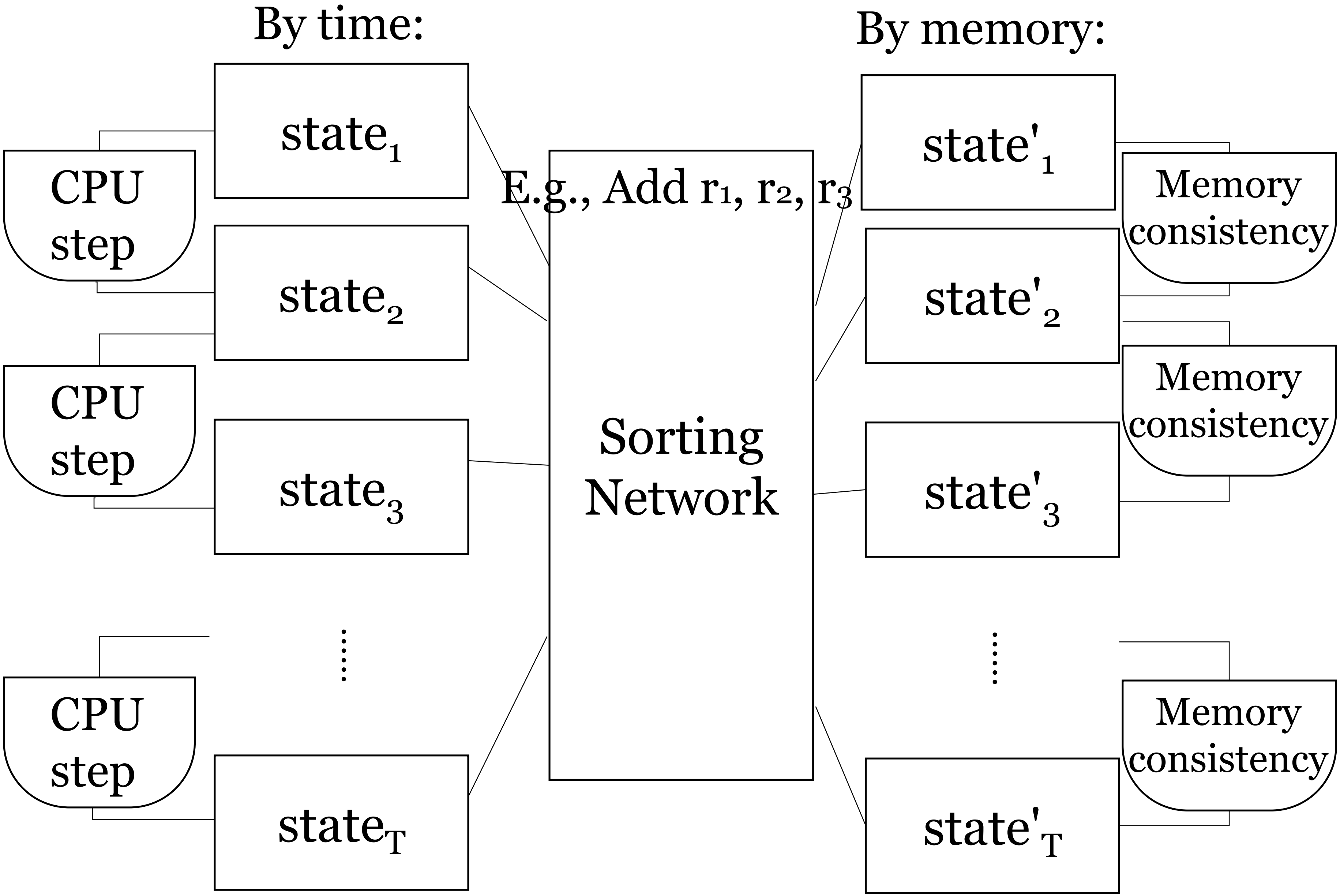
⋮

state_T

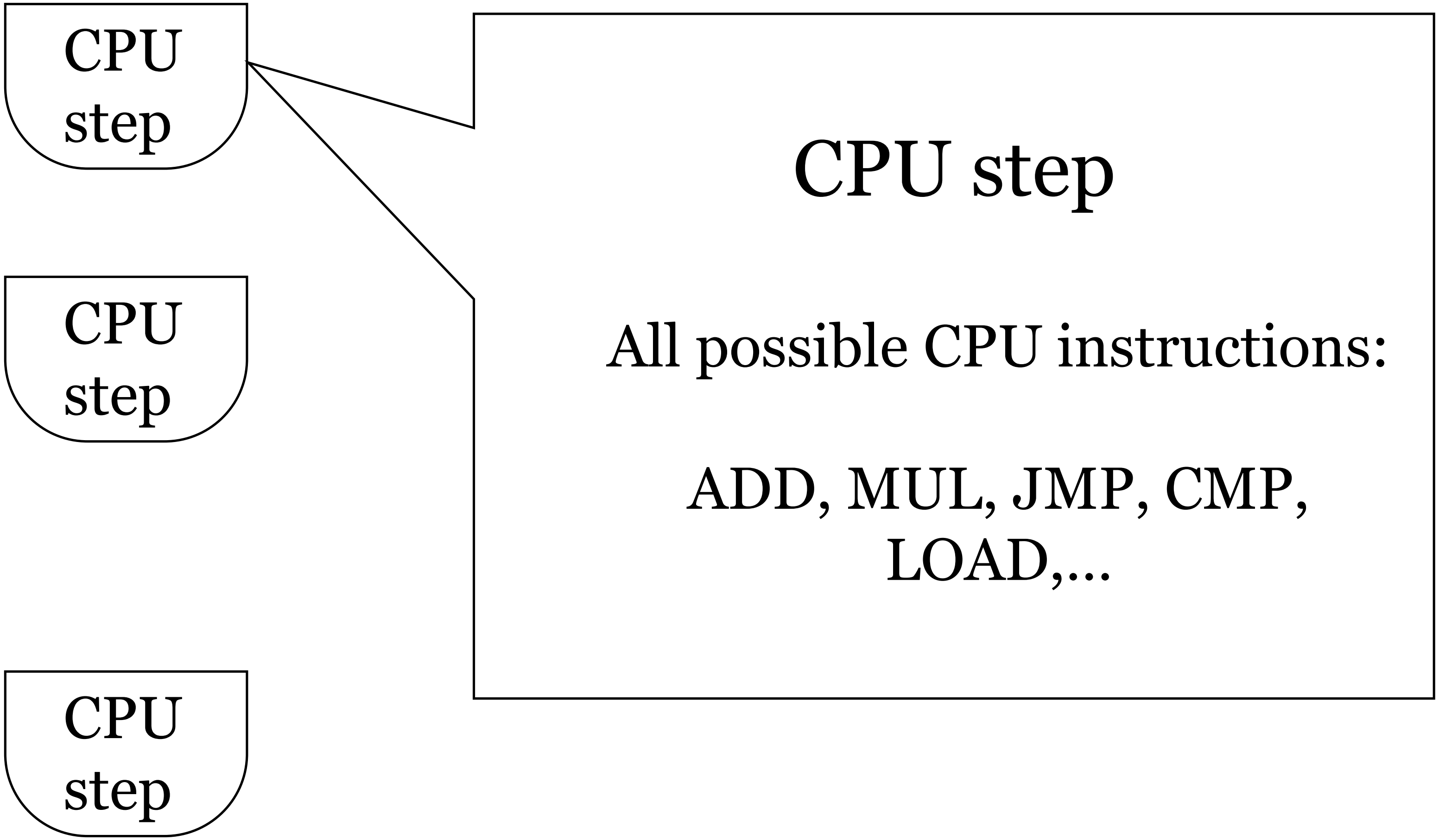
CPU state

- Time
- Program counter
- Instruction number
- Flag
- Registers
- …..

RAM to Circuit Reduction [BCTV14]



Inefficiency: Preprocessing



CPU step

CPU step

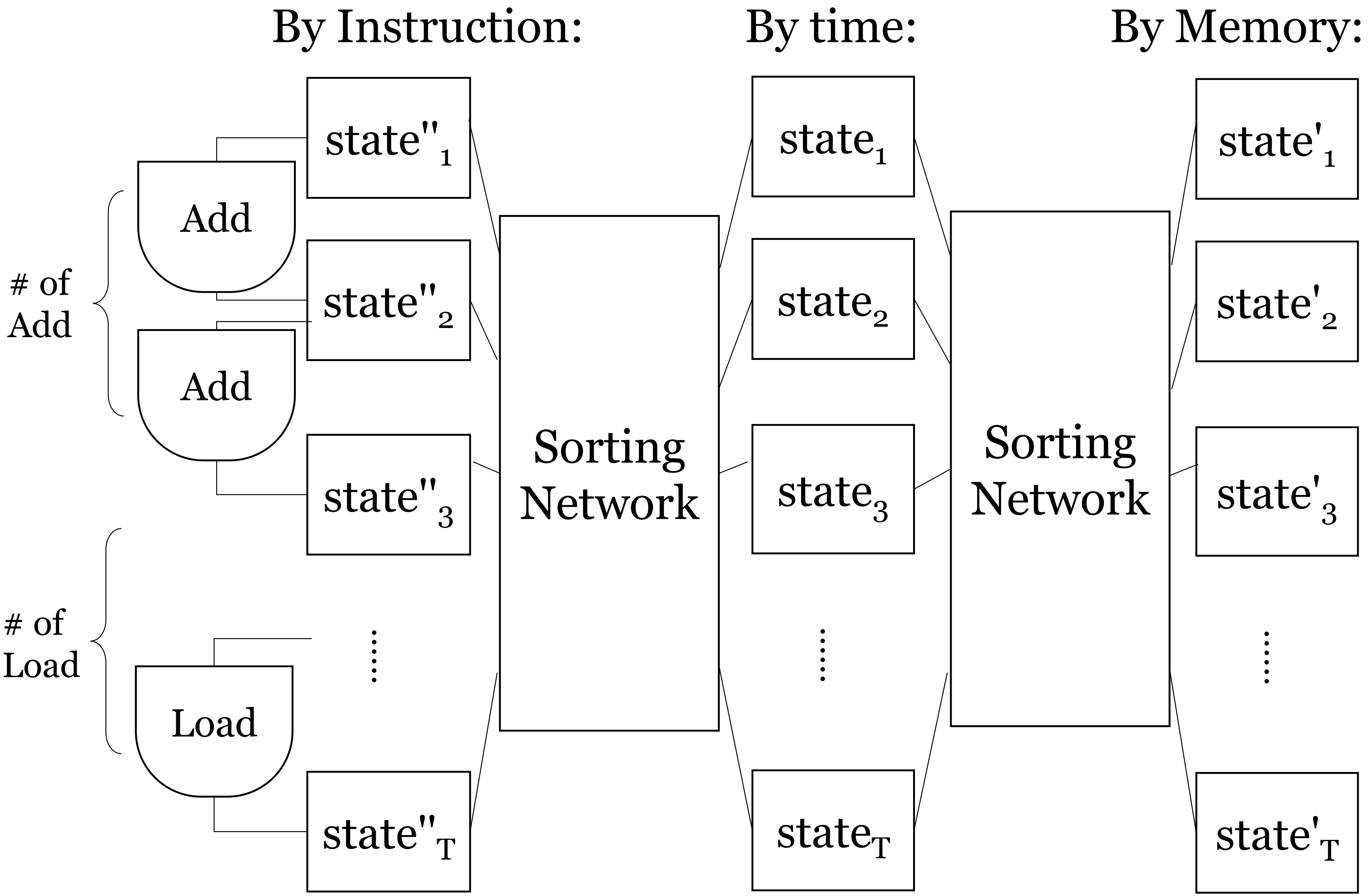
CPU step

CPU step

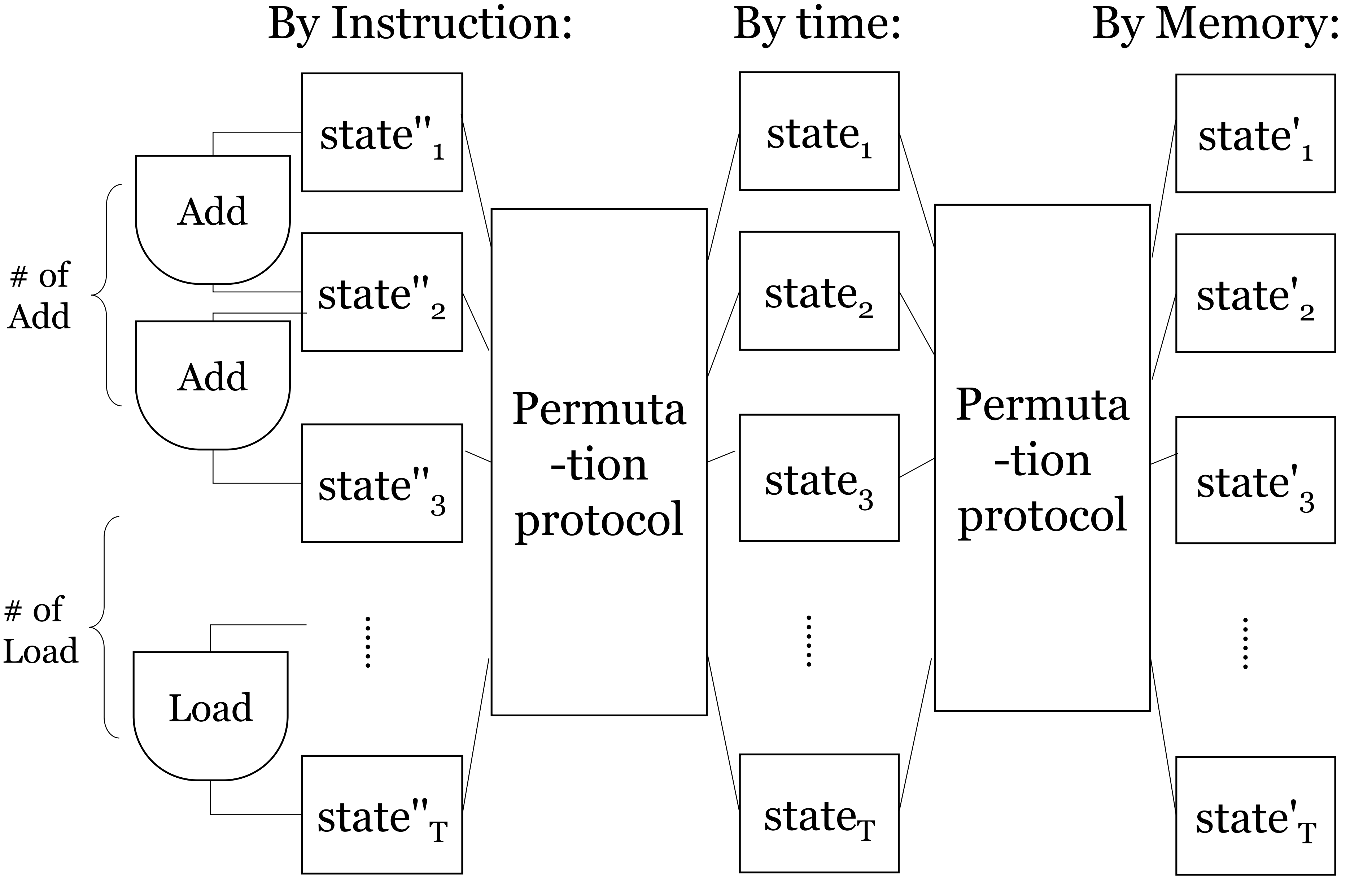
All possible CPU instructions:

ADD, MUL, JMP, CMP, LOAD,...

Our New RAM to Circuit Reduction



Our New RAM to Circuit Reduction



Our New Verifiable RAM

- 8× faster prover time
- 120× smaller memory consumption

  (up to 2 million CPU steps)
- Prover time linear in #of CPU steps T
- One preprocessing for both RAM and circuit

Summary

Verifiable Polynomial Delegation + Interactive Proof

- vSQL, verifiable databases
- Verifiable RAM

Ongoing work:

- Verifiable RAM with states
- Zero-knowledge with applications to crypto-currencies

Thank you!!!
Q&A