Proving the correct execution of concurrent services in zero-knowledge

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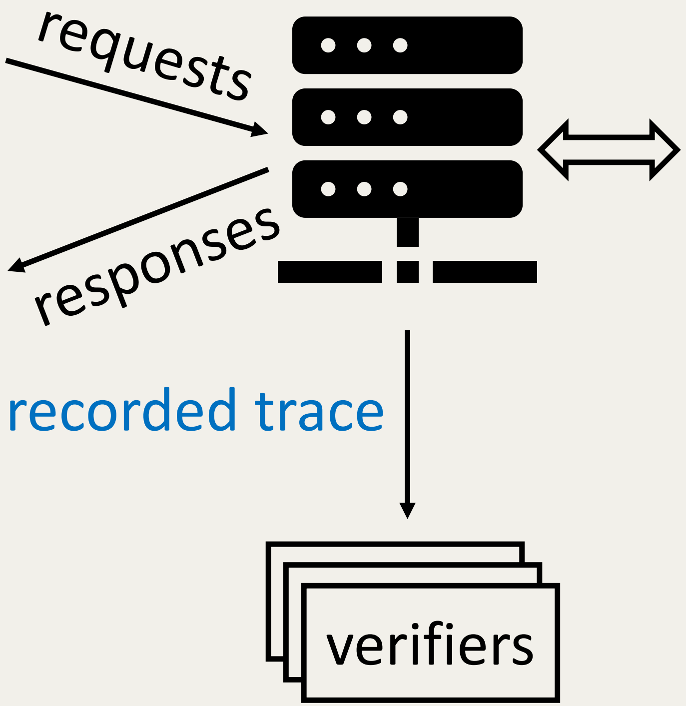
Software verification != Proving correct executions

Verifies that code obeys a desired specification (first three talks)

A cryptographic proof that desired code was correctly executed (this talk)

Neither subsumes the other

Consider a cloud-hosted wallet service (e.g., Square, WeChat Pay)



clientId	balance
1	200
2	500
3	100

key-value store

Verify trace by replay

API

- Issue (…)
- Transfer(…)
- Withdraw(…)

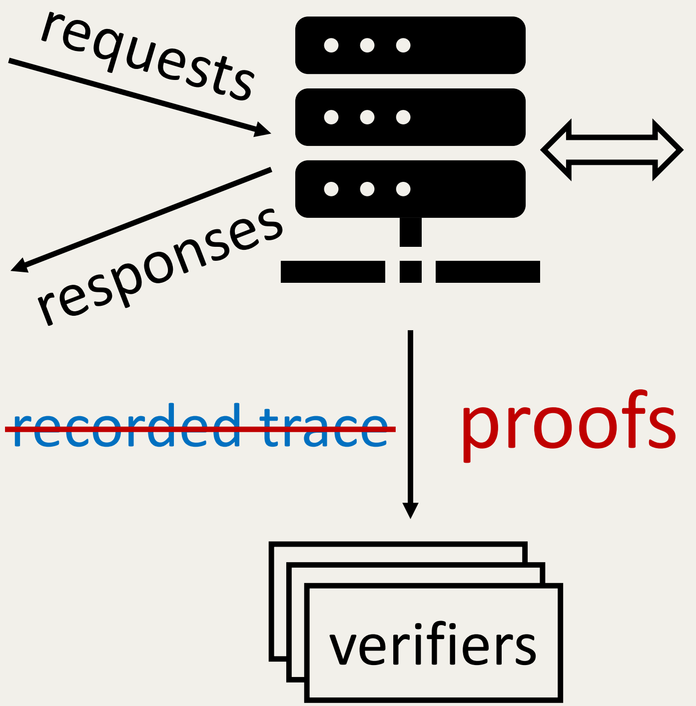
Issues with verifiability via record-and-replay

1. Sacrifices privacy: exposes requests and the internal state to a verifier
   - For example: account balances in the wallet app

Verifiable state machines address both problems

2. Verification via replay is expensive
   - Verifiers must reexecute all requests
   - Recorded trace can be large → network costs are high

A verifiable state machine:



clientId	balance
1	200
2	500
3	100

key-value store

~~Verify trace by replay~~

Verify proofs

- Proofs are zero-knowledge: they do not reveal requests, responses, or the state
- Proofs are succinct: each proof is small and verification is inexpensive
- If the service errs, verifiers output reject (except for a small probability, $<1/2^{128}$)

Prior work on verifiable state machines

- The underlying theory dates back to 90s: Babai et al.[STOC91], …

cost reductions by 10^{20}x

- Pepper[HotOS11, NDSS12], CMT[ITCS12], Ginger[Security12], TRMP[HotCloud12]
- Zaatar[EuroSys13], Pinocchio[S&P13], Allspice[S&P13], SNARKs-for-C[CRYPTO13]

support stateful computations

- Pantry[SOSP13], Geppetto[S&P15], CTV[EUROCRYPT15], vSQL[S&P17], …

storage interfaces: key-value stores, etc.

Prior work suffers from two major issues

1. Producing proofs about storage operations is computationally expensive
   Several seconds to minutes of CPU-time/operation

2. They can only produce proofs about sequential executions → each request must be processed before the next

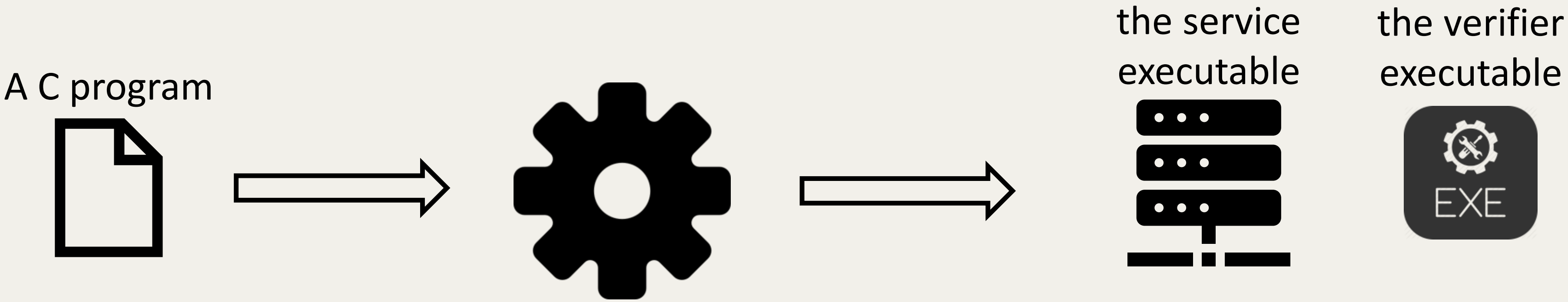
For the wallet service app (on a single CPU core):

Pantry [SOSP13] achieves < 0.15 requests/second

Geppetto [S&P15] achieves < 0.002 requests/second

Our system: Spice

- Features a new storage primitive: 29—2000x more efficient
- Supports concurrent request processing, with transactional semantics
- Includes a toolchain:



- We built three apps: a wallet service, payment network, and a dark pool
- Throughput: 488—1048 reqs/sec (512 CPU-cores)
  - This is 18,000—685,000 higher throughput than prior work

Rest of this talk

- **Background**
- Overview of Spice
- Experimental results

Background: Pantry[SOSP13]

Under Pantry, a service is expressed using:

subset of C ✚ **storage primitives**

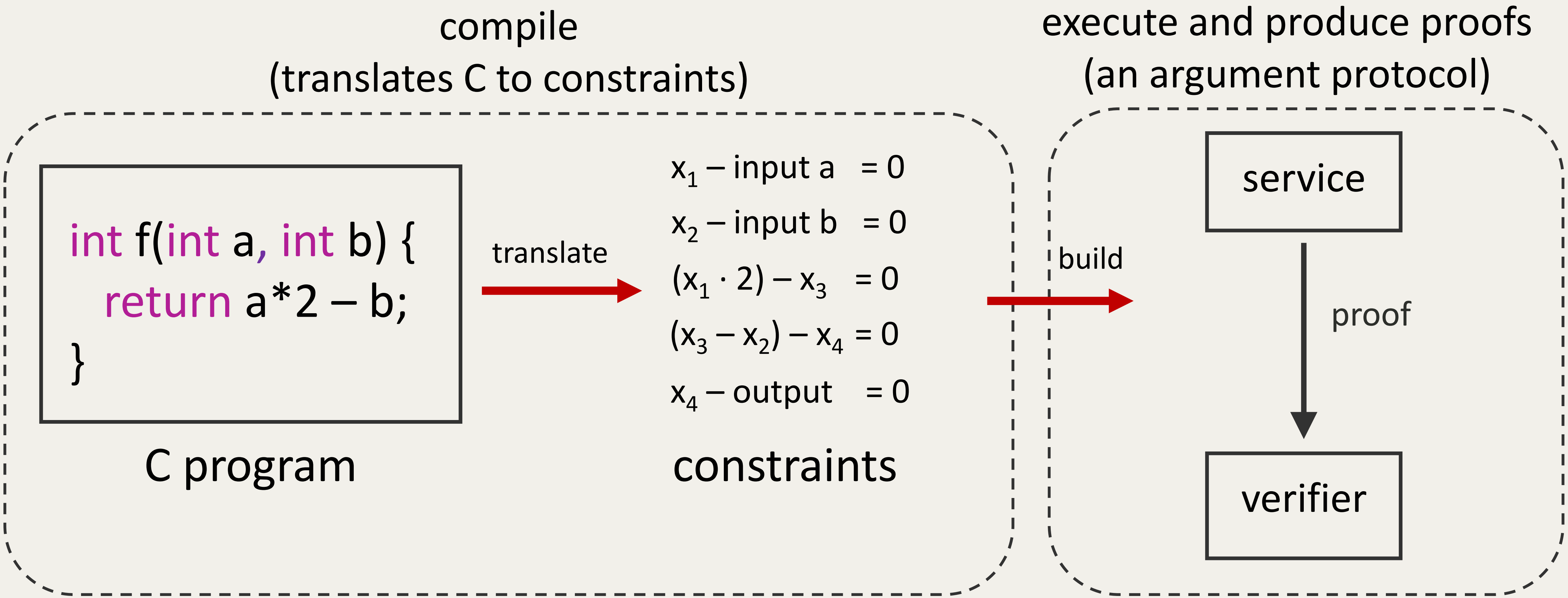
subset of C:

- Arithmetic operations
- Bitwise operations
- Conditional control flow
- Volatile memory (with pointers)
- Loops (with bounded iterations)

storage primitives:

- Key-value ops: get, put, etc.

Mechanics of Pantry [SOSP13] to produce proofs



Background: Pantry[SOSP13]

Under Pantry, a service is expressed using:

subset of C + **storage primitives**

- Arithmetic operations
- Bitwise operations
- Conditional control flow
- Volatile memory (with pointers)
- Loops (with bounded iterations)

An attempt:

```
Value get(Key k) {
  Value v = service_get(k);
  return v;
}
```

service supplies state ←

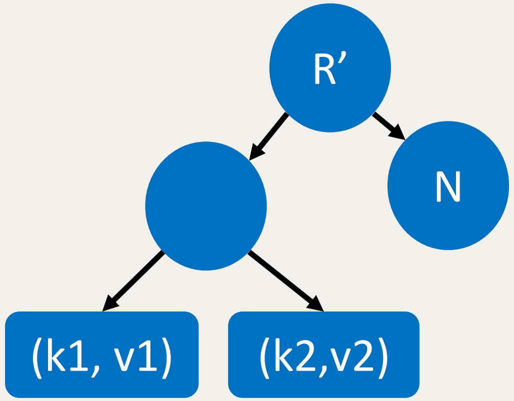
key-value store
maintained by service

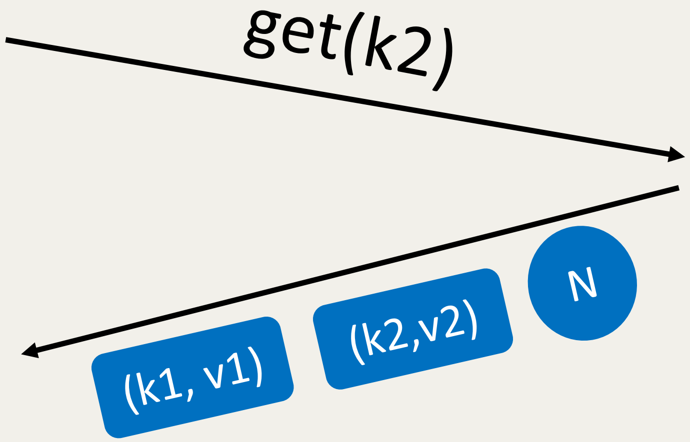
clientId	balance
1	200
2	500
3	100

service could supply incorrect values

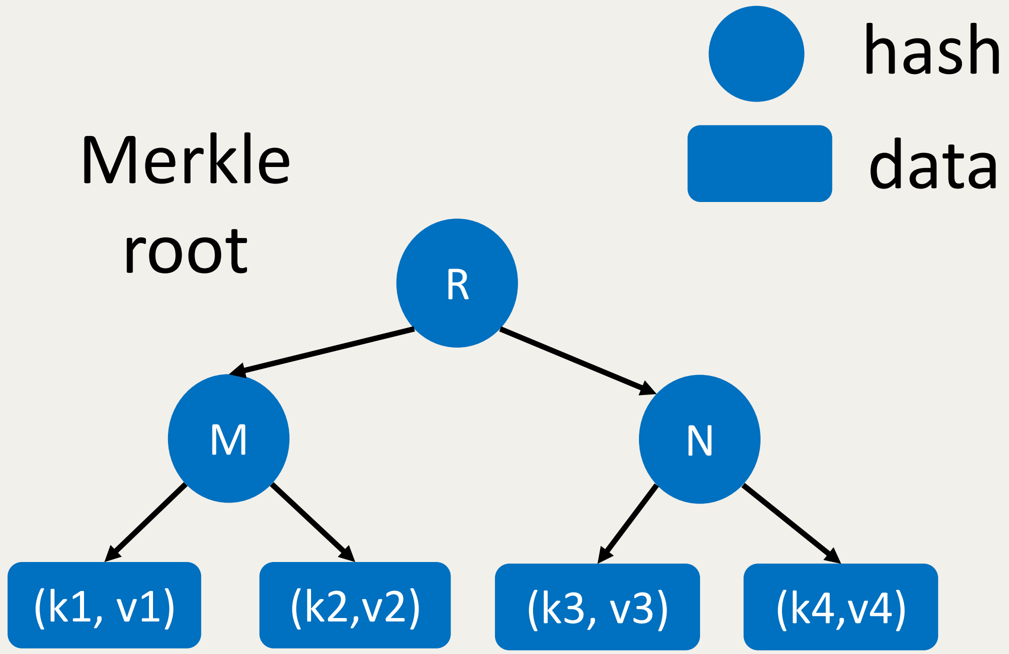
Merkle trees provide the necessary building block

```
Value get(Key k, Root R) {
  Value *v = service_get(k);
```






```
  assert R’ == R; // fails for incorrect value
  return v[0];
}
```



key-value store
maintained by the service

Issues with using Merkle trees for key-value stores

1. Cost of a get/put is logarithmic in the size of the state

2. The root of the tree serves as a contention point

   → supports only sequential executions

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- Experimental results

Spice in a nutshell:

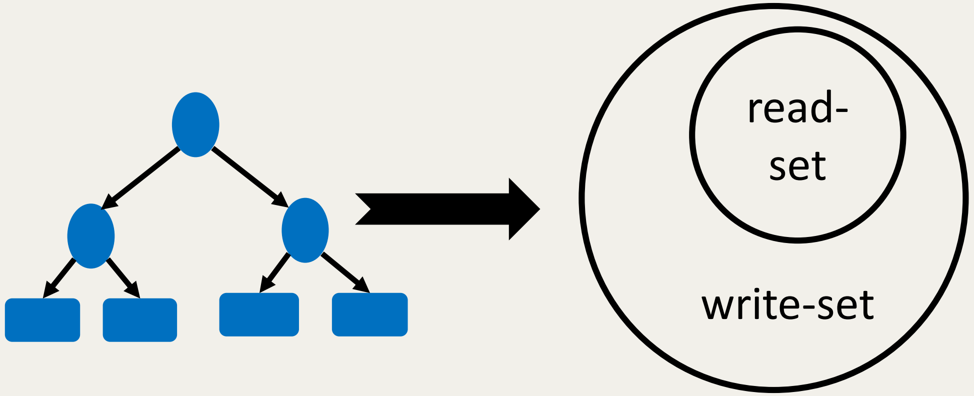
subset of C

- Arithmetic and bitwise ops
- Conditionals, loops, memory
- …

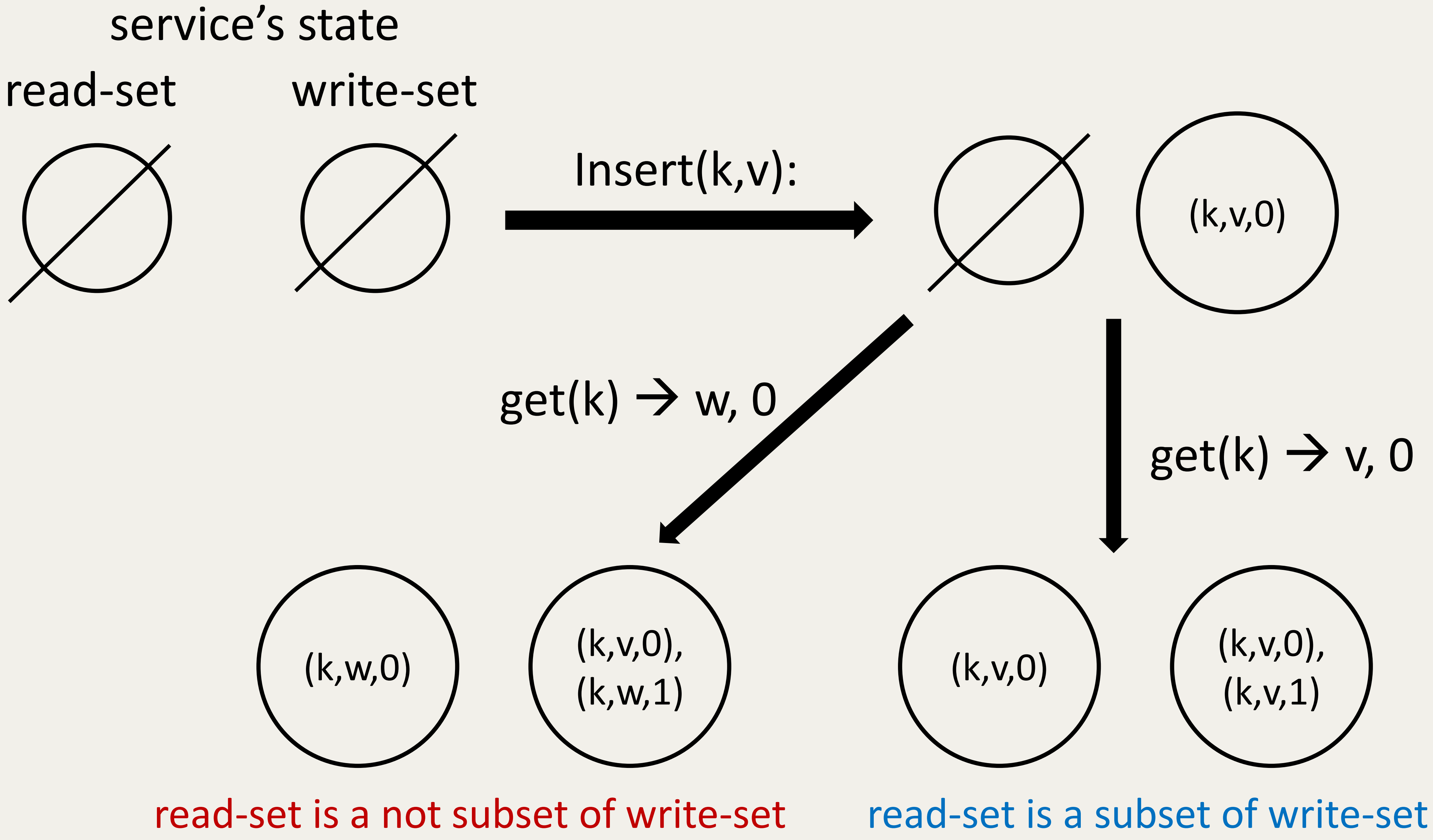
Compile and apply argument protocol

Succinct zero-knowledge proof

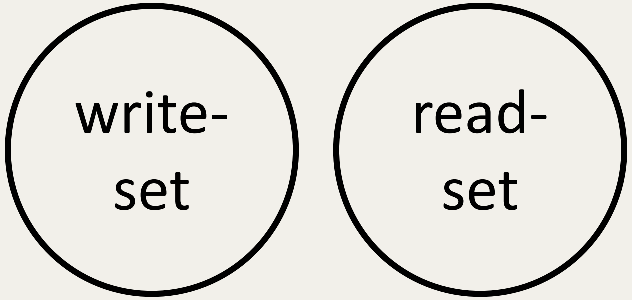
storage primitives



[Blum et al. FOCS91, Clarke et al. ASIACRYPT03, Arasu et al. SIGMOD17]


service’s state
read-set
write-set
Insert(k,v):
(k,v,0)
get(k) → w, 0
get(k) → v, 0
(k,w,0)
(k,v,0),
(k,w,1)
(k,v,0)
(k,v,0),
(k,v,1)
read-set is a not subset of write-set
read-set is a subset of write-set

service’s state



An equivalent of Merkle root

```
struct set-root {
  set-hash rs; // set-hash of read-set
  set-hash ws;
}
```

$$\text{Set-Hash}(\{A, B\}) = \text{Set-Hash}(\{A\}) * \text{Set-Hash}(\{B\})$$
$$= \text{Set-Hash}(\{B\}) * \text{Set-Hash}(\{A\})$$

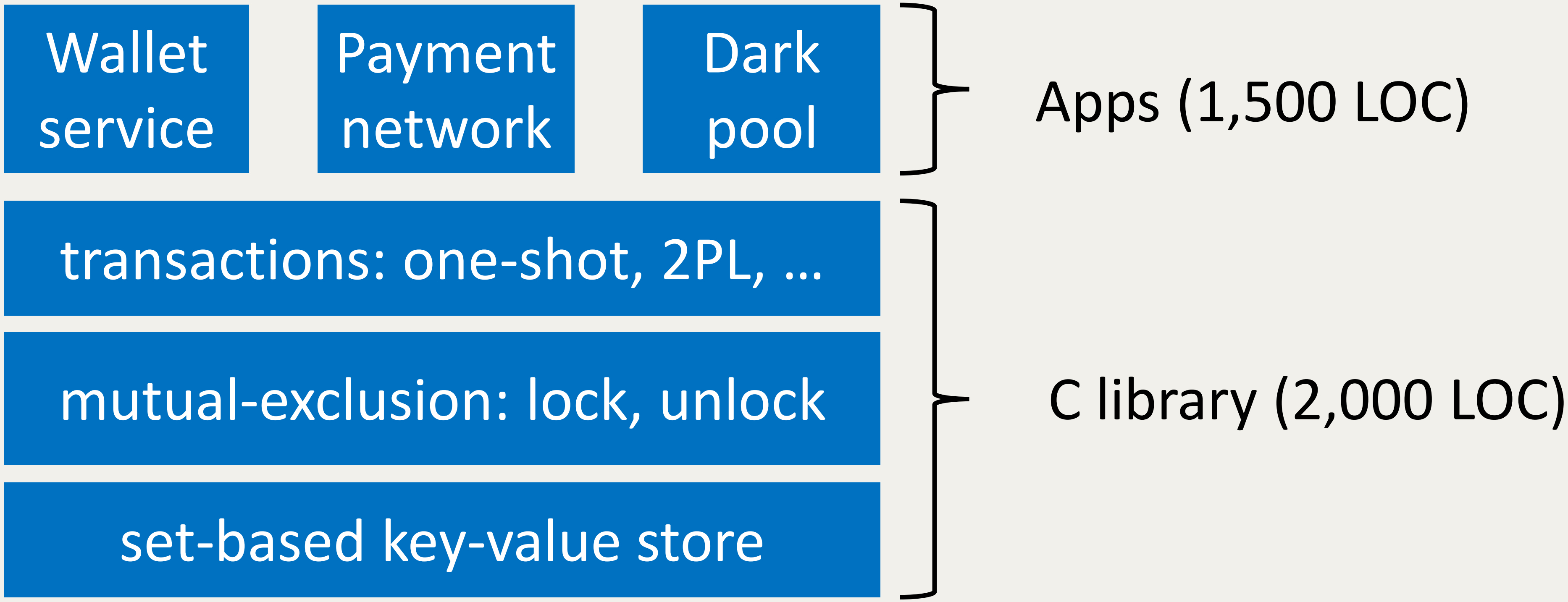
Takeaways on set-based storage:

get, put add an element to read-set and write-set → cost of a get, put is a constant

service periodically proves read-set \subset write-set → cost is linear in state size, but amortized over a batch

non-conflicting set operations commute → multiple writers and concurrent request processing

We built transactions and apps atop set-based storage



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- **Experimental results**

Evaluation questions

1. How does Spice compare with the prior state-of-the-art?
2. What is the end-to-end performance of apps built with Spice?

Evaluation testbed:

`Azure D64s_v3` instances: 32 CPUs, 2.4 Ghz Intel Xeon, 256 GB RAM, running Ubuntu 17.04

(1) How does Spice compare to prior work?

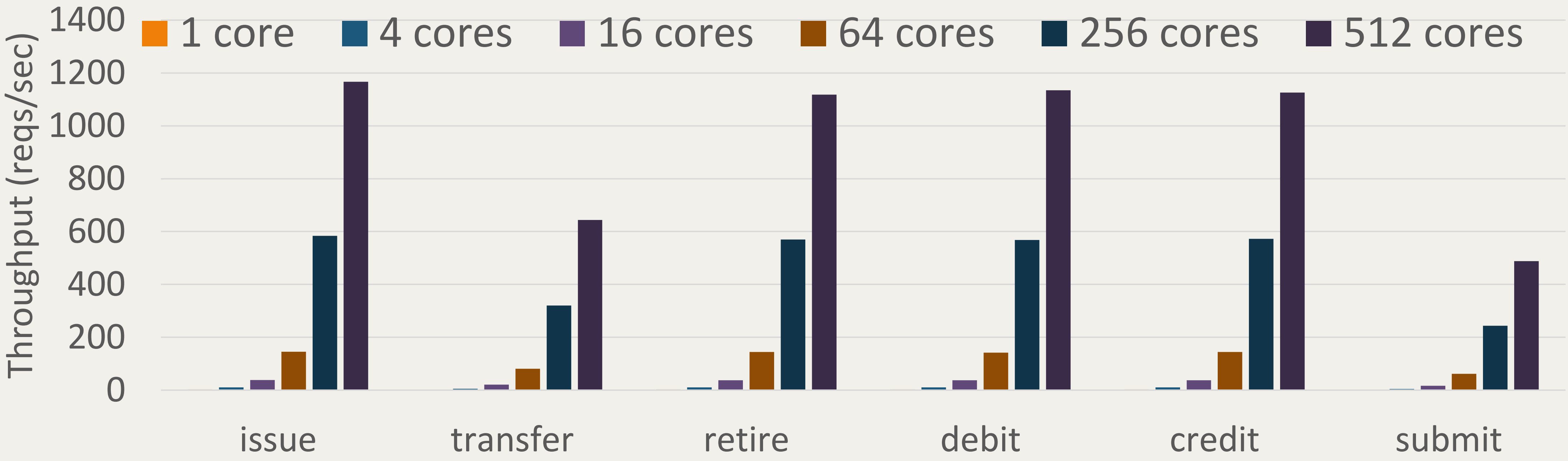
A million key-value pairs

Transactions with a single operation, keys chosen with a uniform distribution

Metric: number of ops/second (i.e., proofs/sec)

	get	put
Pantry [SOSP13]	0.078	0.039
Pantry++	0.15	0.076
Geppetto [S&P15]	0.002	0.002
Spice (1-thread)	3.6	3.6
Spice (512-threads)	1,366	1,370

(2) End-to-end performance with varying #CPUs



- TPS is 18,000—685,000x better than prior state-of-the-art
- Verification throughput: >1,000 proof verifications/sec (4 CPU-cores)

Limitations of Spice

1. CPU-cost to produce proofs remains large (compared to executions without proofs): >1000x

2. Spice amortizes the cost of producing a proof (that read-set \subset write-set) over a batch of requests
   - Introduces latency for producing proofs (7.5 minutes in our experiments)
   - Tunable, but lower latency increases CPU-costs

Summary

- Verifiable state machines add verifiability to services—without compromising their privacy

- Spice is a substantial progress toward building verifiable state machines
  - 18,000—685,000x better performance (over prior state-of-the-art)
  - Spice supports realistic apps with thousands of transactions/sec

- We predict: Spice or a variant will be a key tool in building secure systems