Cobra: Making Transactional Key-Value Stores Verifiably Serializable

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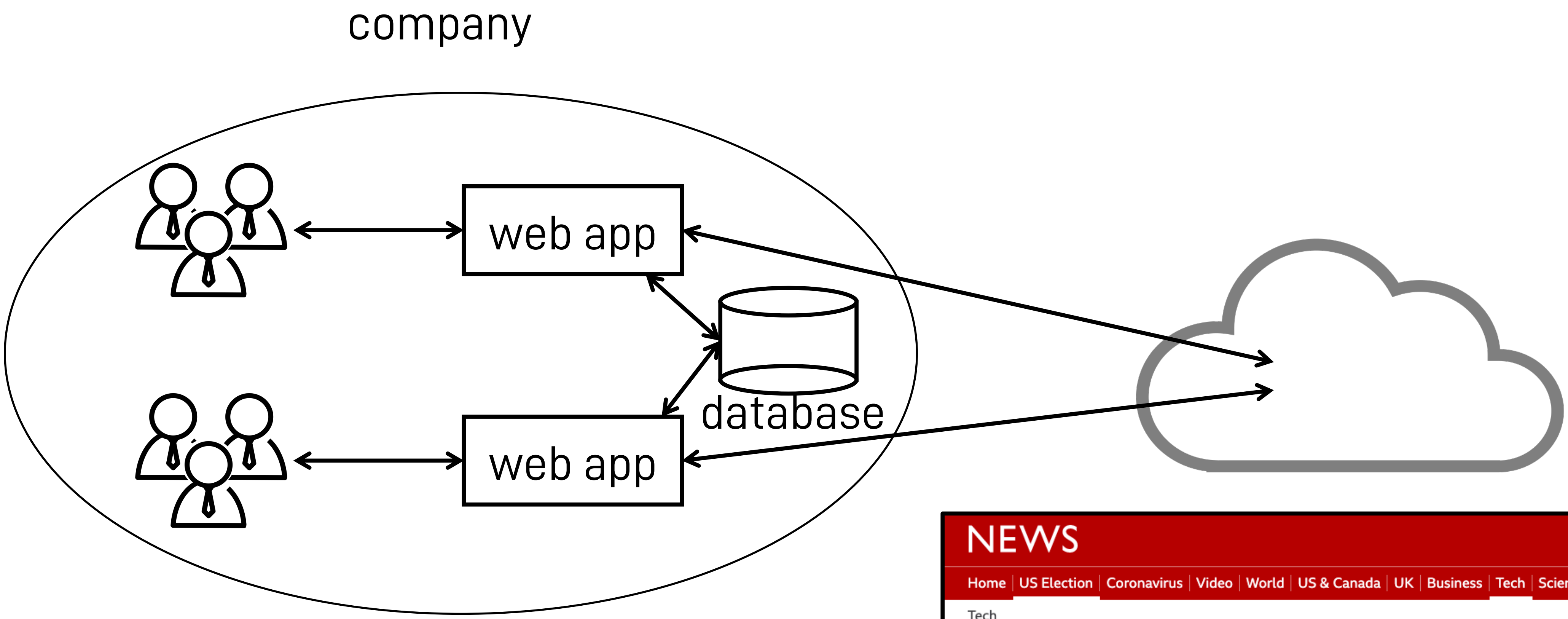
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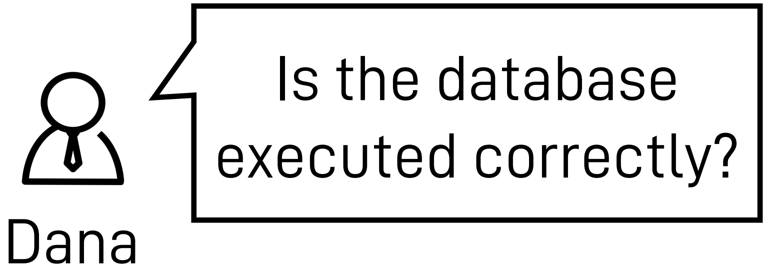
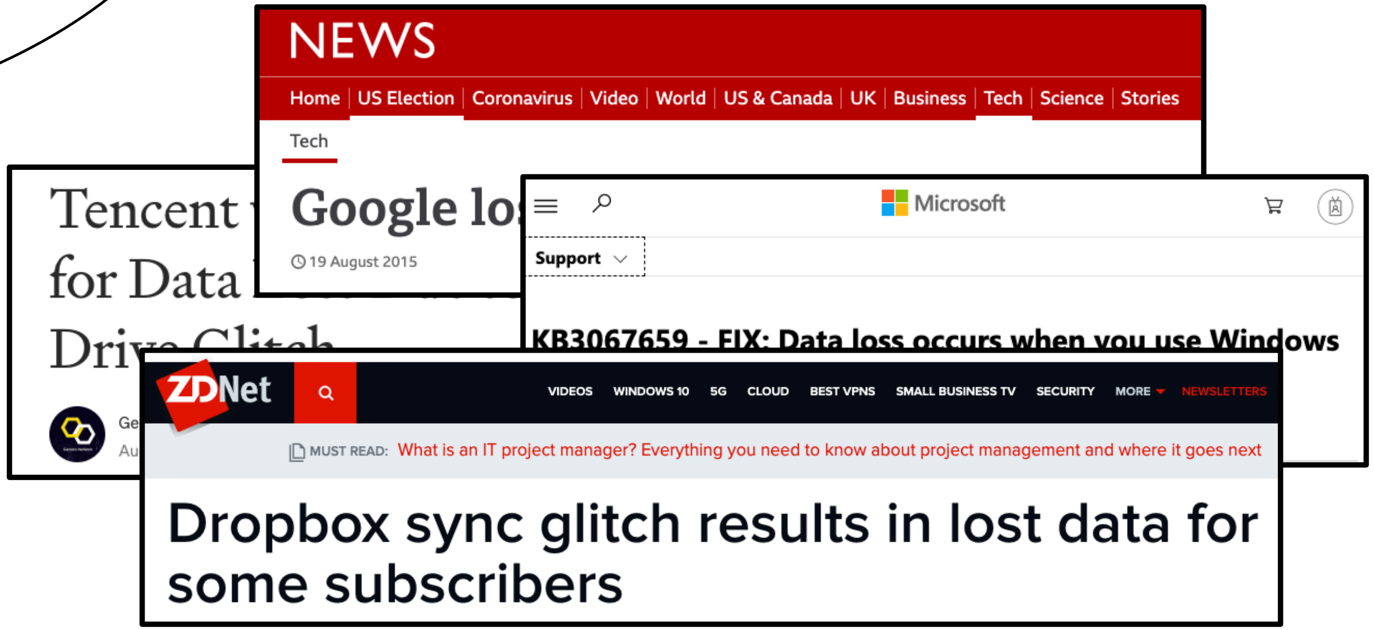
web app
web app
database


Is the database executed correctly?
Dana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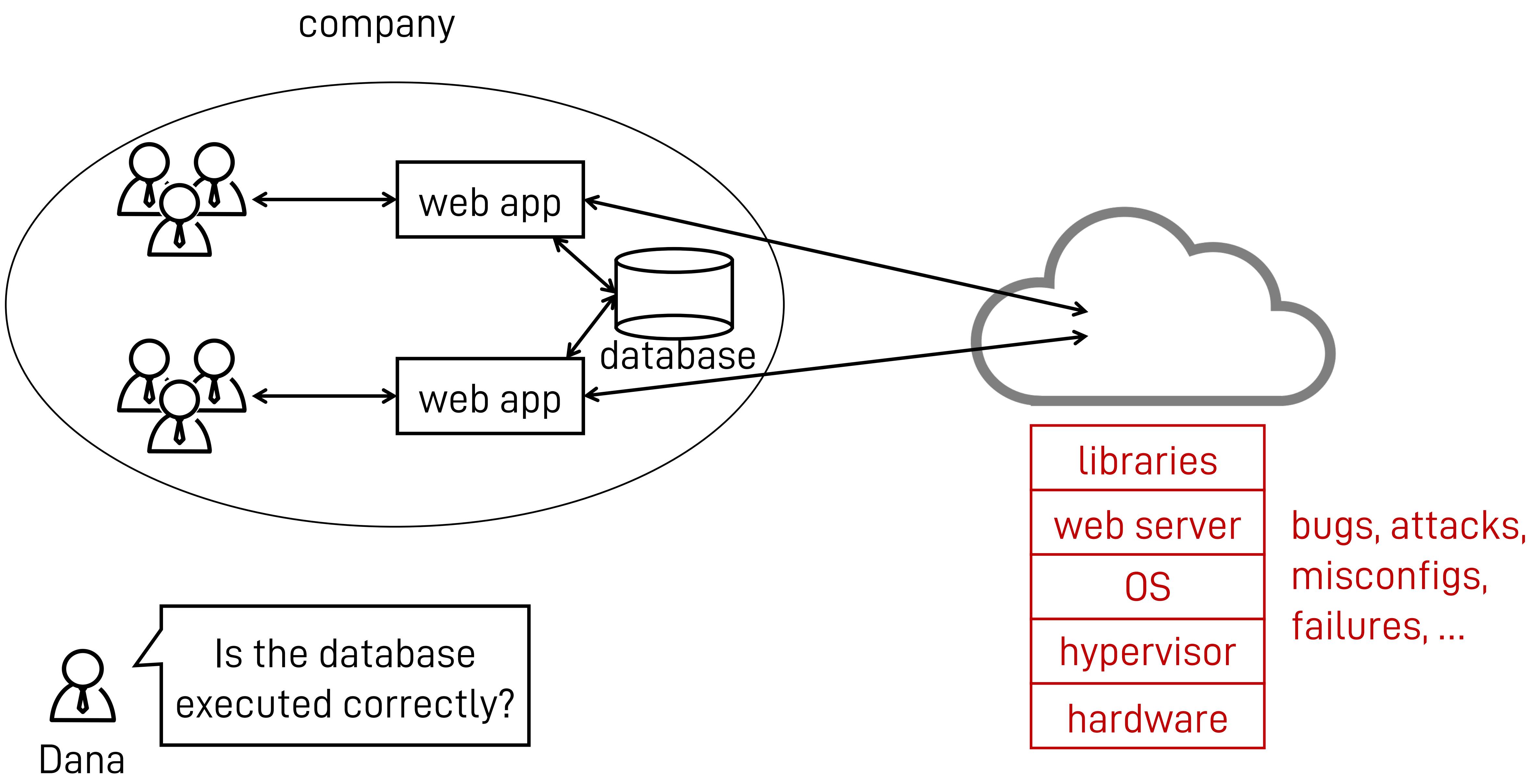
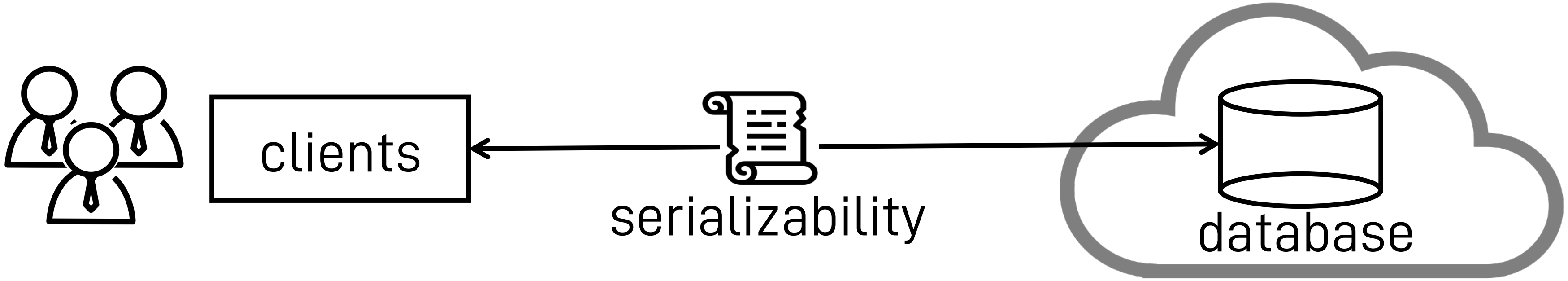
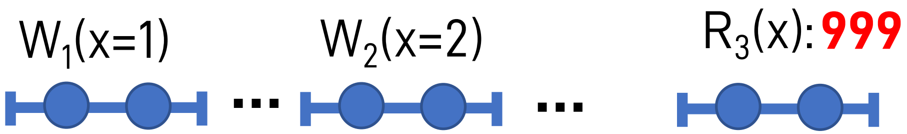

company
web app
web app
database
libraries
web server
OS
hypervisor
hardware
bugs, attacks,
misconfigs,
failures, ...
Is the database
executed correctly?
Dana

Serializability is a correctness contract



clients' transactions = sequential execution of these transactions

- Serializability implies basic data integrity, tolerating faults, ...



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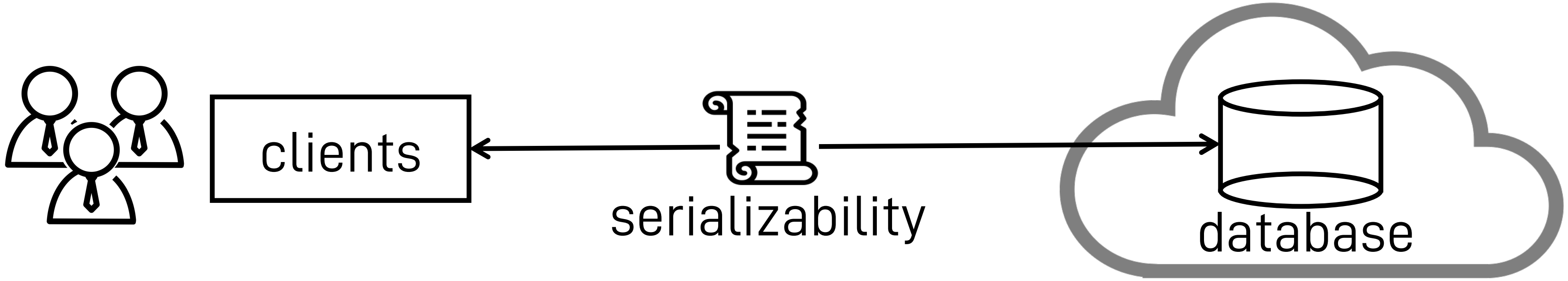


gold standard
isolation level
&
correctness contract

serializability
violations exist in
production systems

The underlying problem is ...

a) ... black-box checking of

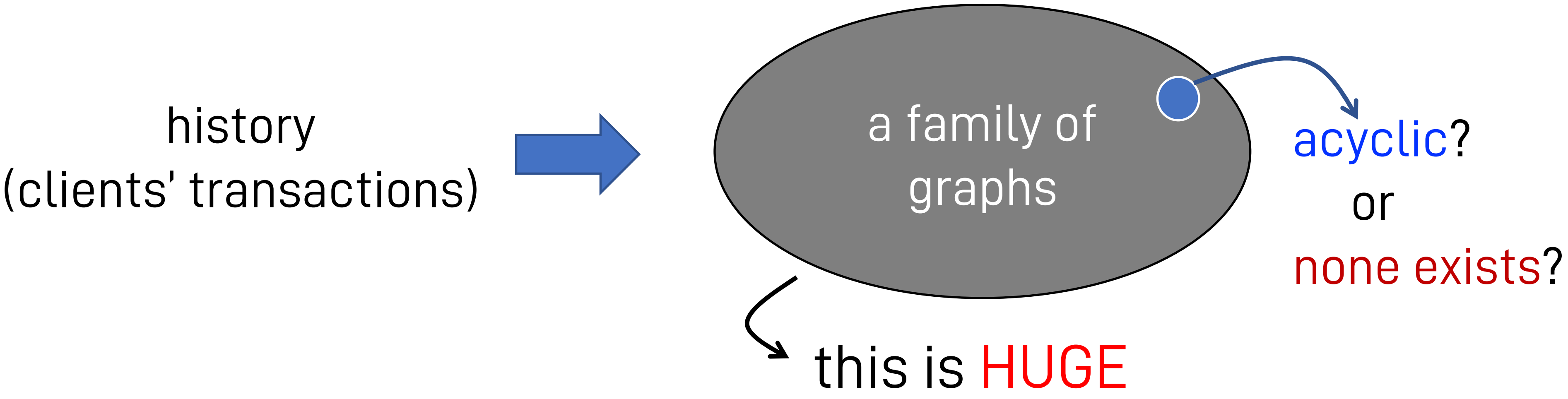
b) ... serializability

c) ... while scaling to real-world workloads.

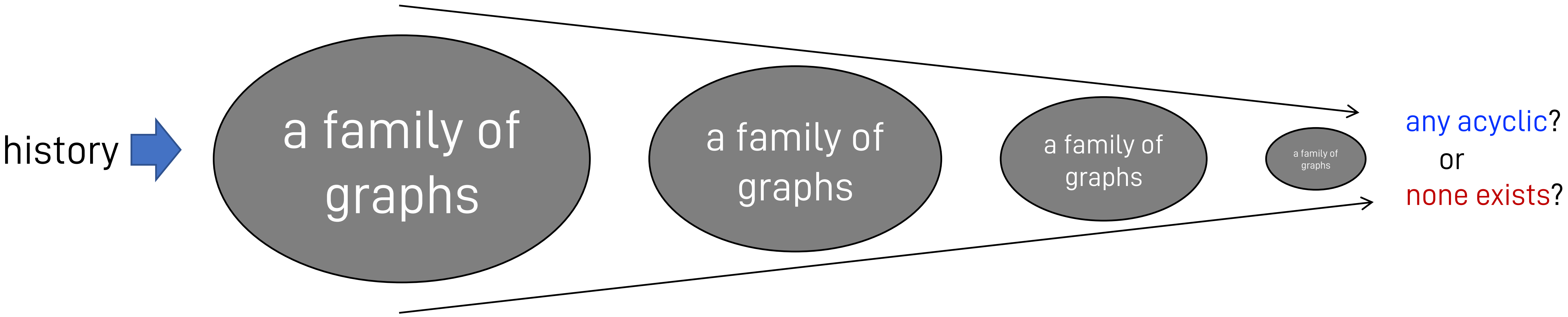
Note: we verify the executions, not the implementation.

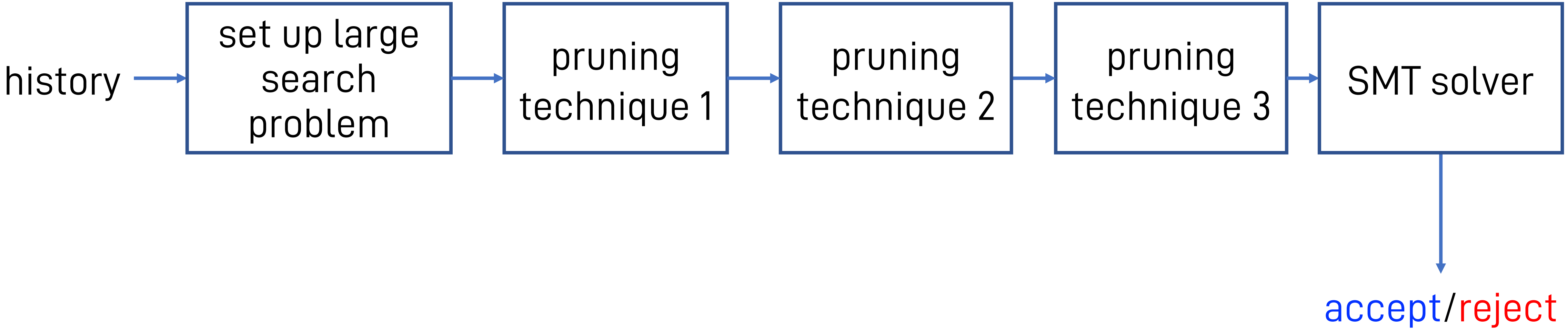
Cobra: verifying serializability of black-box databases

Cobra:

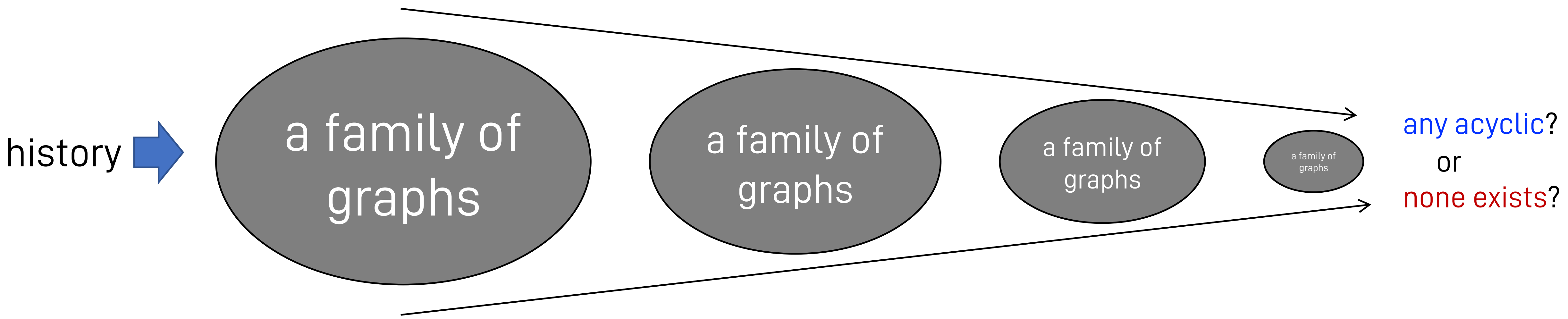


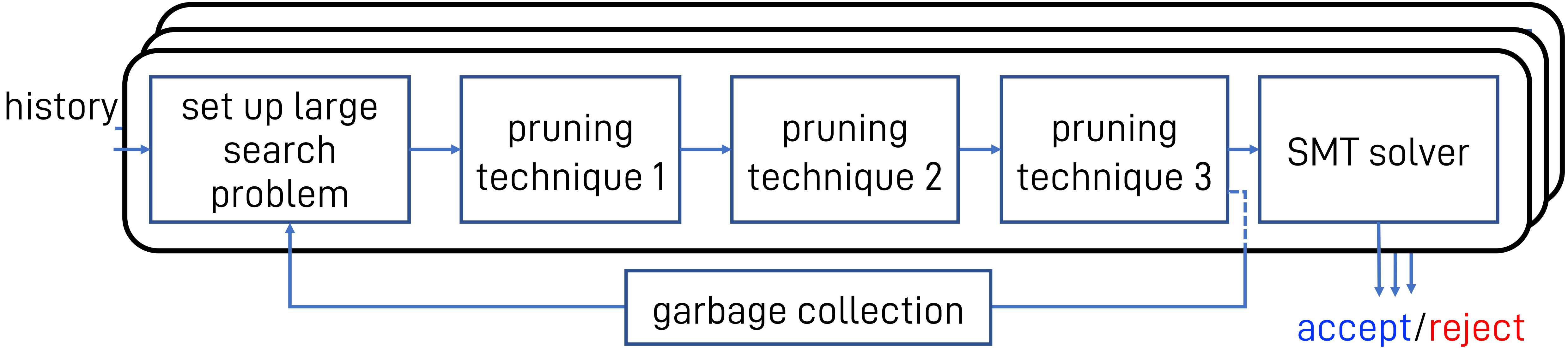
Cobra: verifying serializability of black-box databases





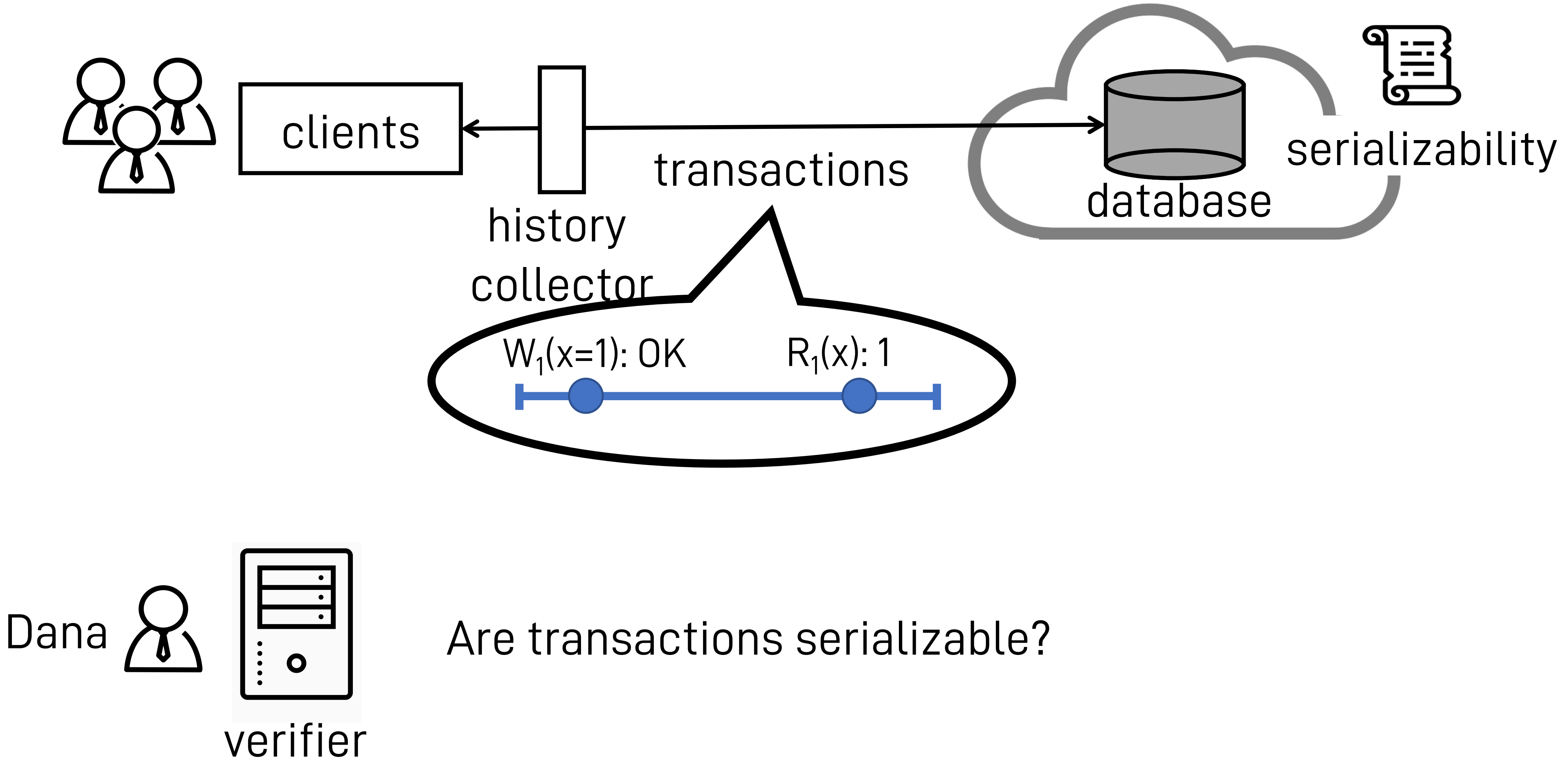
Cobra: verifying serializability of black-box databases





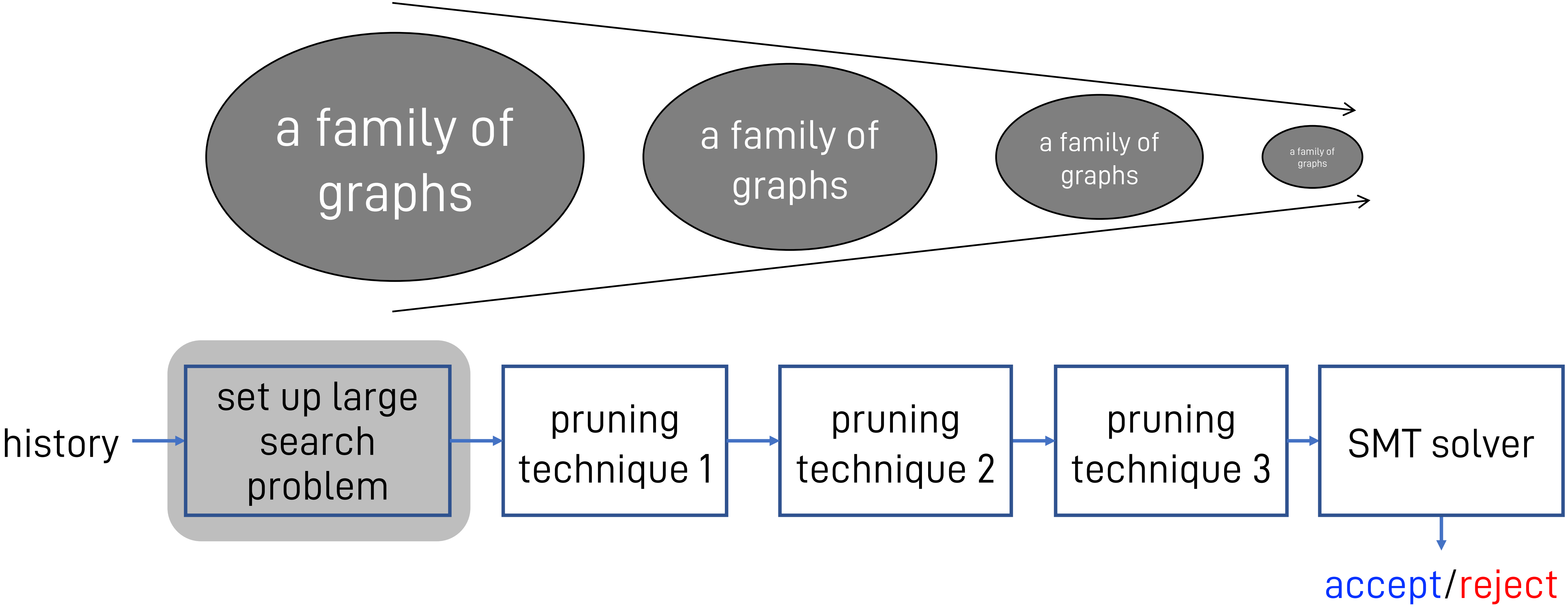
Rest of the talk

- The underlying problem
- Solution: Cobra


clients
history
collector
transactions
$W_1(x=1)$: OK
$R_1(x)$: 1
database
serializability
Dana
verifier
Are transactions serializable?

Starting point: brute-force search on a polygraph

- [Papadimitriou 79]: build a polygraph (a family of graphs) and search
- Step 1: building a polygraph from a history
- Step 2: searching for an acyclic graph


a family of graphs
a family of graphs
a family of graphs
a family of graphs
history
set up large search problem
pruning technique 1
pruning technique 2
pruning technique 3
SMT solver
accept/reject

Starting point: brute-force search on a polygraph

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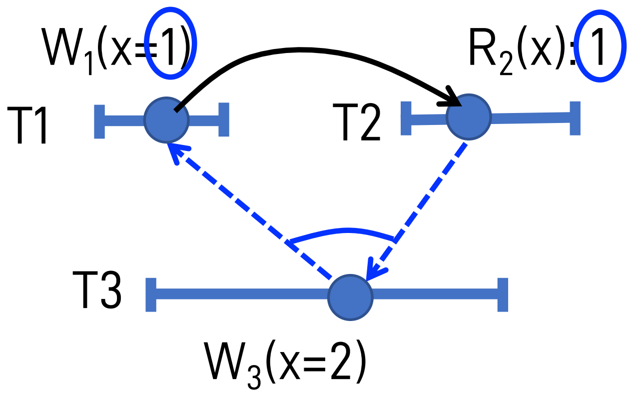

polygraph = (V, E, C)

V = { T1 , T2 , T3 }

E = { T1 ⟶ T2 }

C = { <T3 ⟶ T1, T2 ⟶ T3> }

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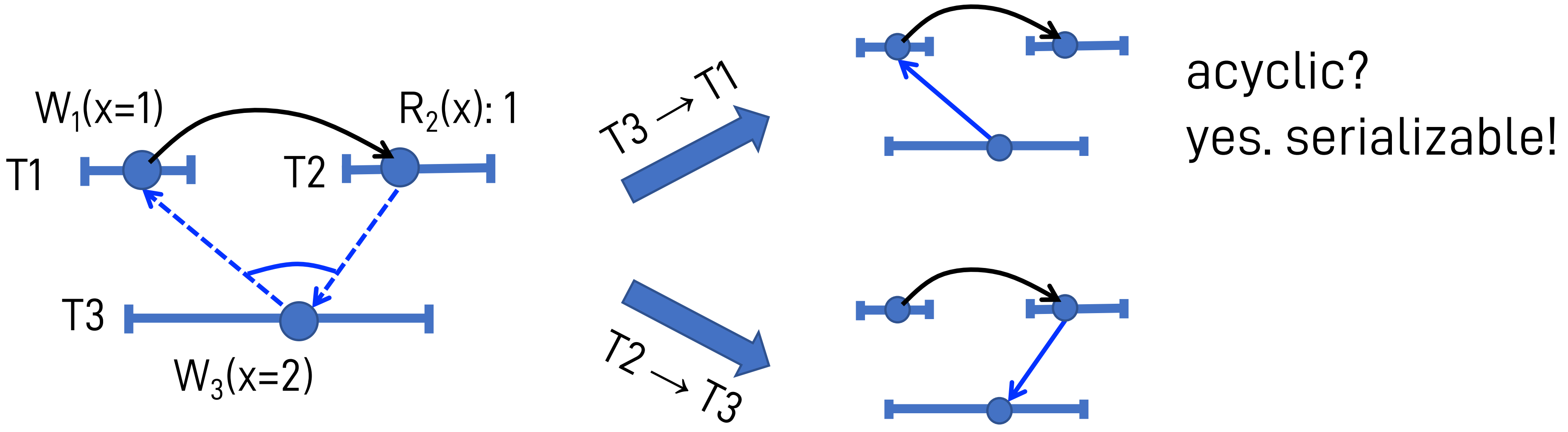
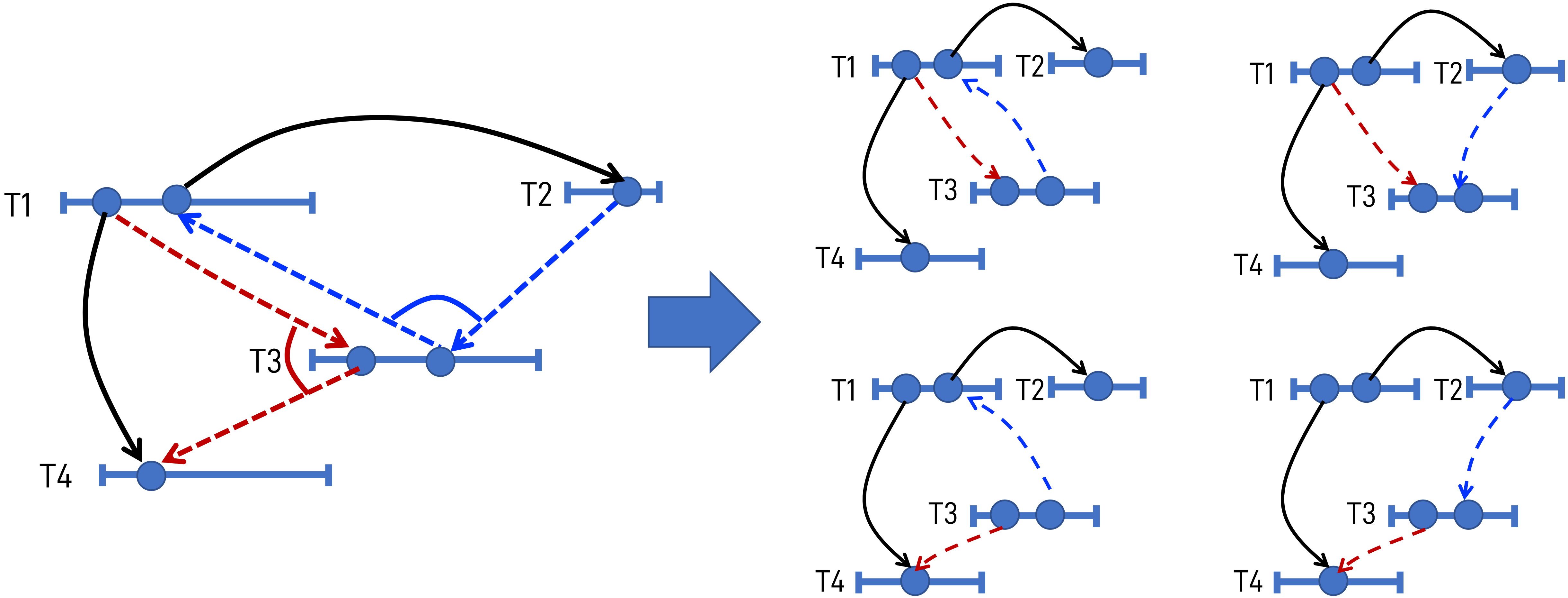




polygraph (V, E, C)

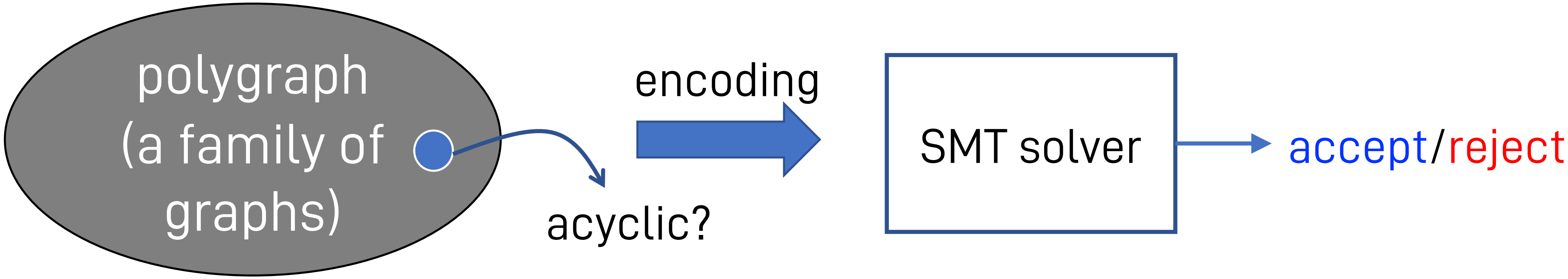
the search space is $2^{|C|}$

Outline

- The underlying problem
- Solution: Cobra

Checking serializability may be tractable in practice

- Intuitions:
  - advances of SAT/SMT solvers
  - heuristically solving many hard problems
- Baseline: encode the problem and use SMT solvers



Cobra aims at real-world workloads

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  - heuristically solving many hard problems
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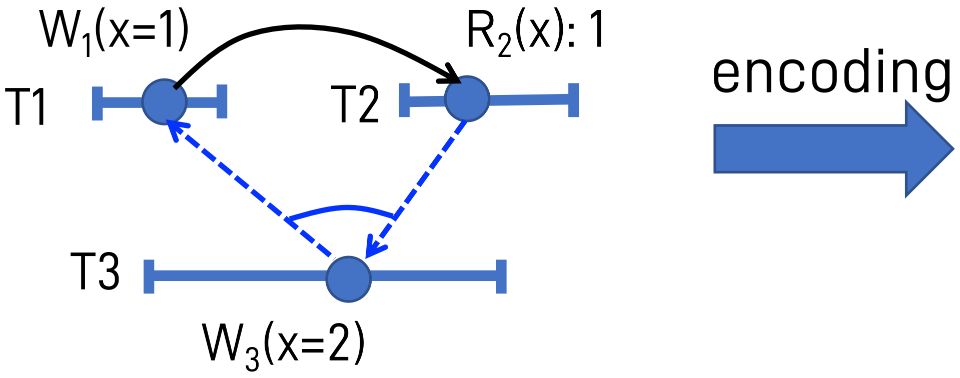

Edges:

$e_{(T1,T2)}$ = True

Constraints:

con = ($e_{(T3,T1)}$=True AND $e_{(T2,T3)}$=False) OR
($e_{(T3,T1)}$=False AND $e_{(T2,T3)}$=True)

Acyclicity:

graph with edges=True is acyclic

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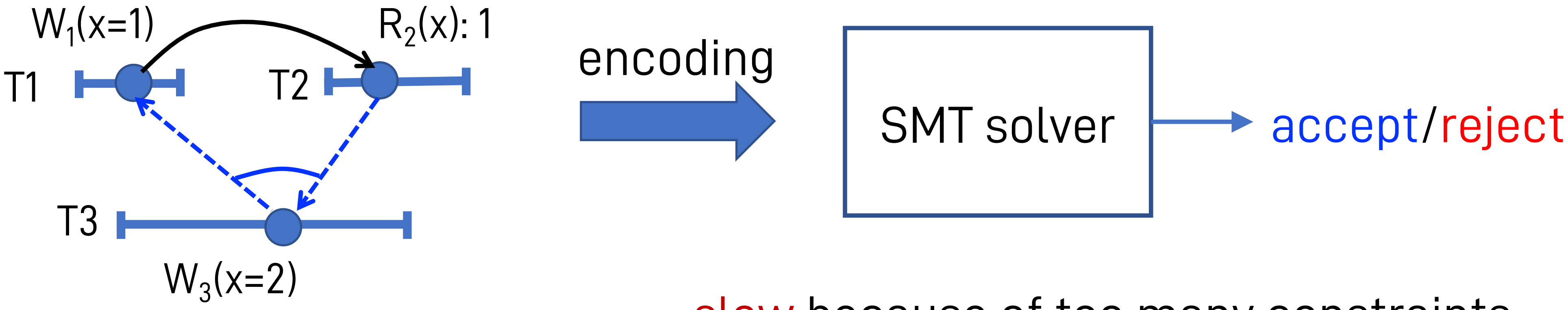
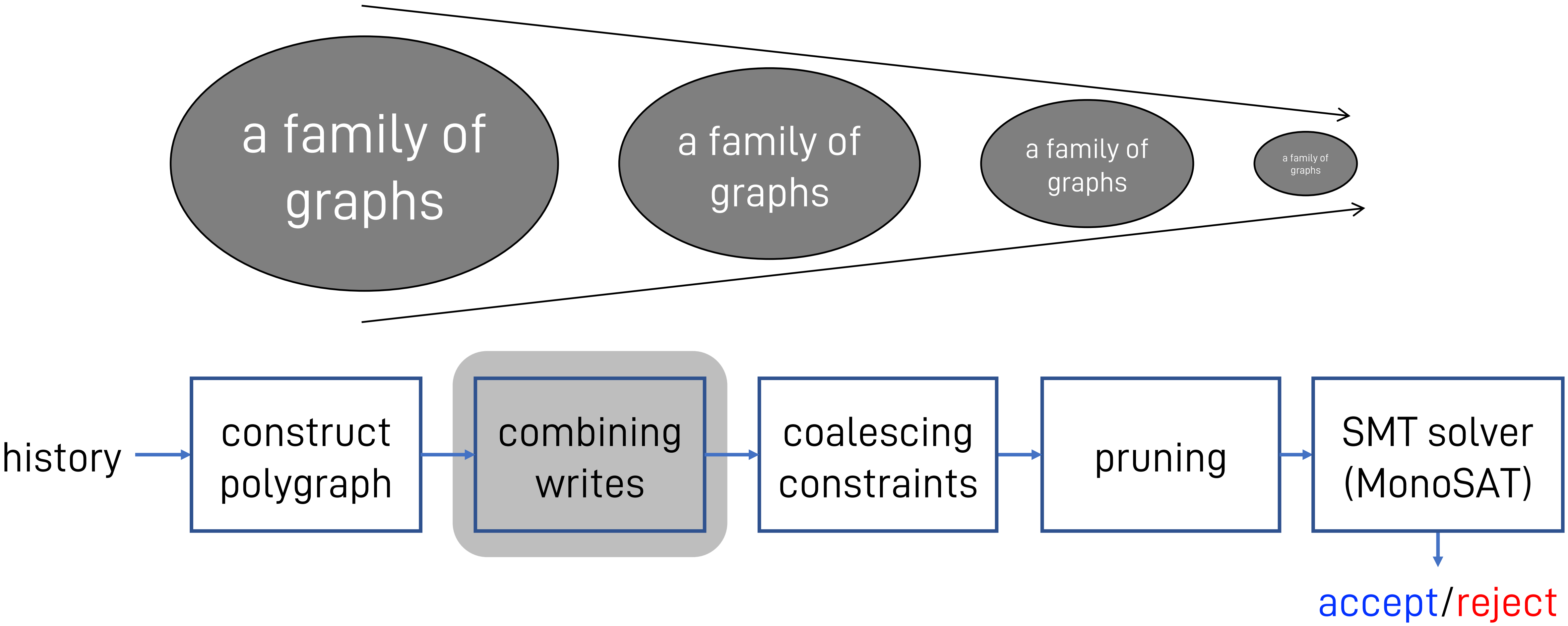


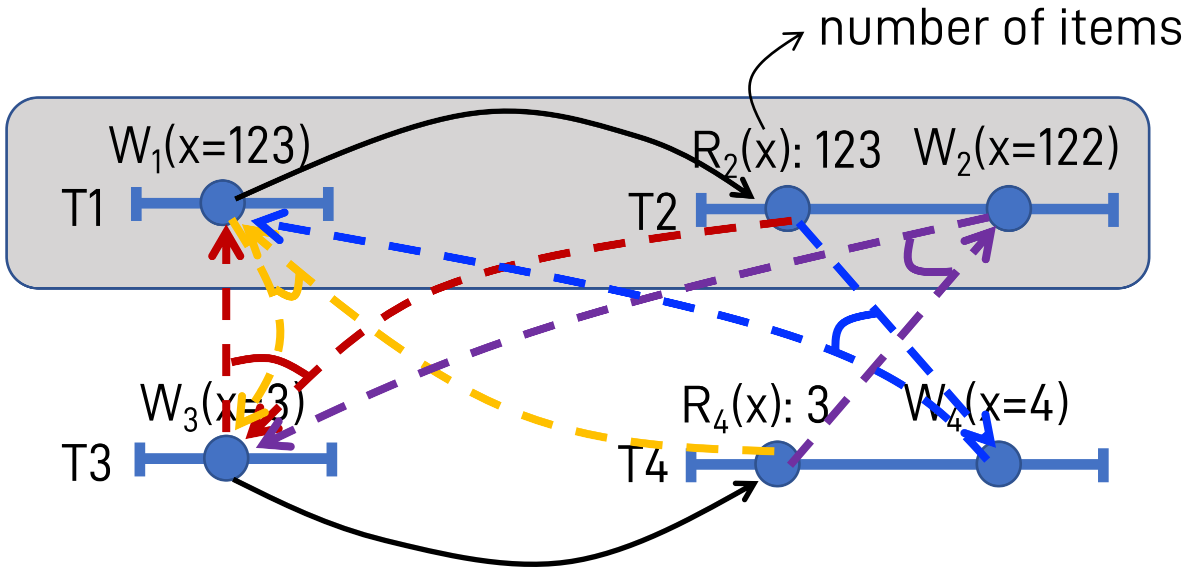
slow because of too many constraints

How to reduce constraints in a polygraph?



Combining writes exploits a common pattern

- Read-modify-write is a common pattern in practice.



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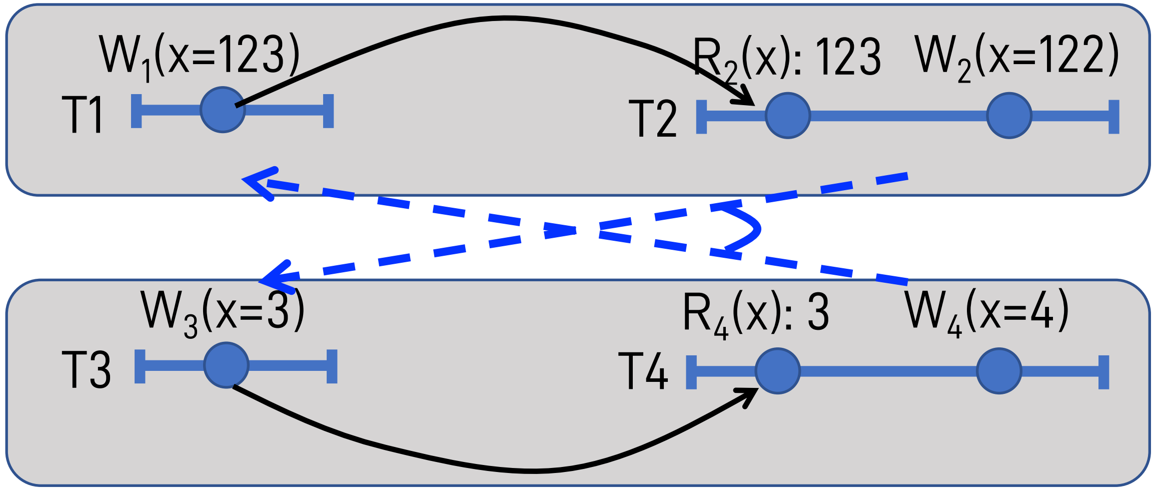
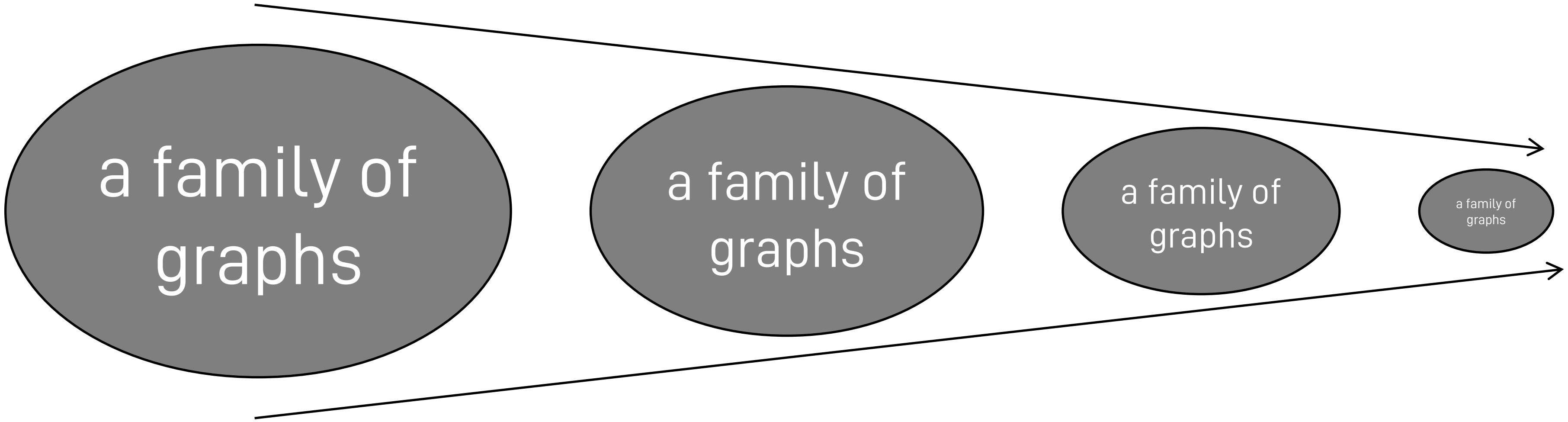
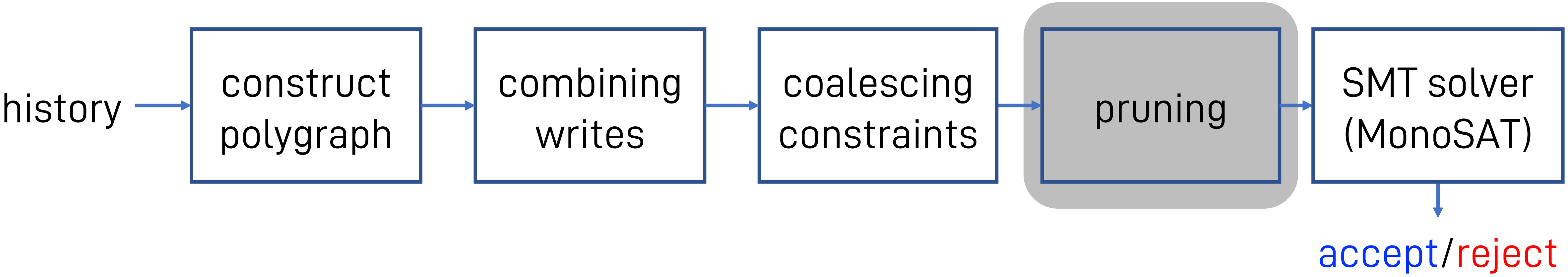


Cobra produces just one constraint.

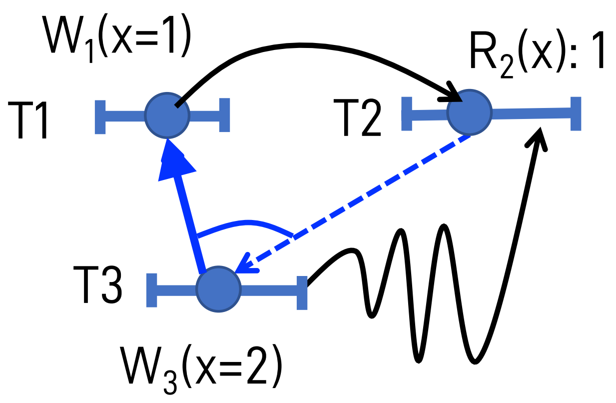
Cobra exploits characteristics of the problem





Pruning via graph paths (reachability)

- idea: reduce #constraints by reachability
  1) what can be learned from reachability?
  2) how to get reachability efficiently?



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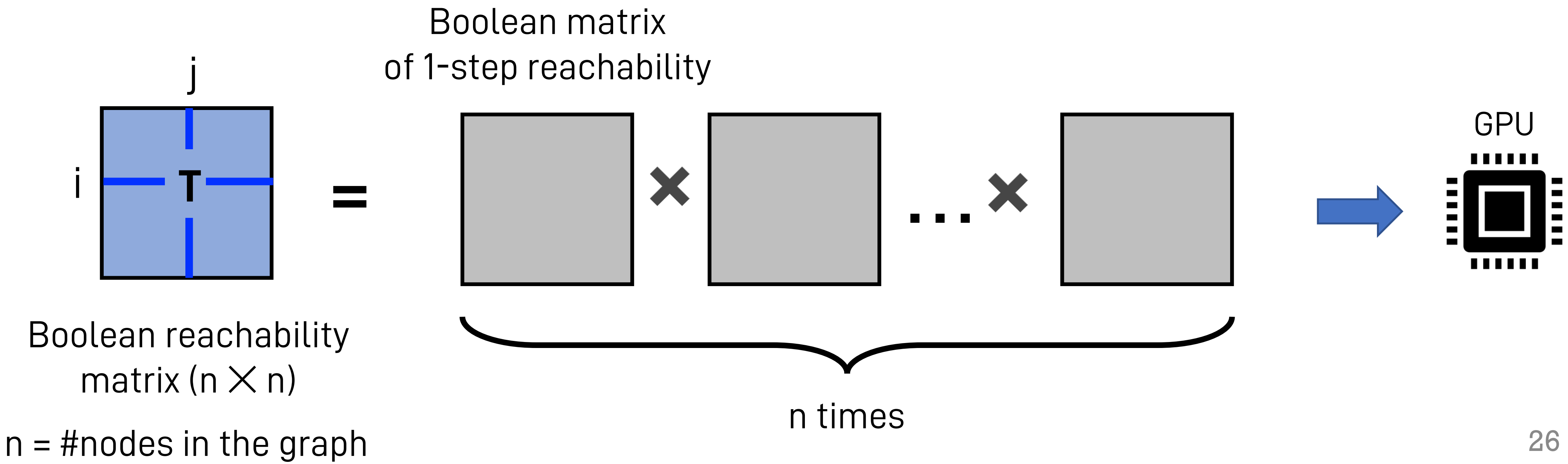
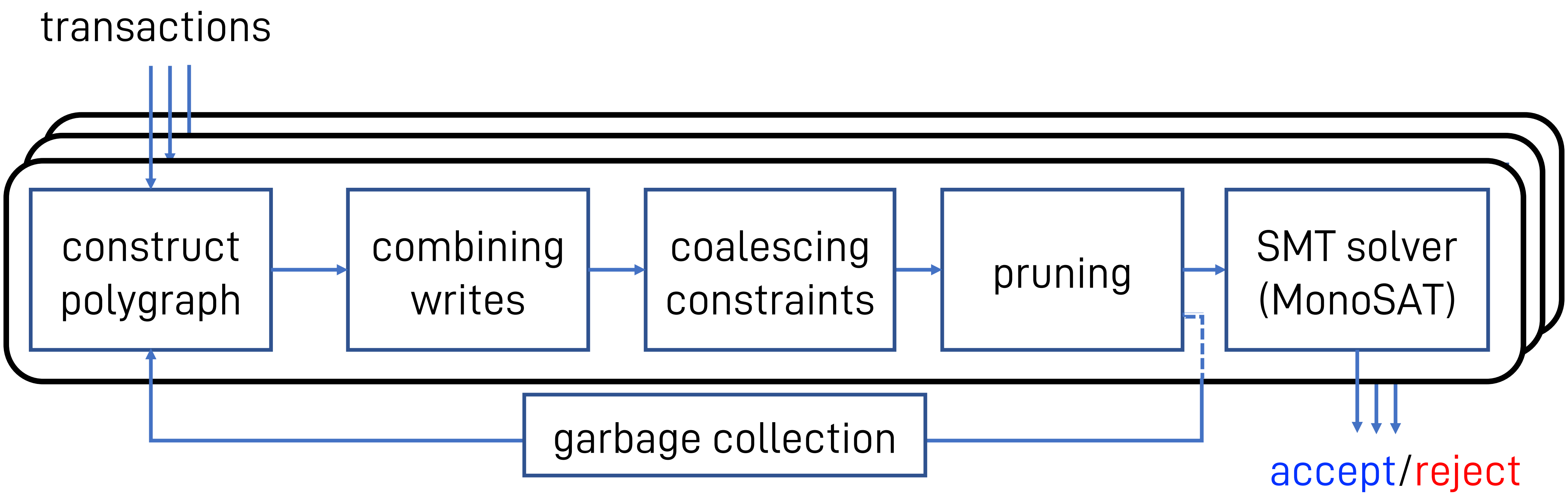


Cobra verifies in rounds to support growing histories



- Cobra needs to delete transactions after each round.

Experimental evaluation

- What are Cobra verifier's costs compared to the baseline (MonoSAT)?

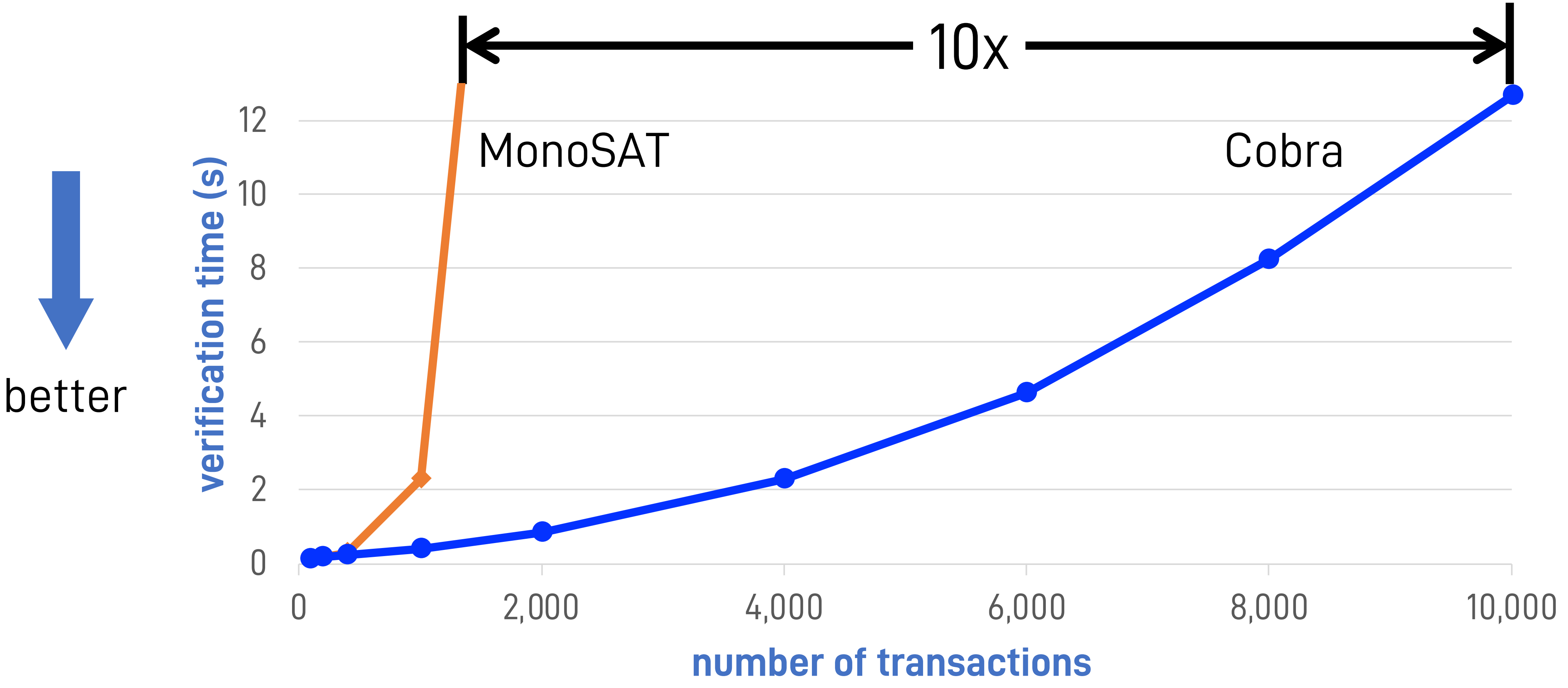
- How much time is spent on each phase of Cobra?

- What is the Cobra's verification throughput?
- How much runtime overhead does Cobra impose for clients?
- What are Cobra's storage and network costs?

Experiment setup

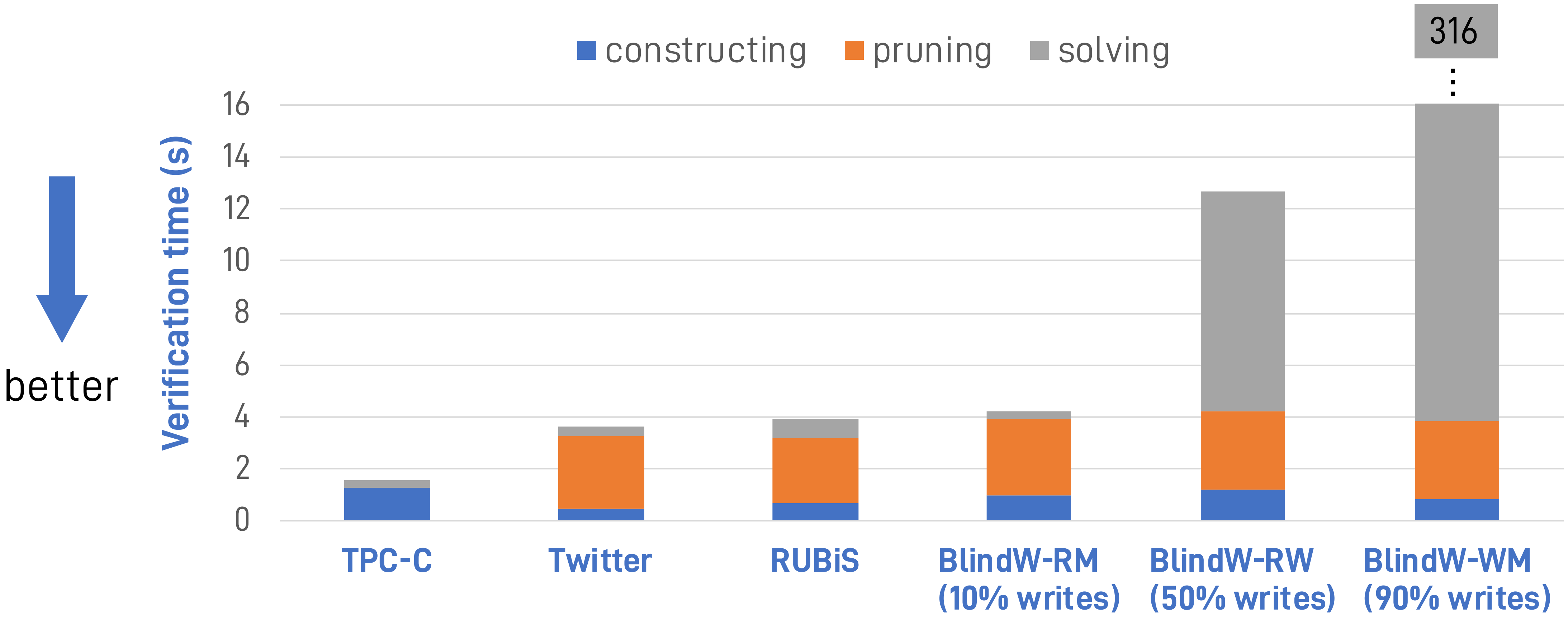
- Benchmarks:
  - TPC-C, Twitter, RUBiS
  - BlindW: RM (90% reads), RW (50% writes), WM (90% writes)
- Databases:
  - RocksDB, PostgreSQL, and Google Cloud Datastore
- Verifier:
  - p3.2xlarge EC2 instance: a V100 GPU, 8-core CPU, 64GB memory

Cobra can handle 10x larger workloads



- BlindW-RW: read-only and write-only transactions (50:50)
- 10k-key DB, 8 operations/txn, 24 concurrent clients

Decomposition of Cobra's verification runtime



- All workloads are with 10k transactions.

Recap

- Cobra verifies …
  - … serializability
  - … of black-box databases
  - … while scaling to real-world workloads.

Related work

a) black-box checking
b) serializability
c) scaling to real-world workloads

- Serializability checker for black-box databases
  - algorithms without SAT/SMT [BE19, SMWG11]
  - Gretchen, using a constraint solver (fzn-gecode)
- Elle, an isolation anomaly checker
- Checking/ensuring storage consistency
- Execution Integrity

Related work

a) black-box testing
b) serializability
~~c)~~ scaling to real-world workloads

- Serializability checker for black-box databases
- Elle, an isolation anomaly checker
  - mode 1: verify serializability by specific APIs and workloads (not black-box)
  - mode 2: testing serializability violations using heuristics (not verification)
- Checking/ensuring storage consistency
- Execution Integrity

Related work

~~a)~~ black-box checking
~~b)~~ serializability
c) scaling to real-world workloads

- Serializability checker for black-box databases
- Elle, an isolation anomaly checker
- Checking/ensuring storage consistency
  - Concerto [AEKKMPR17]
  - requiring extra information from the database [RGAKW12, ZK12]
  - relying on synchronized clocks [LVAHSTKL15]
  - requiring client-to-client communication [SCCKMS10]
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✕ {
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  - replication: PBFT [CL99], Ethereum
  - attestation: SGX-/TPM-based systems
  - probabilistic proofs: Pepper [SMBW12], Pinocchio [PGHR13], Pantry [BJRSBW13]
  - others: Ripley [VPL09], AVM [HARD10], Verena [KFPC16], Orochi [TYLW17]

Summary

- Cobra verifies serializability of a black-box database

  ... for real-world workloads.

- Users of cloud databases used to have to assume serializability;

  but now, with Cobra, they can be sure.

- Code is released at:

  https://github.com/DBCobra/CobraHome