Towards Database Virtualization for Database as a Service

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CAVEAT:

Representative not exhaustive

Moving to the Cloud

Why cloud? (are you really asking?)

- Economy-of-scale arguments
- Pay-per-use value to customers

Moving to DaaS

Why Database as a Service (DaaS) for tenants?

- DB management drama becomes provider's problem
- (Ideally) high level Service Level Agreement (SLAs / SLOs)
- Accelerate development lifecycle

Why Database as a Service (DaaS) for providers?

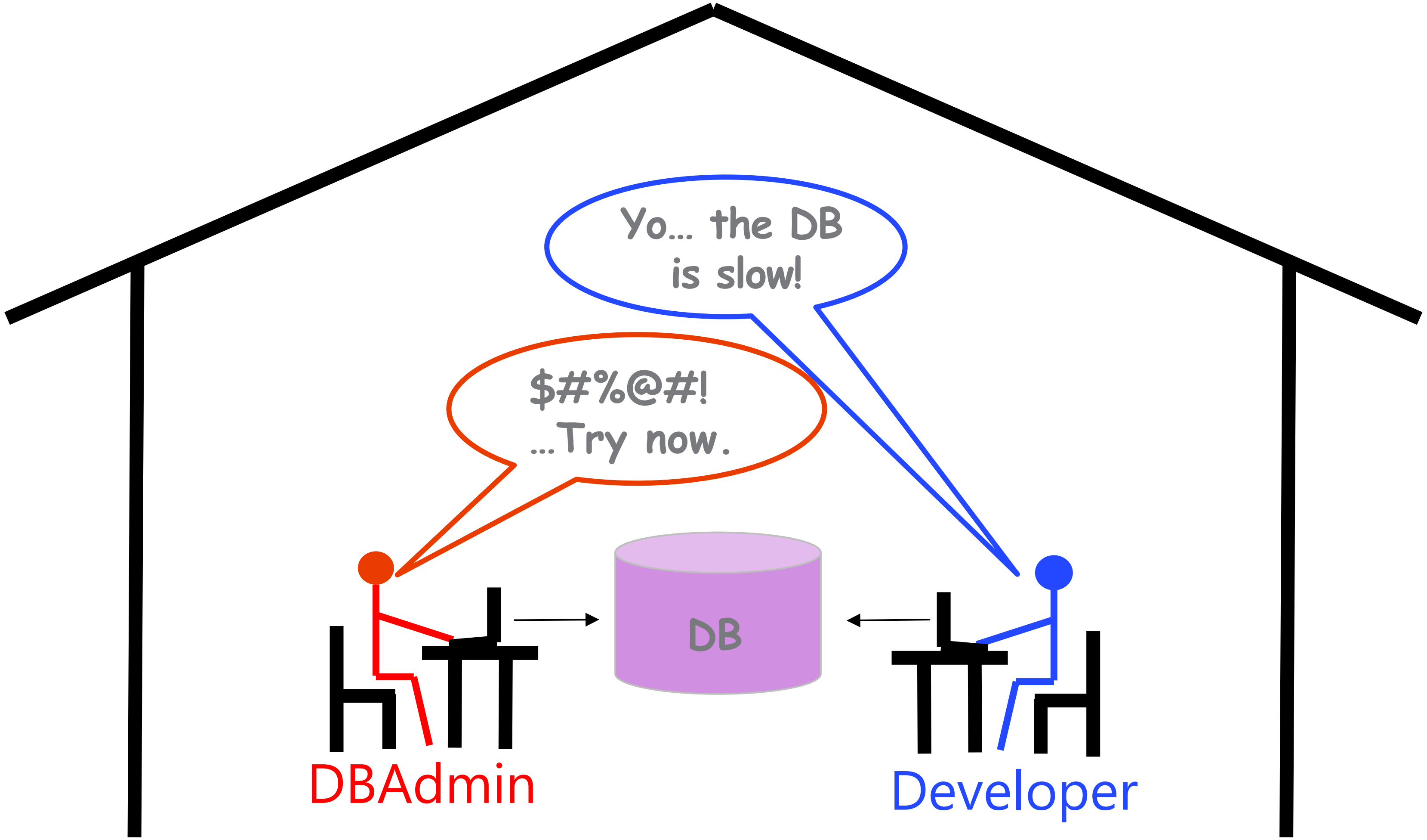
- Internalize a high-cost portion of service (admin)
- Scale + density + uniformity → lower cost

The illusion we are aiming for...

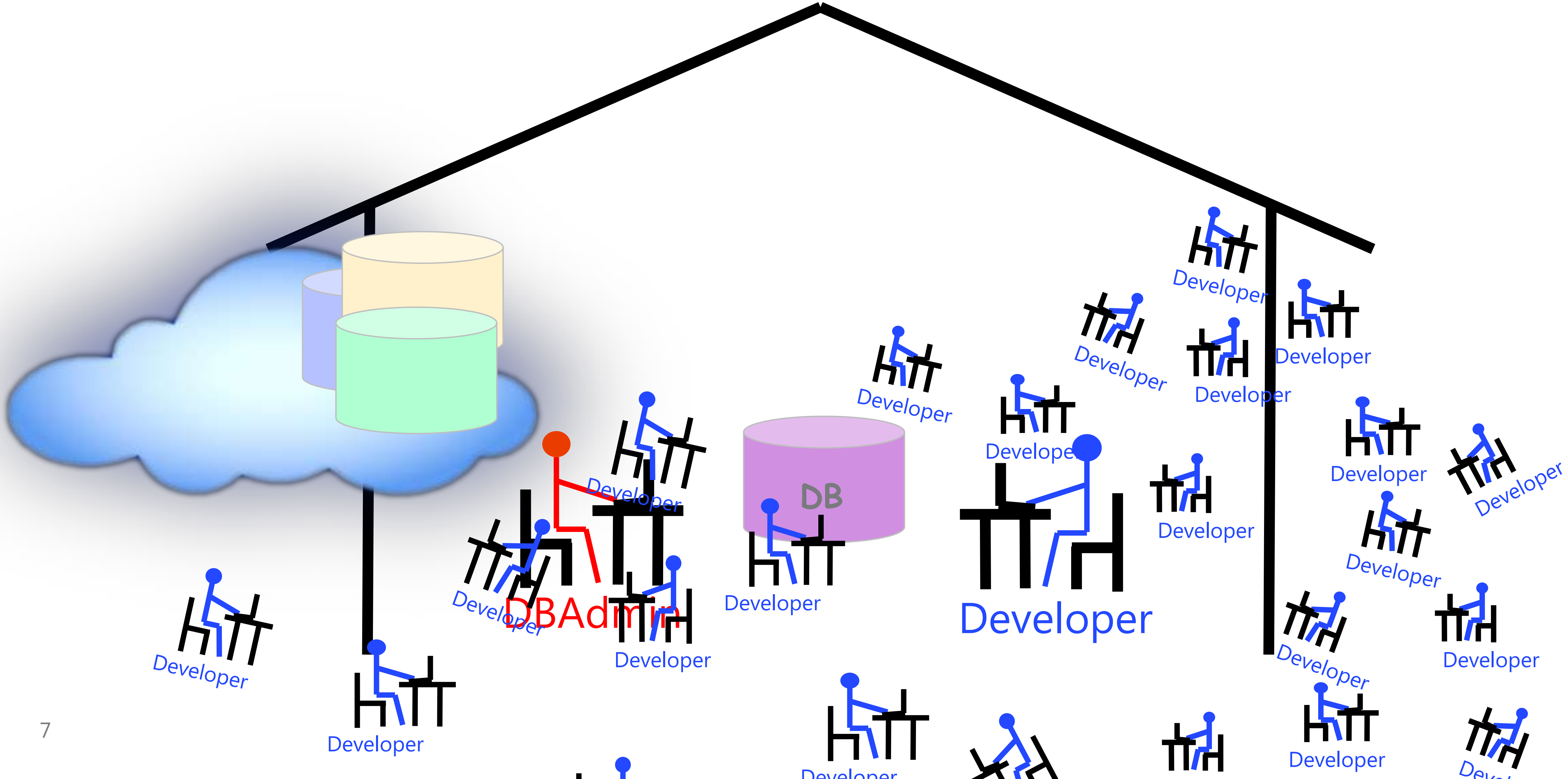
Tenant's view

Provider's view

Traditional DB deployments



What changes in DBaaS?



Commercial DaaS Tuning issue

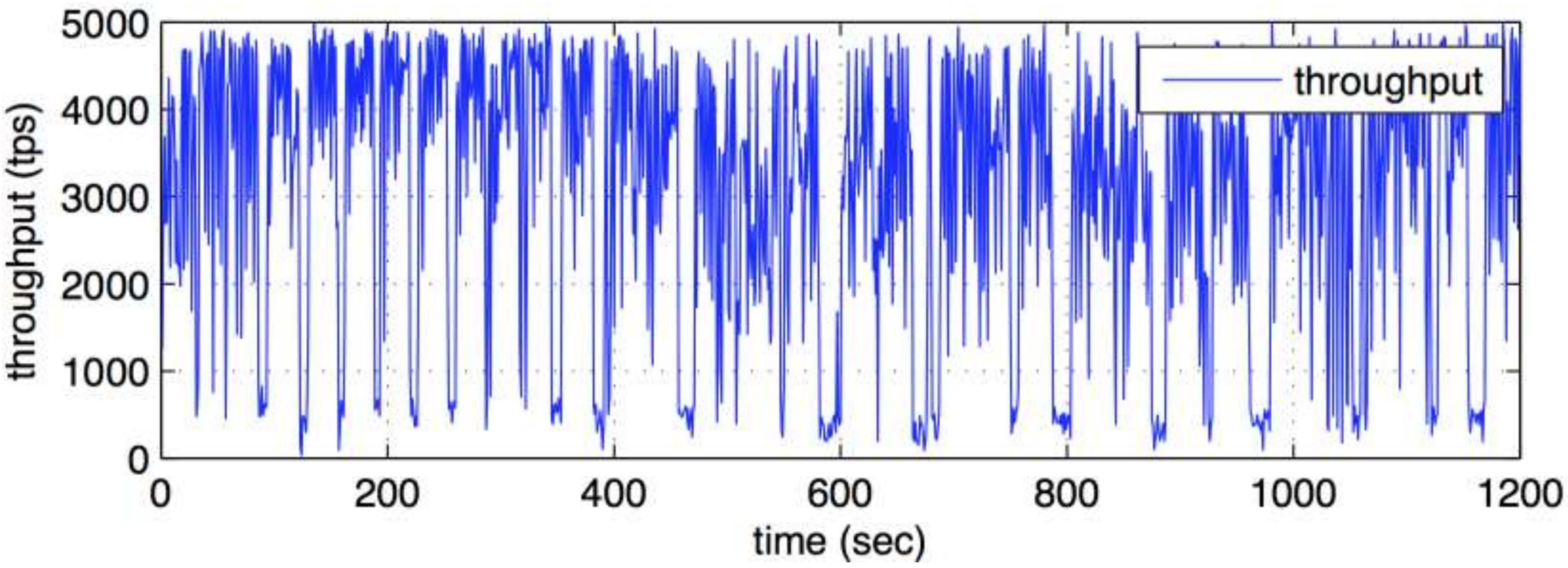
Running max-throughput, write-heavy YCSB workload against:

- fully managed DBMS
- manually tuned DBMS

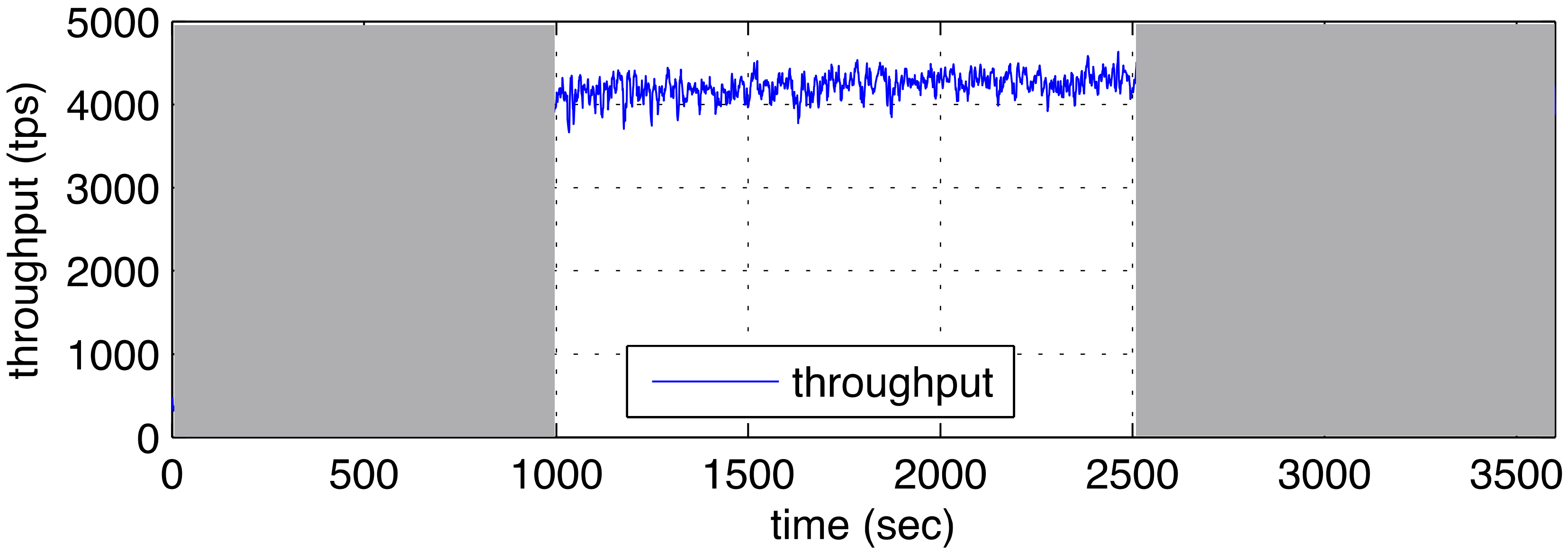
(Same virtualized hardware, same DBMS, different tuning)

Interpretation: default log-configuration is off.

DaaS (managed DBMS)



Manually tuned DBMS



* experiments using OLTPBench: http://oltpbenchmark.com

DaaS: challenges (and agenda)

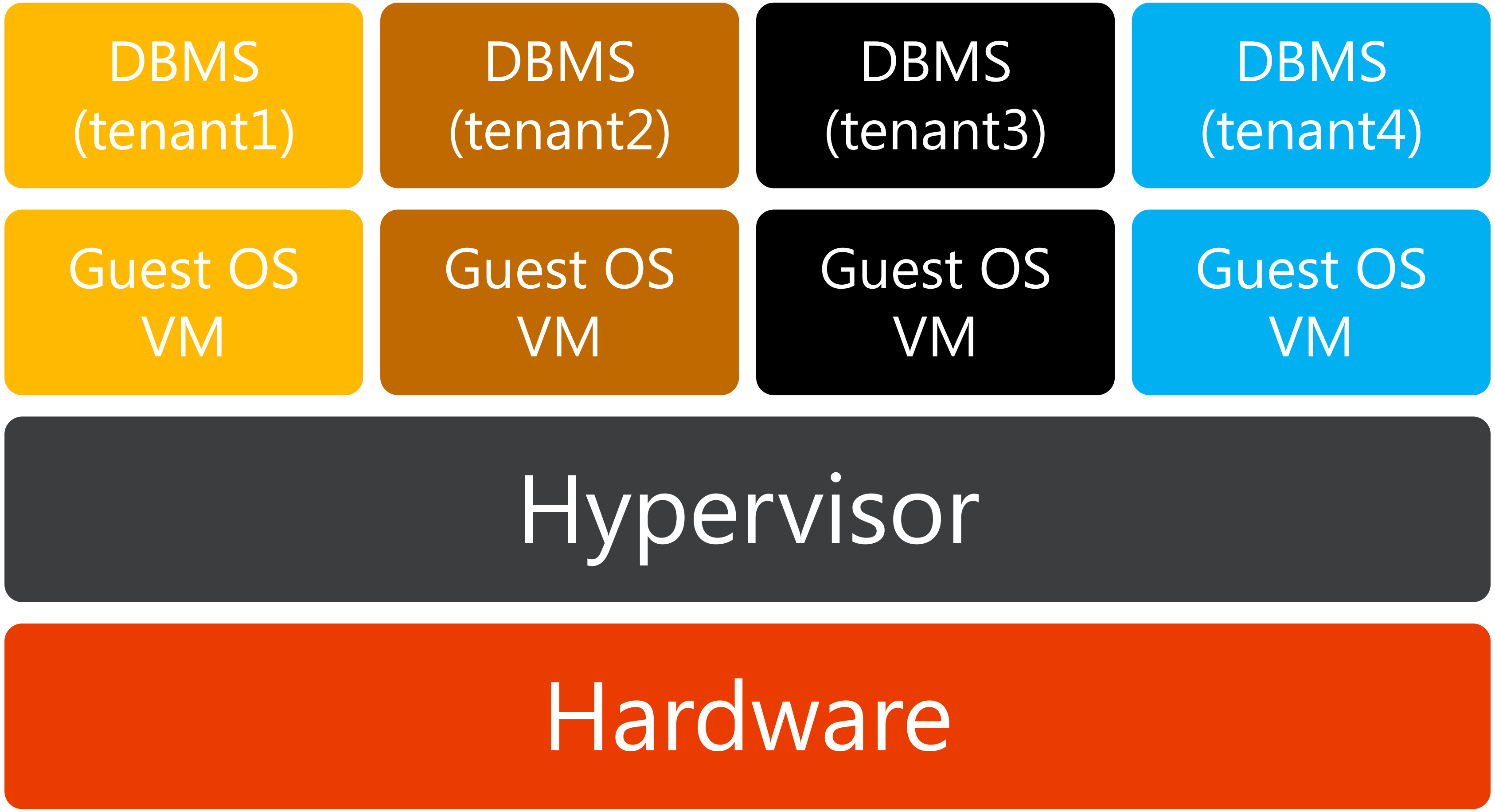
- Multi-tenancy Architectures
- SLA/SLO
  - Definition
  - Enforcement
- High Availability
  - Replication
  - Fault tolerance
- Partitioning
- (security/privacy)

- Workload Characterization
  - Estimation / Prediction
  - Resource Attribution
  - What if analysis
- Resource Management
  - Allocation / Balancing
  - Tenant Placement
  - Admission Control
- Migration
- Performance Isolation

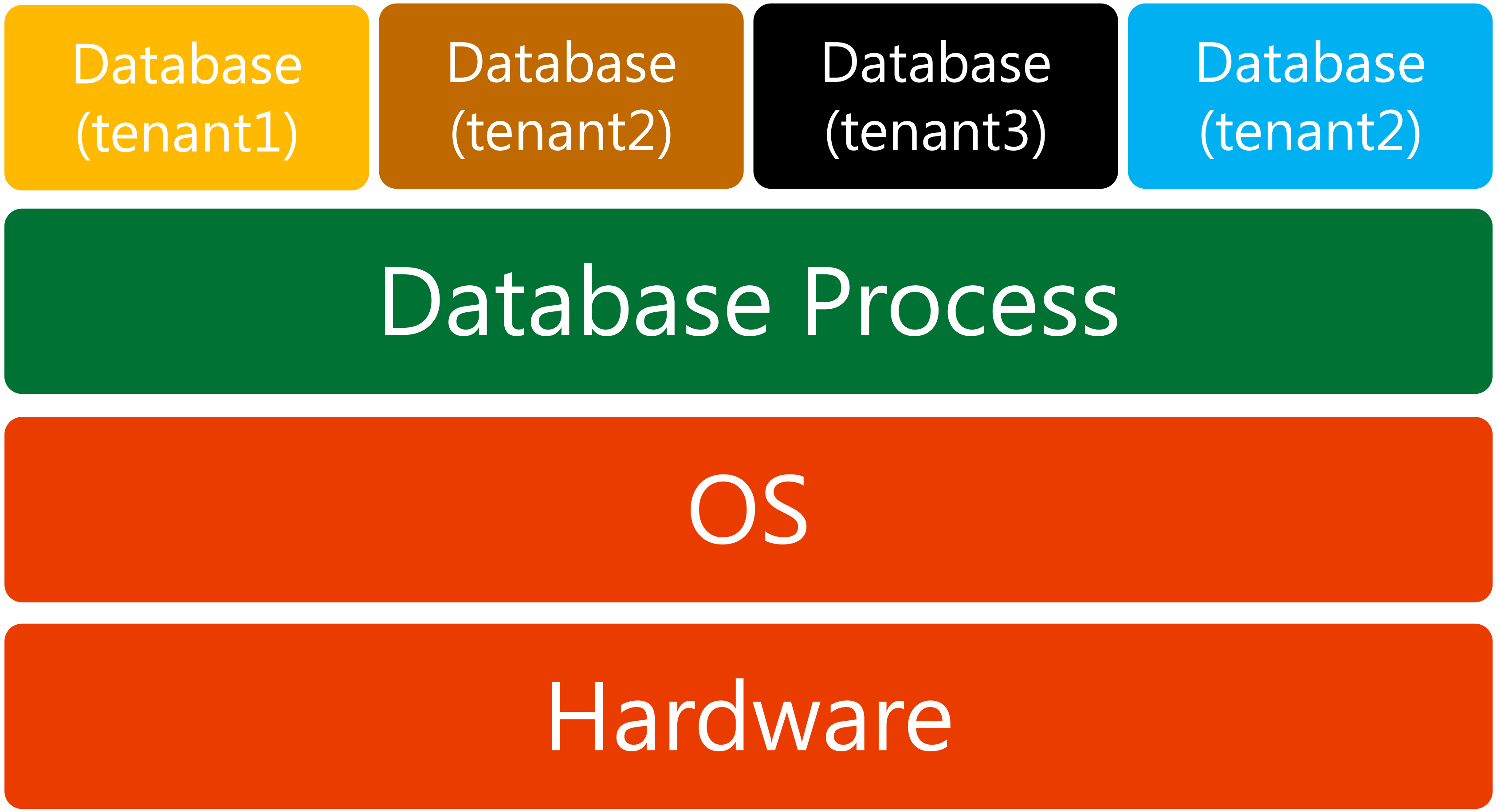
Multi-tenancy architectures

"Most common ways to tackle this problem"

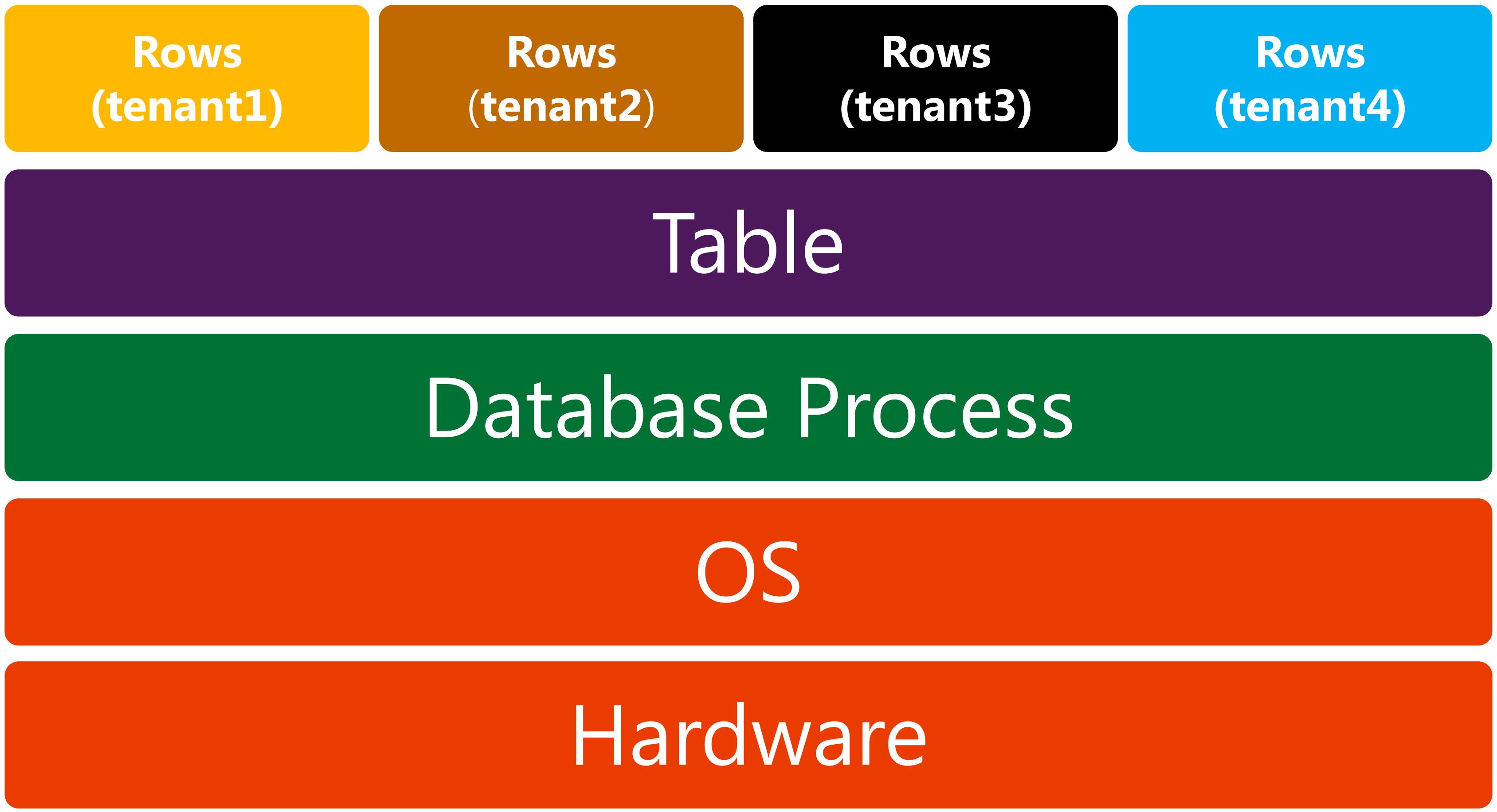
Shared Hardware (DB-in-a-VM)



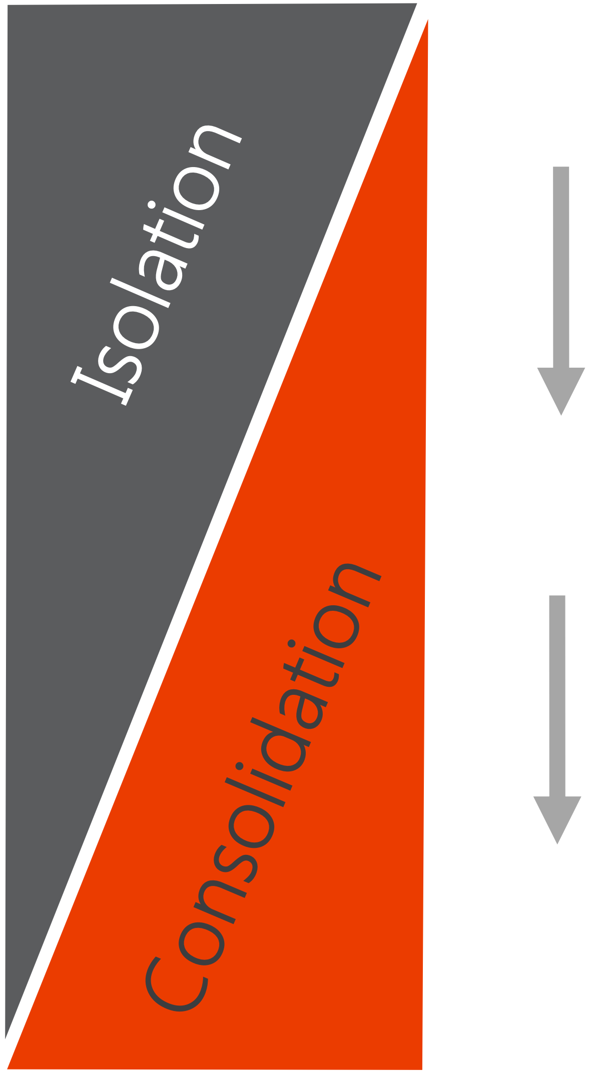
Shared Process



Shared Table



Trade-off



Shared Hardware

Strong Isolation (security, performance)
Mechanics (High Availability, Migration)

Shared Process

Sharing and coordination resource consumption (MEM/CPU/Disk IOps)

Shared Table

Amortize metadata overheads

Multi-tenancy Architectures

Shared Hardware

SmartSLA, RemusDB, Amazon RDS

Shared Process

RelationalCloud, CloudDB, SQLAzure, Delphi, Y! cidr2009

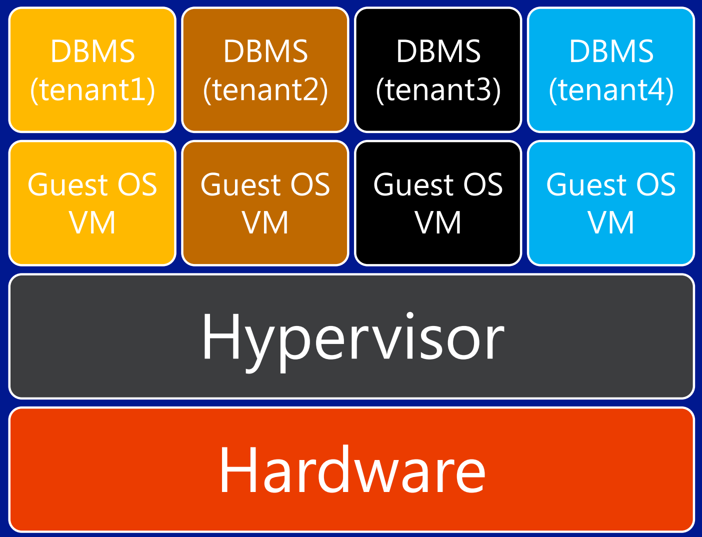
(shared storage) ElasTras, DAX

Shared Table

Force.com, Jacobs/Aulbach

Shared Hardware (DB-in-a-VM)

"Reusing/Specializing VM technologies for DaaS"



Commercial offering: Amazon RDS

Amazon RDS

- Provides pre-configured DBMS (MySQL/Oracle/SQLServer)
- Addresses much of provisioning issues
- Strong Isolation / catch-all configuration

SmartSLA

[Xiong et al. ICDE 2011]

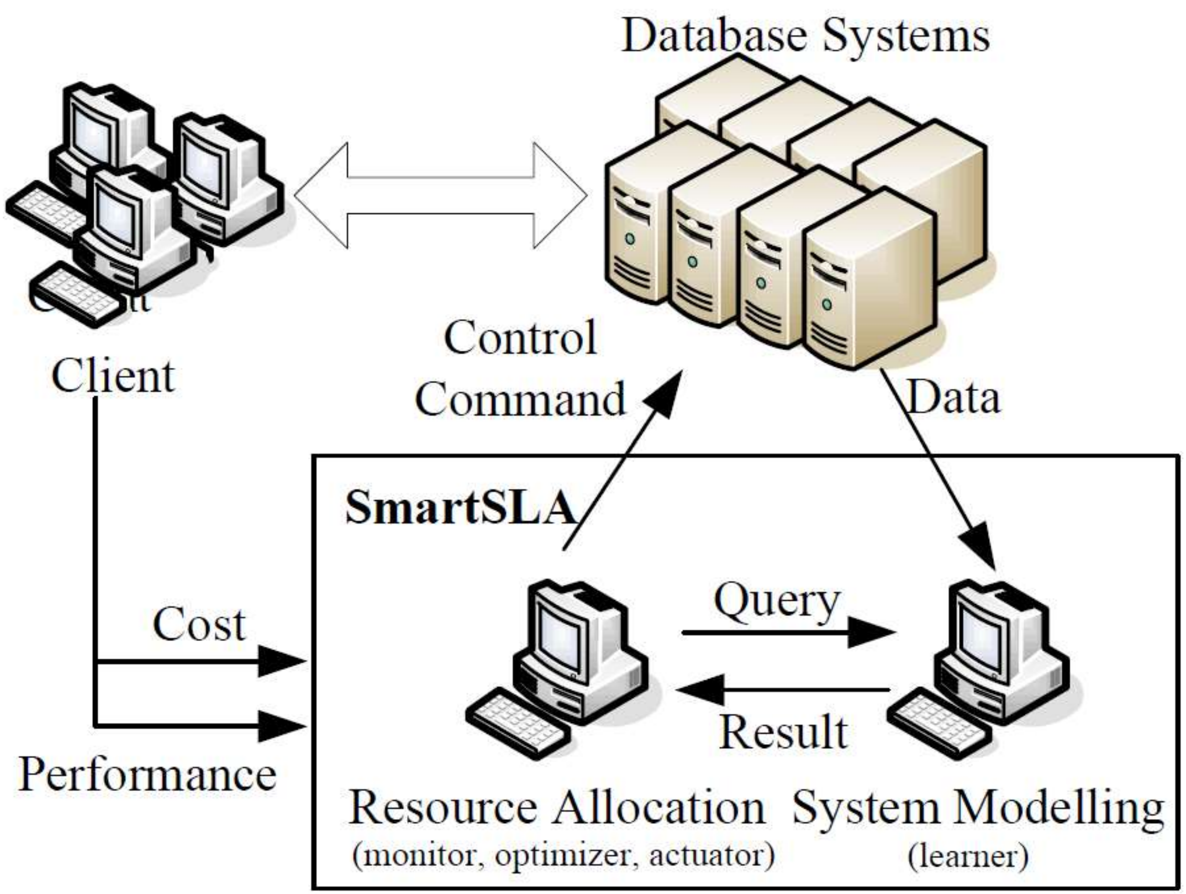
Focus

- Leverage VM-based mechanisms
- Deliver DB-level SLAs

Key Contribution

- SLA violation vs Resource modeling
- Actuation of VM-based mechanisms (cpu, ram, replication)

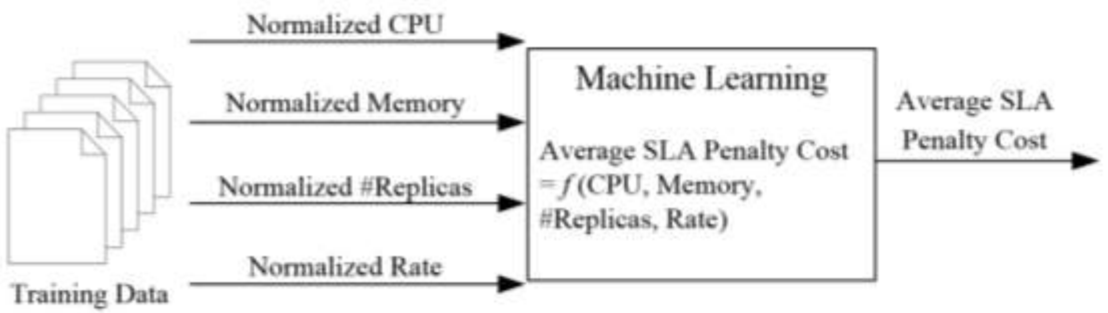
SmartSLA

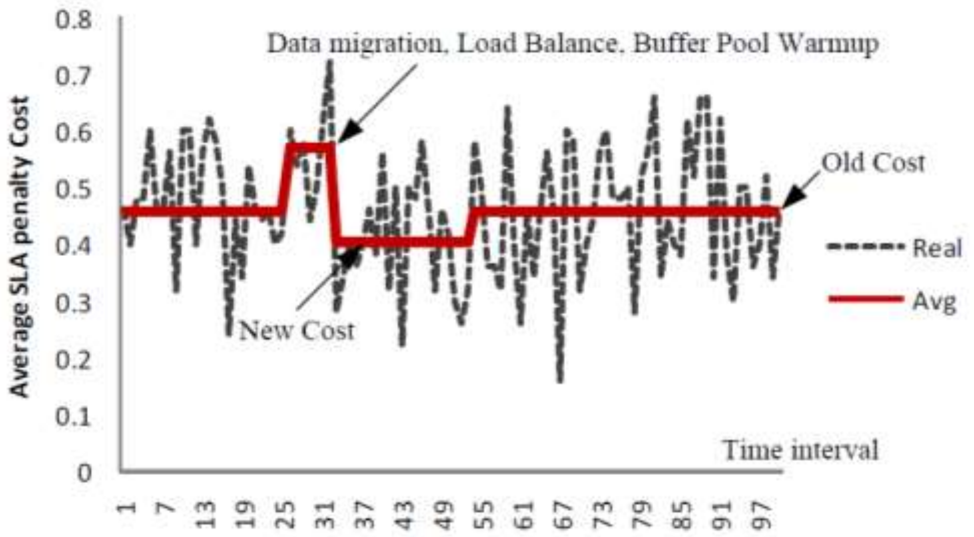


Key mechanism

- Decompose problem in:
  - ML-based model of resource / SLA-penalty
  - Allocation of resource + replication

Estimating SLA violation cost and Allocation





ML Modeling

Build a Map of space

(simple ML/features)

Allocation algorithm

Explore allocation space

Models infrastructure cost for replication

Models cost of increasing replication

REMUSDB

[Minhas et al. VLDB 2011 /VLDBJ 2013]

Focus

- High Availability via VM replication
- OLTP-compatible performance

Key Contributions

- Reuse of mature VM technology *(pro of Shared Hardware)*
- Smart DB-specific tricks to improve performance

REMUS

Leverage Xen VM-replication

- Snapshots the VM state every few tens of ms
- Delays network and disk writes until next checkpoint (consistent)
- Fail-over to secondary and restart from latest checkpoint

Problems

- DBMS bufferpool changes too fast (large deltas to checkpoint)
- Latency overhead is high for OLTP

REMUSDB: DB-specific optimizations

Avoid checkpointing “clean” pages

- no checkpoint for clean pages
- bookkeeping so that secondary fetch from disk if needed

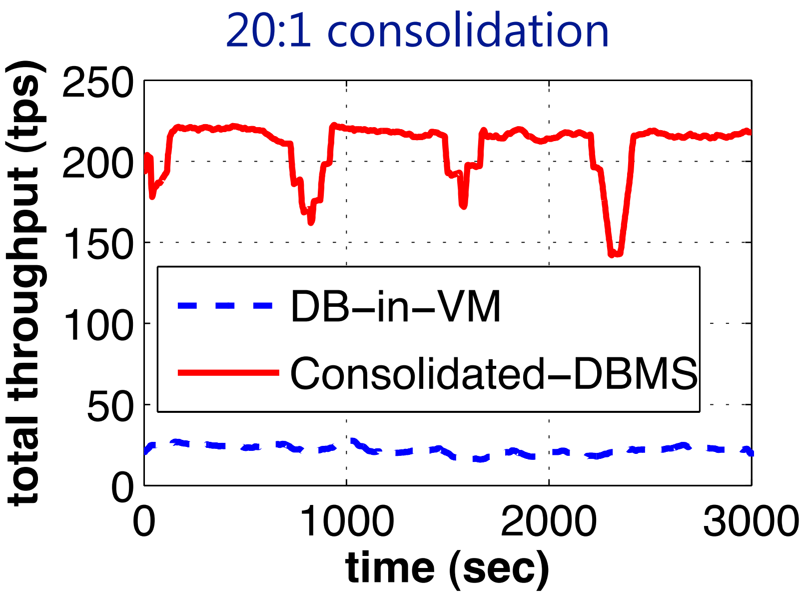
Limit network delay to Commit/Abort

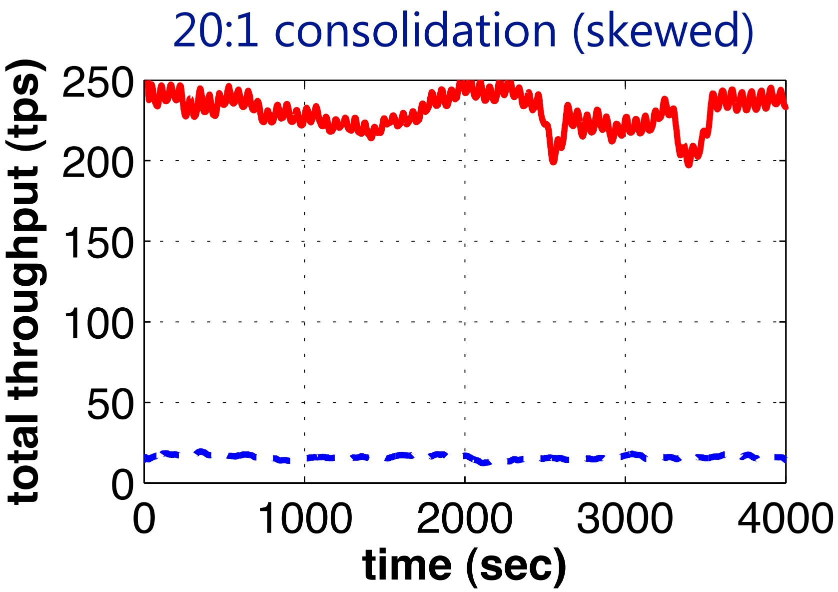
- Leverage transactional semantics
- “delay” only Commit/Abort messages

Reduce impact on throughput

- 32% goes down to about 10%

Shared Hardware shortcomings



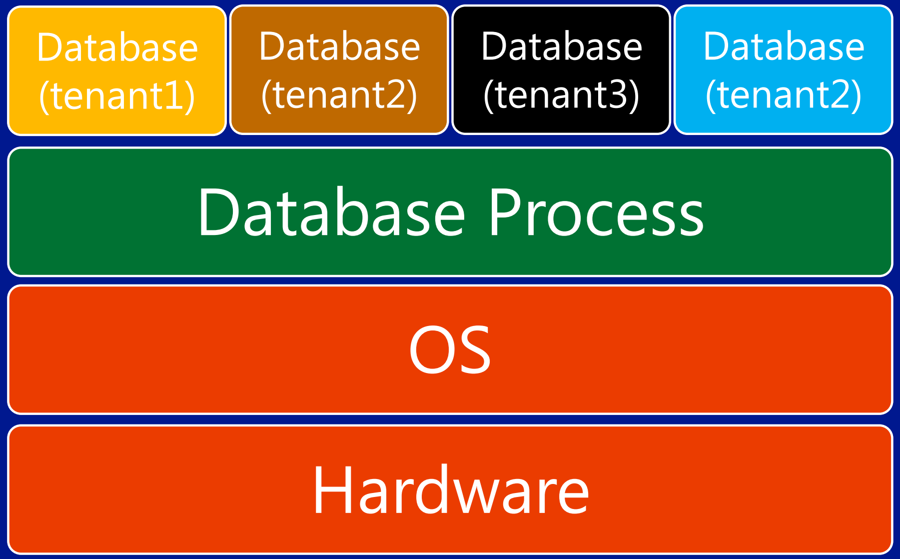


Design mismatch

- DBMS were designed to make full use of dedicate machines
- Aggressively consume idle resources (especially IOPs)
- [Curino et al. VLDB 2010]

Shared Process

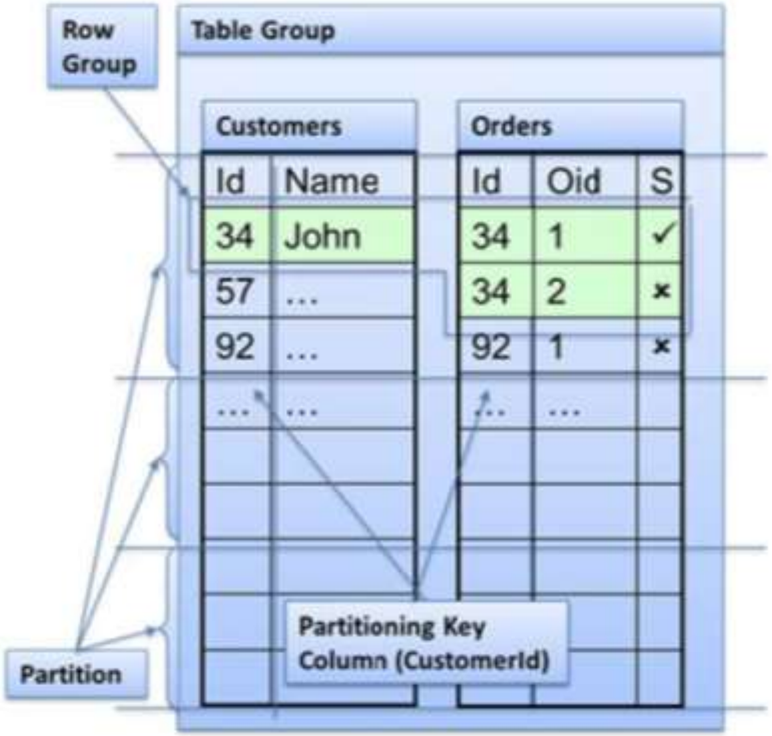
"The DBMS knows best"



Commercial offering: SQLAzure [Bernstein et al. ICDE 2011]

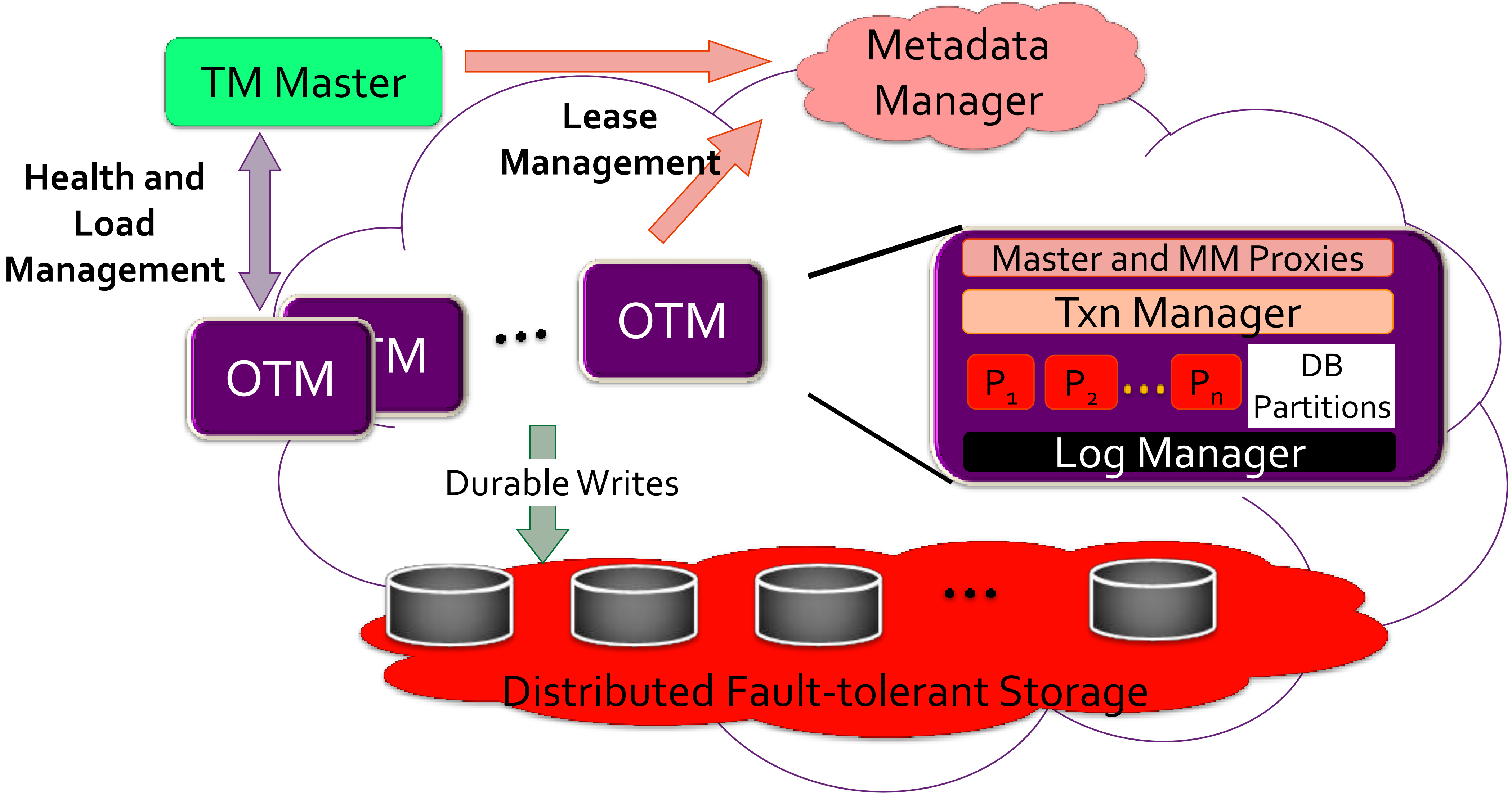
SQL Azure

- Shared DBMS process, Dedicated database
- Shared logging
- Modified version of SQL Server
- High-availability via quorum of replicas
- Support scale-out
    - ACID within a row-group
    - Read-committed across row-group



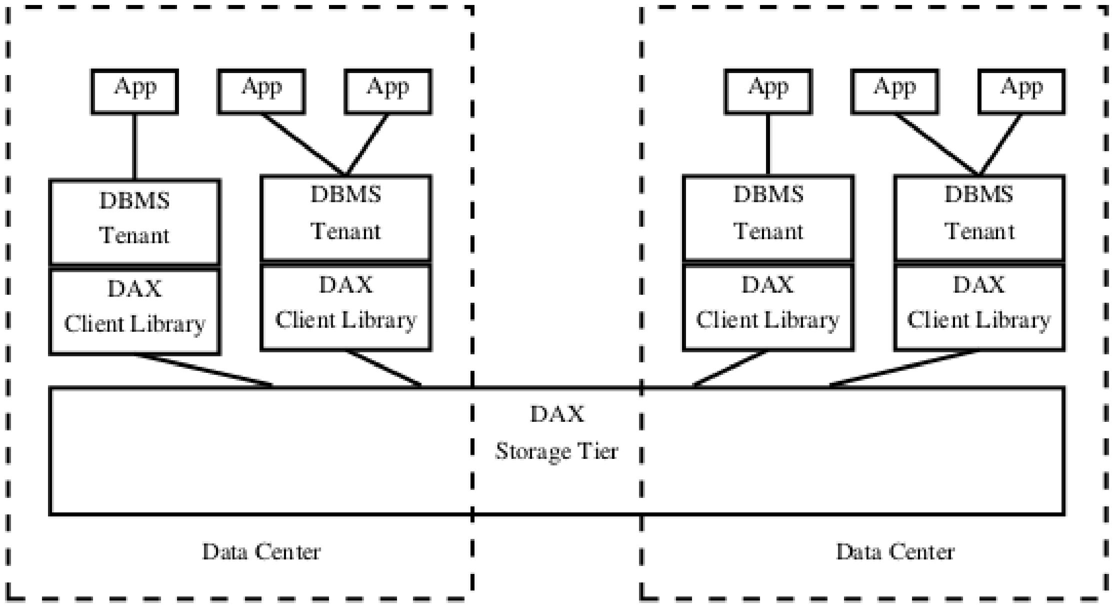
ElasTras Architecture (Shared Storage)

[Das et al. HotCloud 2009]



DAX

[Liu et al. VLDB 2013]



Scalable and fault tolerant m/t achieved by data layer spanning colos

Use Cassandra for storage tier with single owning DB instance

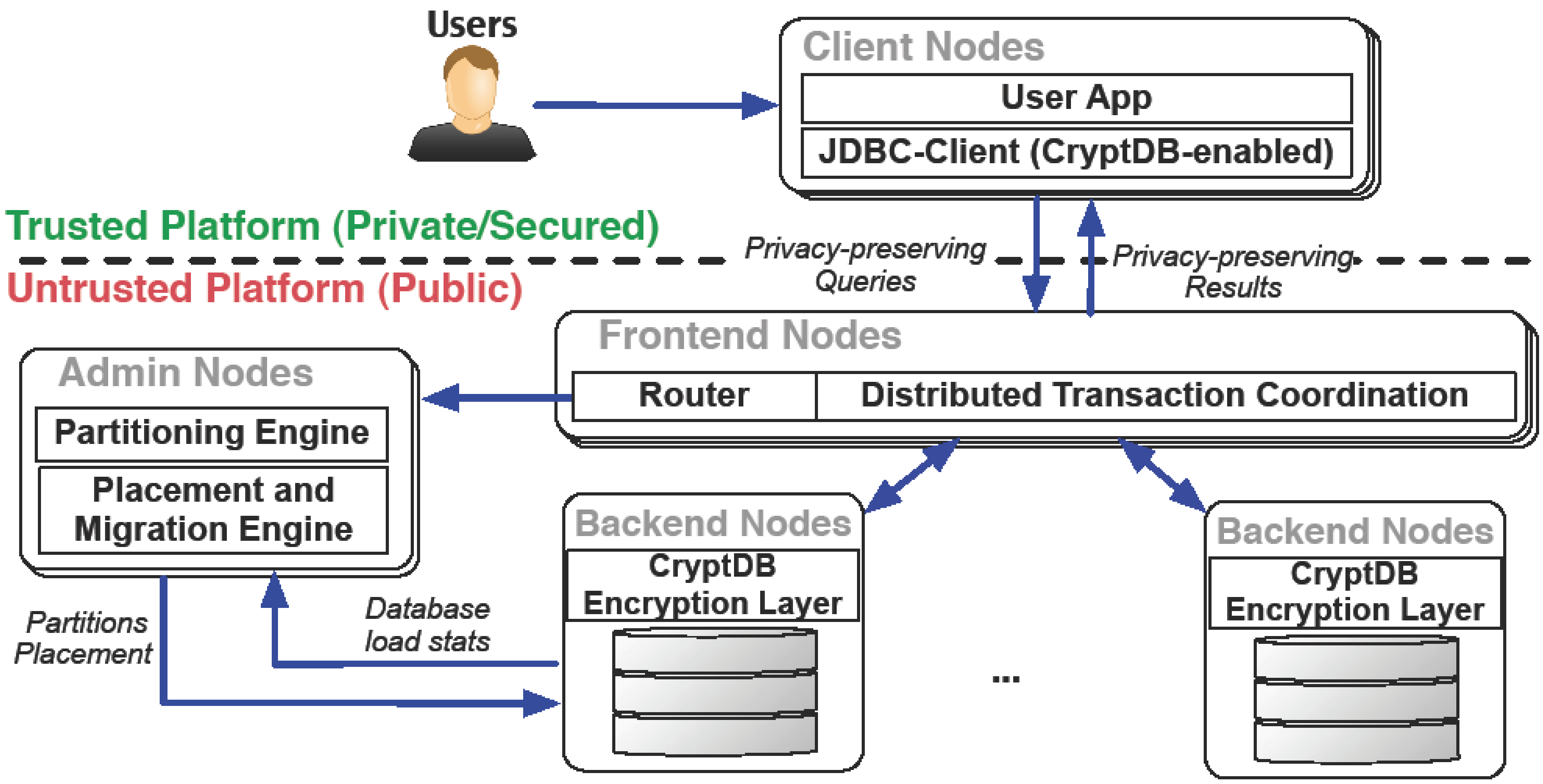
Leverage DB and quorum semantics for performance

- Operation type & R/W/N

Epoch-bounded strong consistency

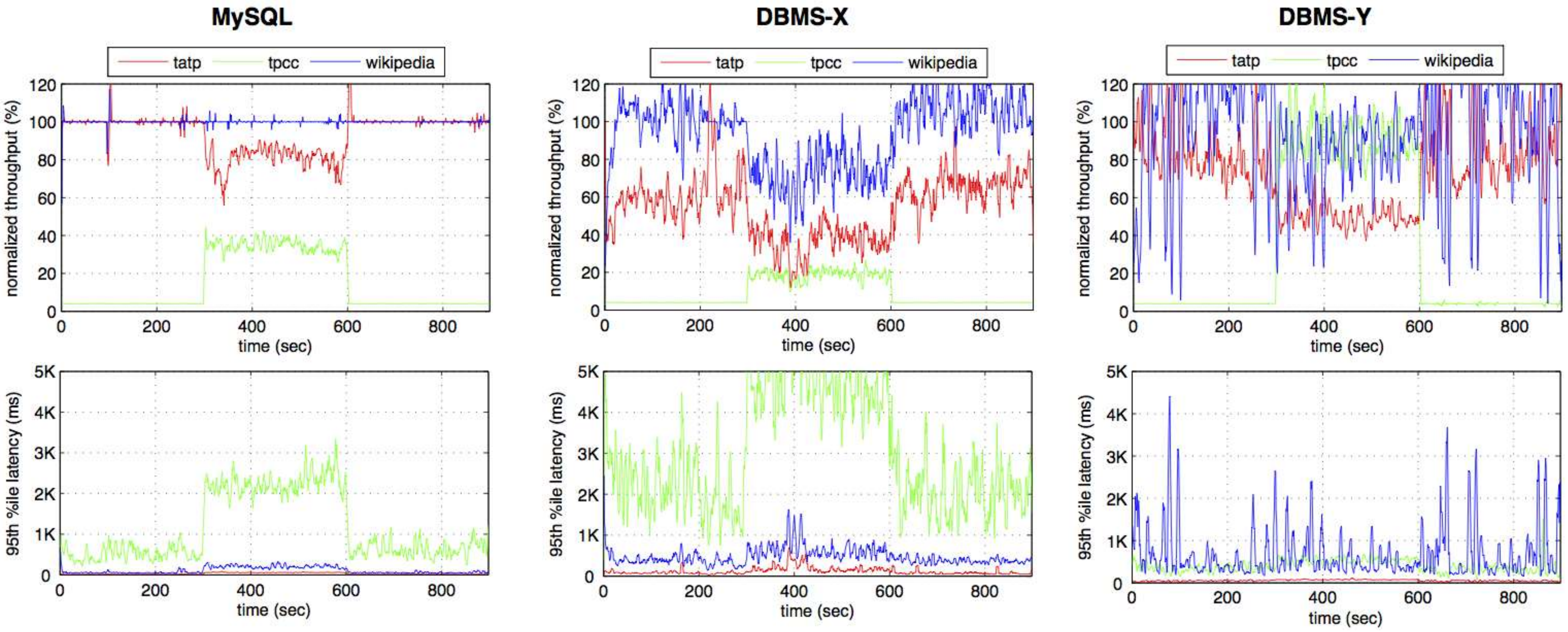
RelationalCloud

[Curino et al. CIDR 2011]



Shared Process shortcomings

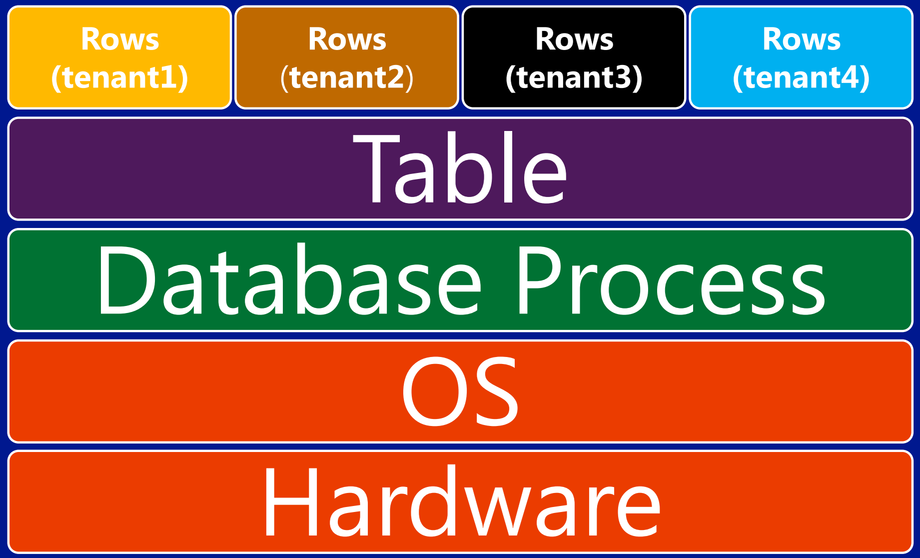
Comparing multi-tenancy (No DBMS is perfect)



* experiments using OLTPBench: http://oltpbenchmark.com

Shared Table

"Extreme multi-tenancy"



[Jacobs and Aulbach BTW 2007]

Key idea

DBMSs don’t scale well at the tenant/schema level

	Memory 1 instance	Memory 10,000 instances	Disk 1 instance	Disk 10,000 instances
PostgreSQL	55	79	4	4,488
MaxDB	80	80	3	1,168
Commercial1	171	616	200	414,210
Commercial2	74	2,061	3	693
Commercial3	273	359	1	13,630

Table 1. Storage Requirements for Schemas Instances (in megabytes)

Force.com and [Aulbach et al. SIGMOD 2008]

Focus

- Target tens of thousands of tenants per server
- Partially shared schema (polymorphic SaaS apps)
- Deal with *schema-level* DBMS scalability limits

Key Contribution

- Clever data design, schema mapping / query rewriting

[Aulbach et al. SIGMOD 2008]

Many variants

- Private Table
- Extension Table
- Universal Table
- Pivot Table
- Chunk Table
- Chunk Folding

```
SELECT Beds
  FROM Account17
 WHERE Hospital='State'.
```
(Q1)

→

```
SELECT Beds
  FROM (SELECT Str1 as Hospital,
               Int1 as Beds
          FROM Chunk_int|str
         WHERE Tenant = 17
           AND Table = 0
           AND Chunk = 1) AS Account17
 WHERE Hospital='State'.
```
($Q1_{Chunk}$)

Shared Table shortcomings

- Focused on extreme multi-tenancy
  - Middleware-based querying rewriting
    - Ad-hoc security
    - Hard to provide performance isolation
  - Only for small / low-activity tenants

DaaS: challenges (and agenda)

- Multi-tenancy Architectures ✓
- SLA/SLO ✓
  - Definition
  - Enforcement
- High Availability ✓
  - Replication
  - Fault tolerance
- Partitioning
- (security/privacy)

- Workload Characterization
  - Estimation / Prediction
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Partitioning

“Chop it and scale it out”

Schism

[Curino et al. VLDB 2010]

Positioning

Partitioning for shared-nothing DBMSs (RelationalCloud)

Focus

automatic partitioning of arbitrary schemas (many-to-many)

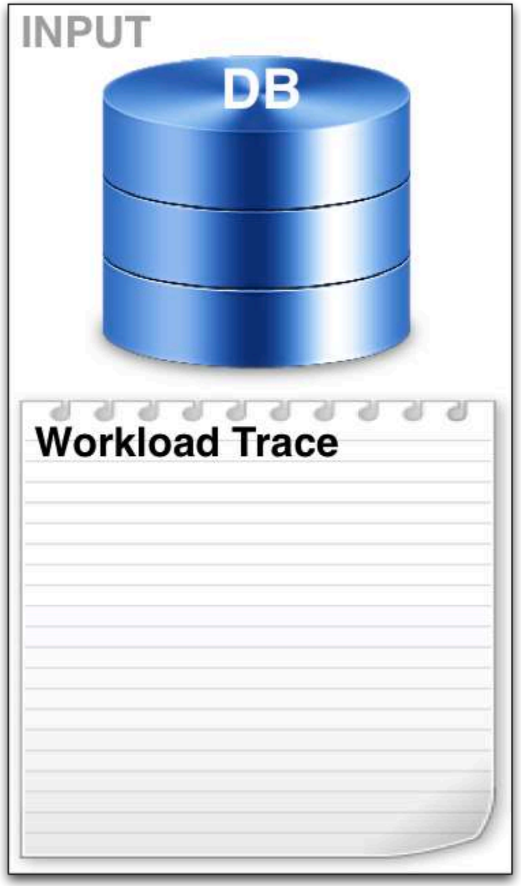
handle access skew, replication

Key Contributions

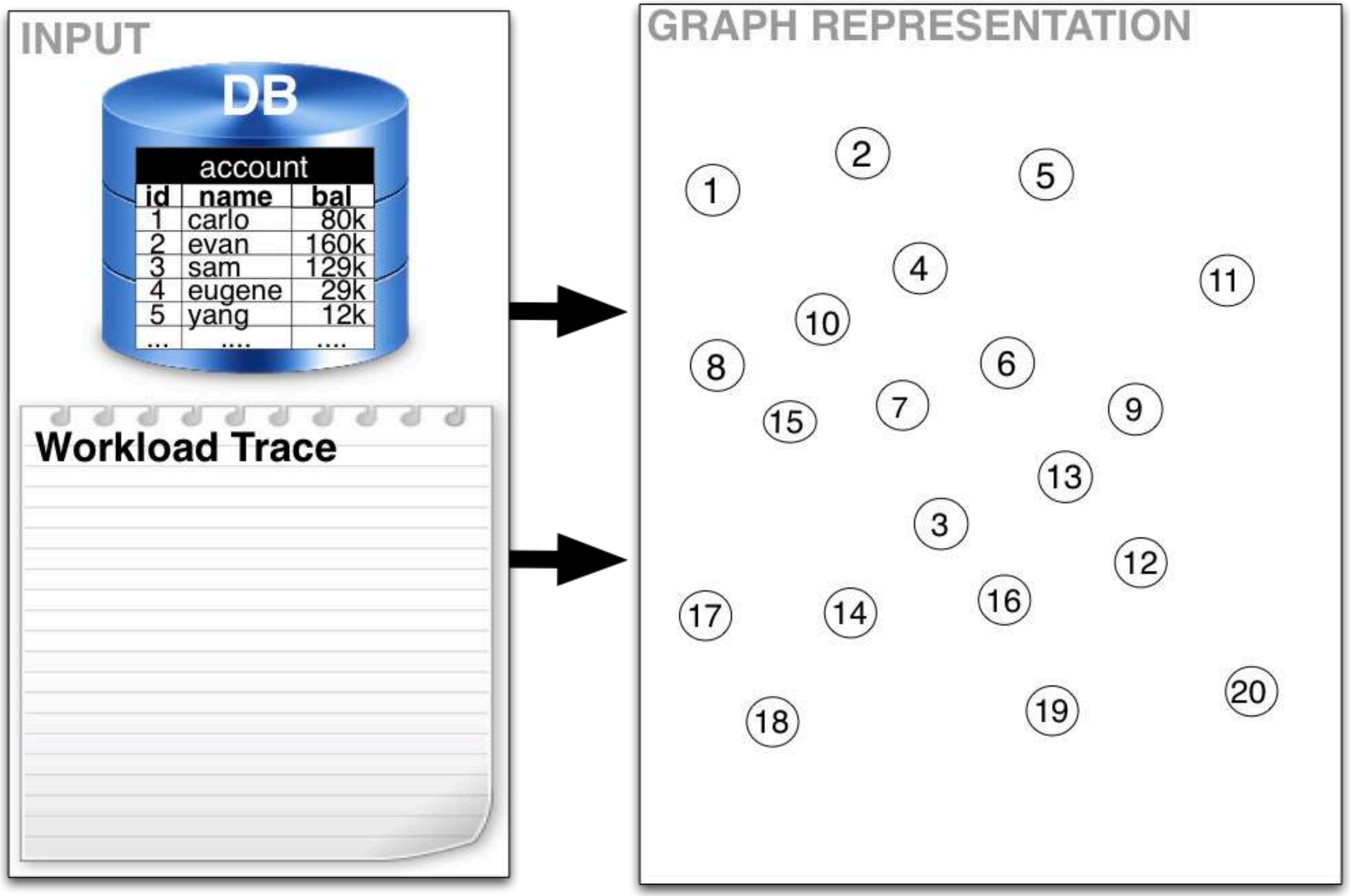
Model the problem as graph-partitioning

"Explain" results using decision trees (practical partition functions)

Schism: Graph-based Partitioning



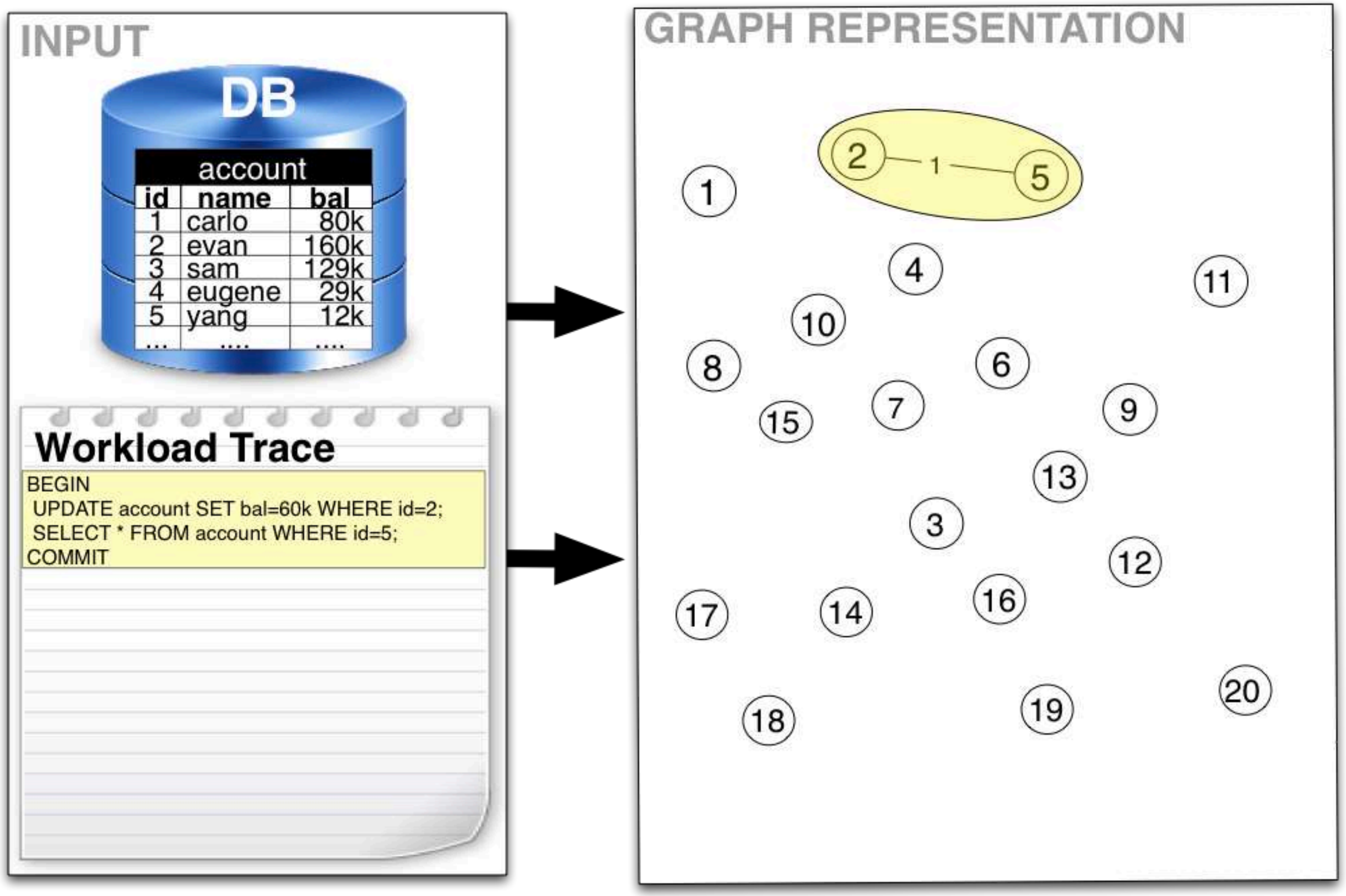
Schism: Graph-based Partitioning



Graph Representation:

tuples in the DB are nodes in the graph

Schism: Graph-based Partitioning



Graph Representation:

tuples in the DB are nodes in the graph

transactions impose edges among the tuples they access

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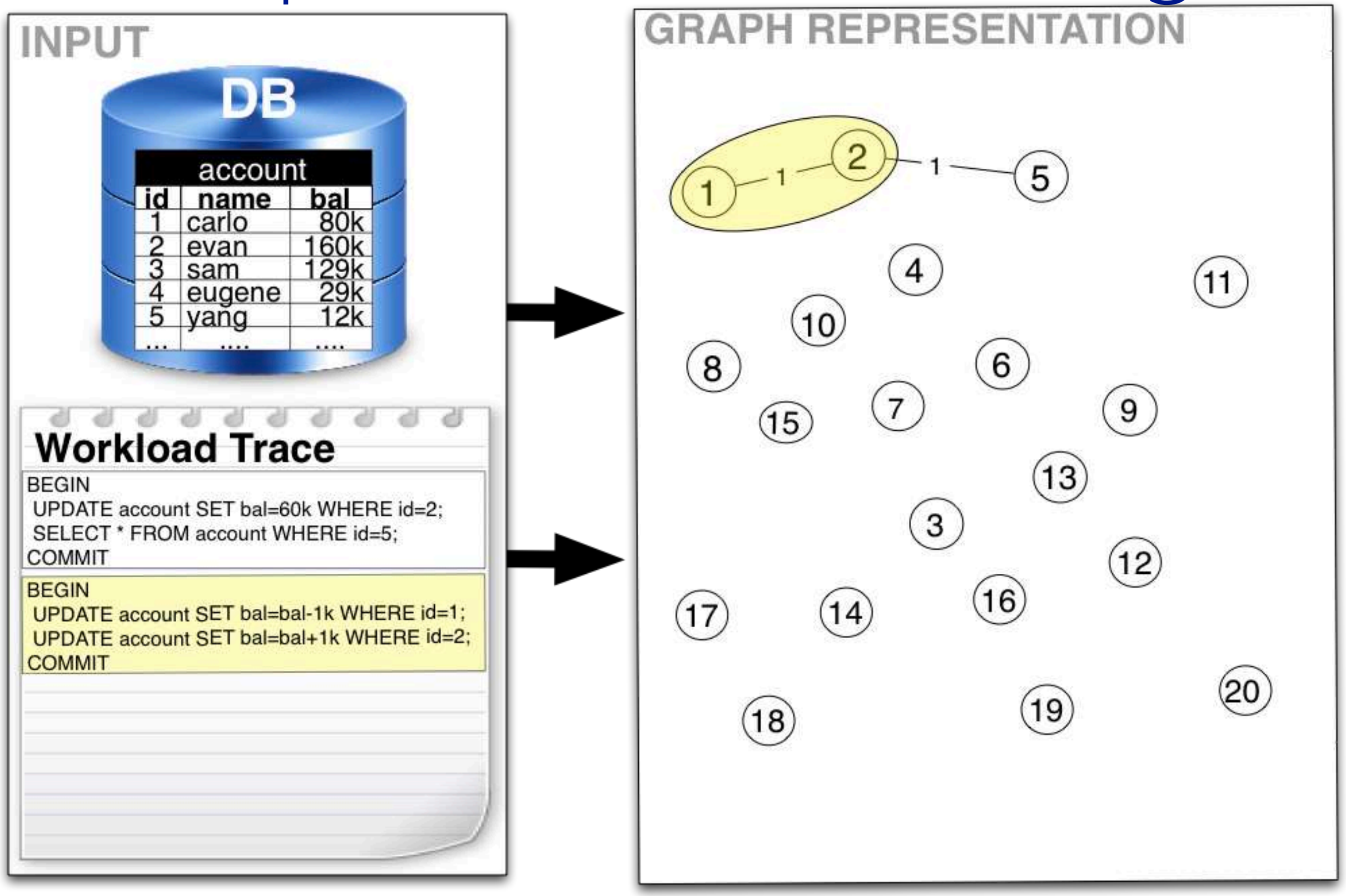

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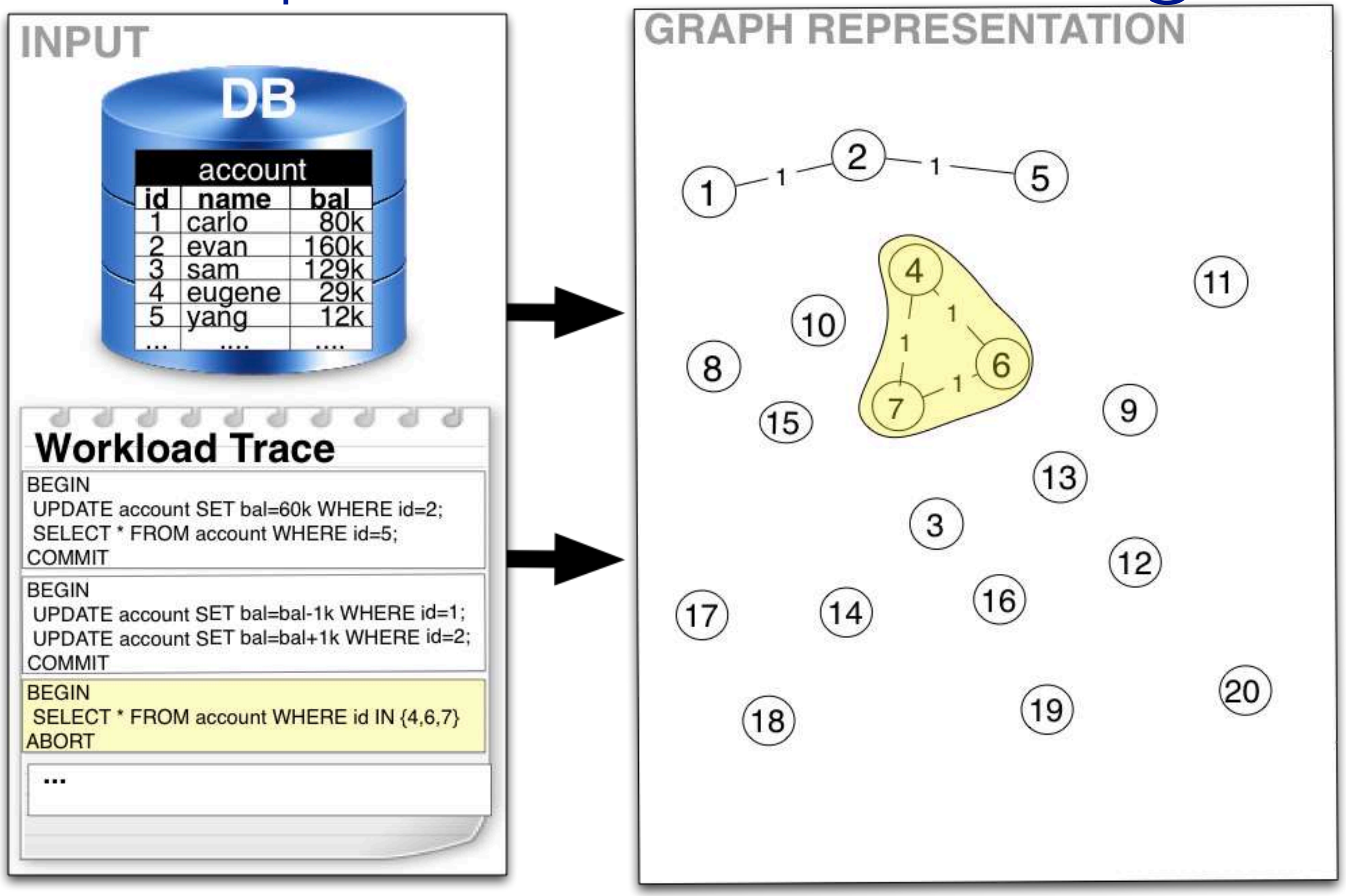

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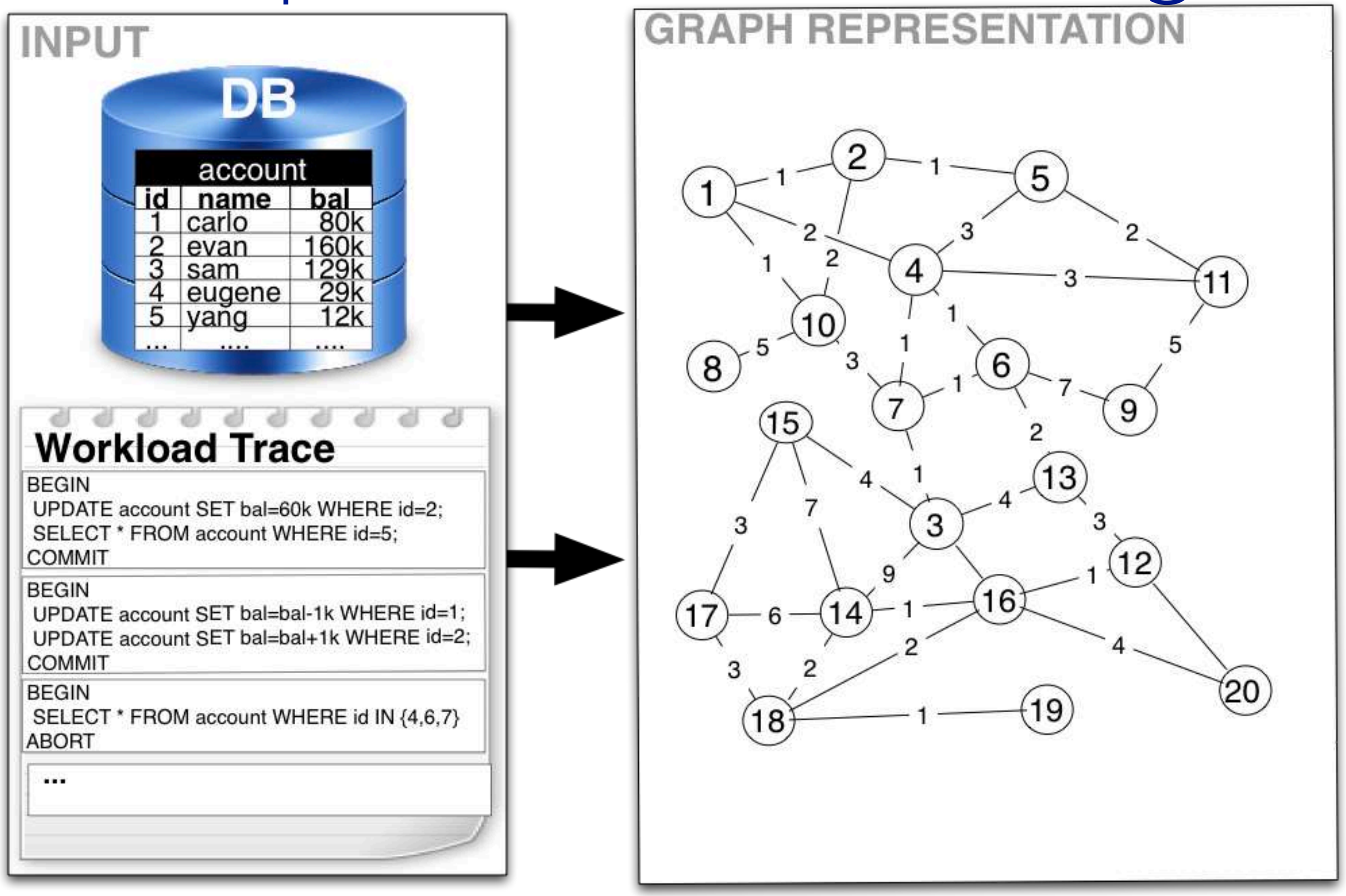

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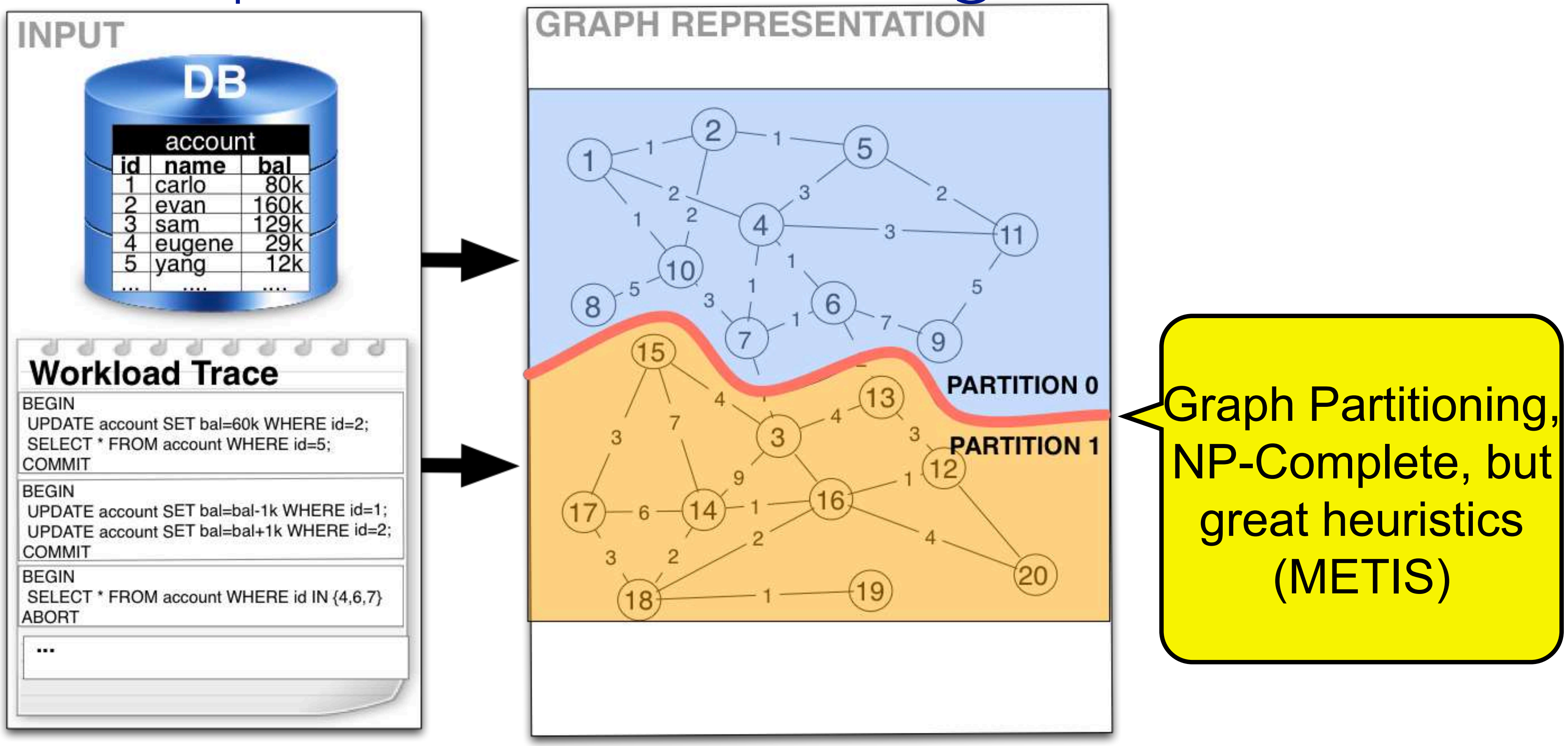
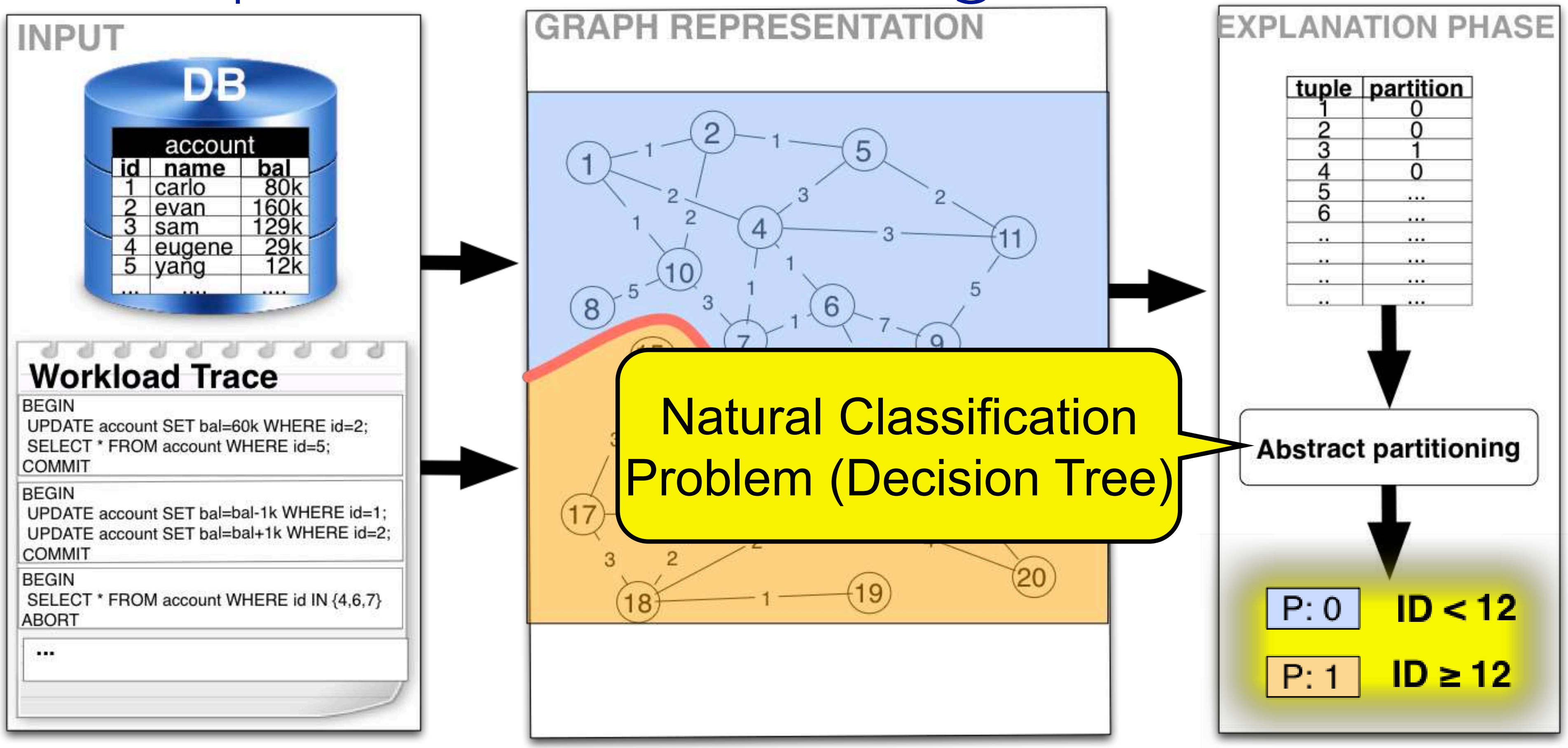


Graph Partitioning: *find K (close to) balanced partitions of the nodes that minimize the weight of the cut edges (i.e., minimize distributed transactions)*

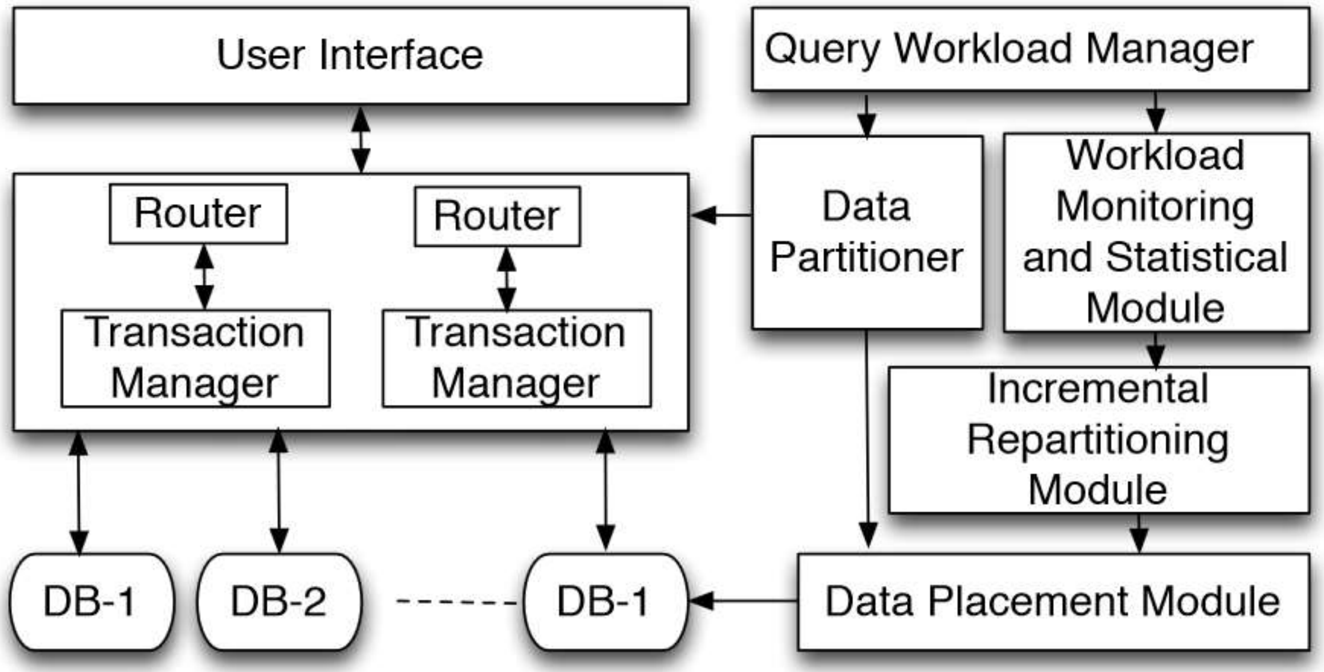
Schism: Graph-based Partitioning



Explanation: *compact, predicate-based representation of the graph-partitioning solution*

SWORD

[Quamar et al. EDBT 2013]



Key Contributions

- Repartitioning heuristics
- Scaling to larger problems by pre-processing (hyper)graph
- Greater focus on replication for fault-tolerance
- Use of quorums (not just ROWA)

Horticulture

[Pavlo et al. 2012]

Focus

- Time-varying skew
- Handle Store procedures natively

Key Contributions

- Schema and workload-driven partitioning
- Large neighborhood search (rich cost model + cheap estimation)
- Horizontal partitioning + table replication + index replication

Horticulture: Cost Model

Both distributed transactions and temporal skew heavily impact performance

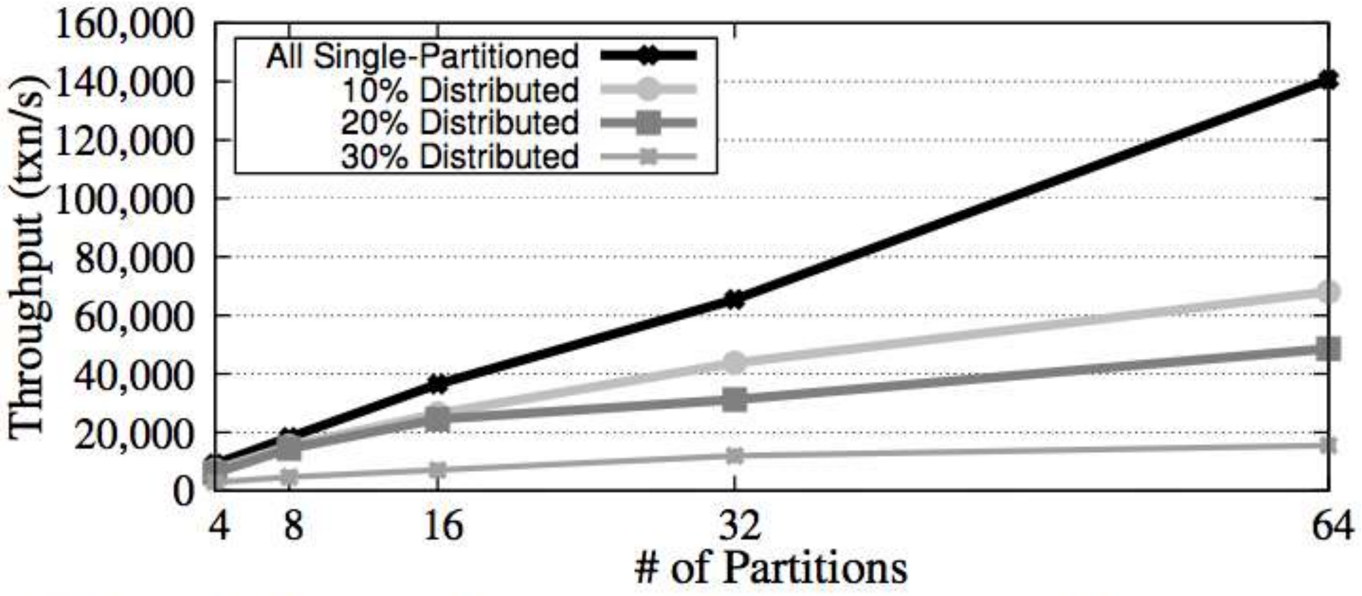


Figure 2: Impact of Distributed Transactions on Throughput

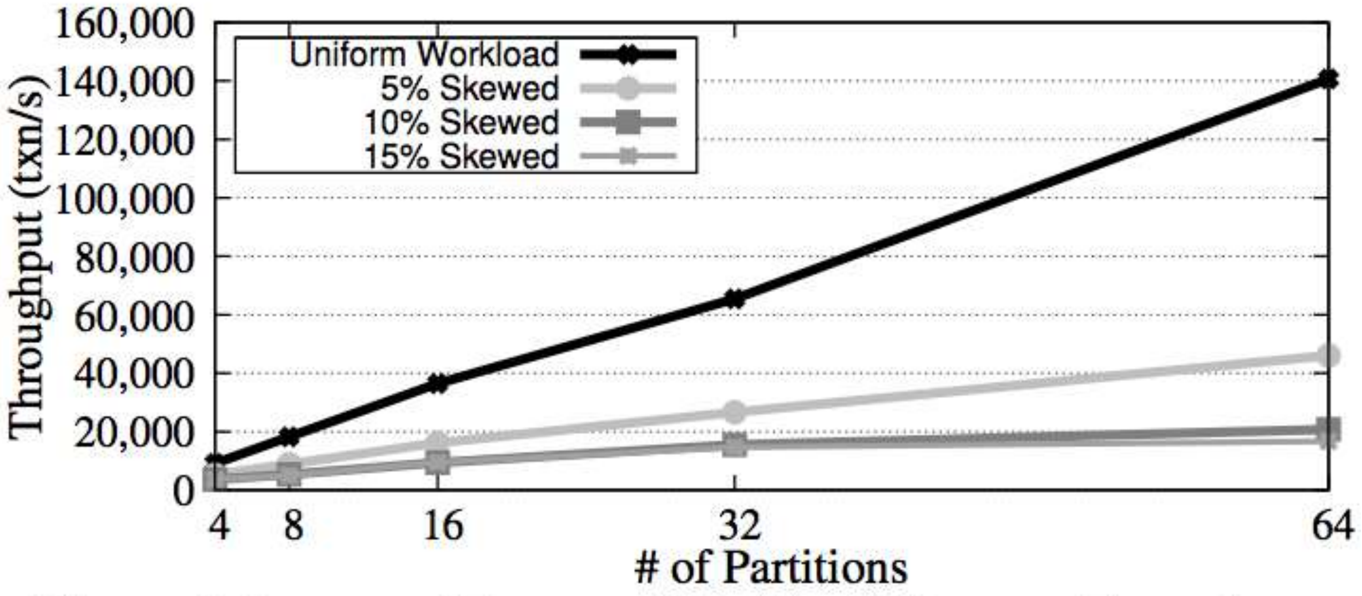
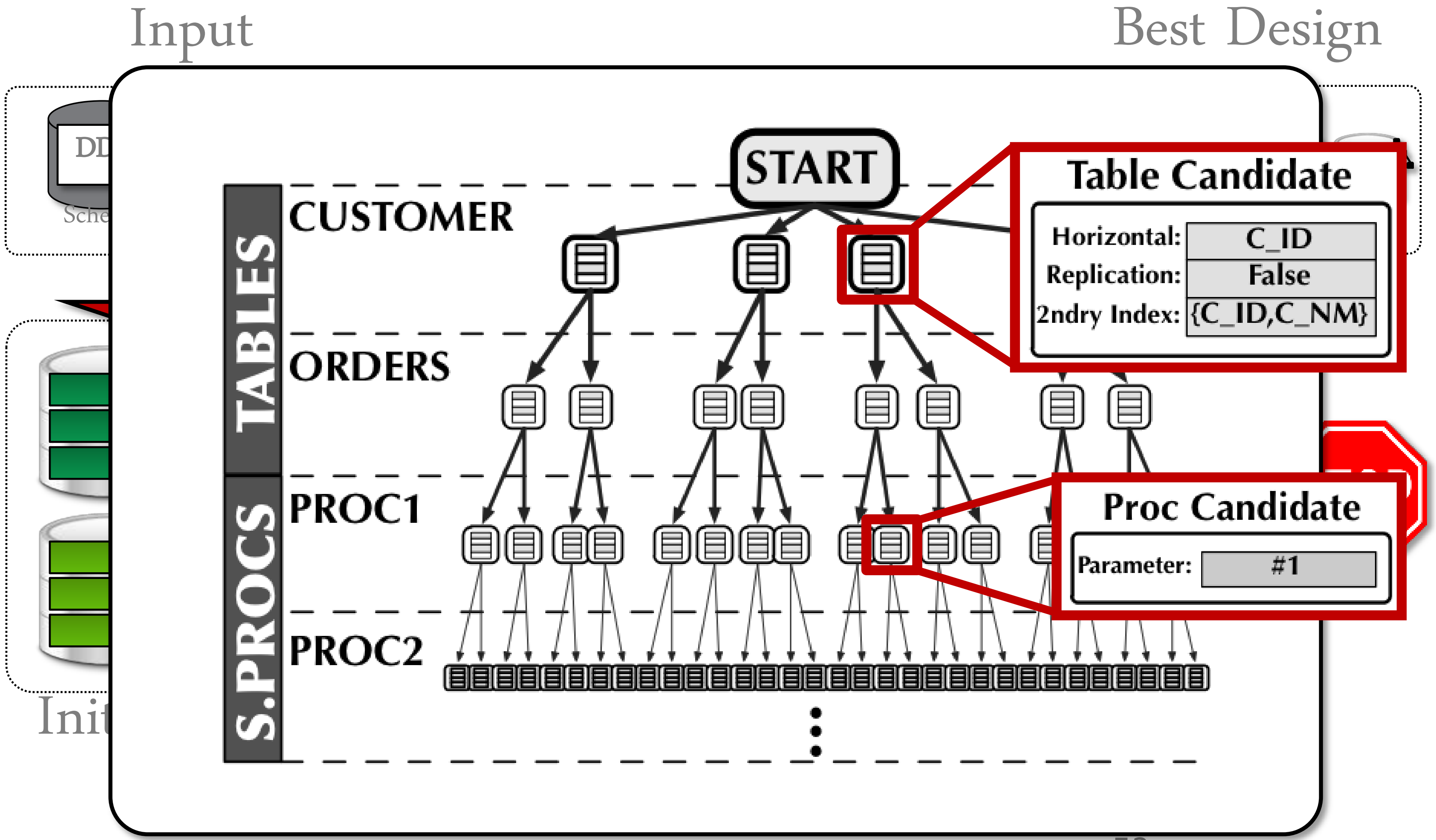


Figure 3: Impact of Temporal Workload Skew on Throughput

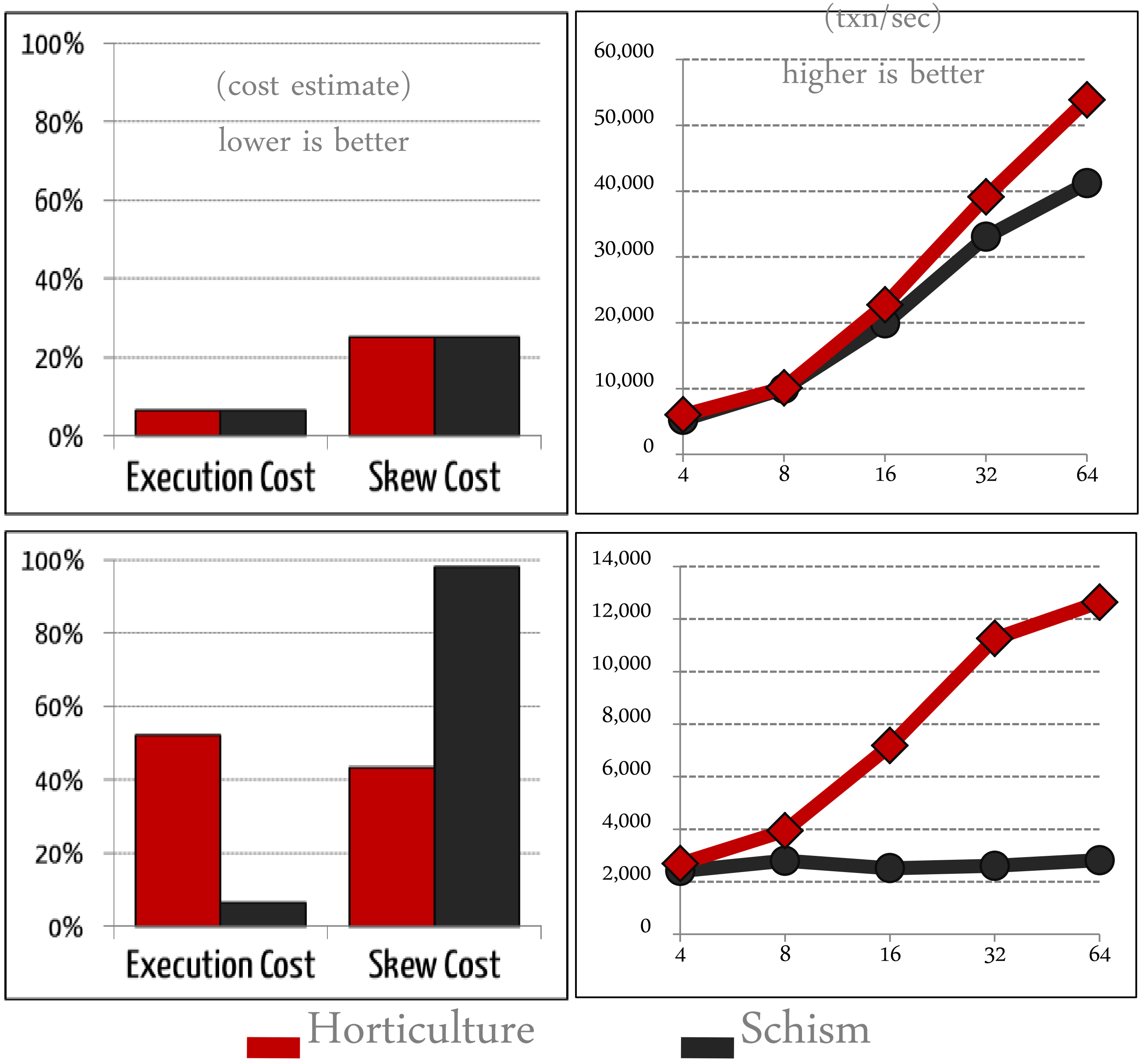
Horticulture: Large Neighborhood search



Throughput comparison (for H-Store)

TPC-C

TPC-C Skewed



Where are we with partitioning?

Problems we know how to solve:

- OLAP (tons of classic work)
- OLTP (few recent papers, good grasp on the problem)

More to do:

- OLAP-OLTP mixed workloads partitioning
- Coordinating replication (and erasure codes) for:
  - Performance, Fault-tolerance
- Geo-distributed placement/replication

DaaS: challenges (and agenda)

Multi-tenancy Architectures ✓
SLA/SLO ✓
- Definition
- Enforcement

High Availability ✓
- Replication
- Fault tolerance

Partitioning ✓
(security/privacy)

Workload Characterization
- Estimation / Prediction
- Resource Attribution
- What if analysis

Resource Management
- Allocation / Balancing
- Tenant Placement
- Admission Control

Migration
Performance Isolation

Managing Resource Contention

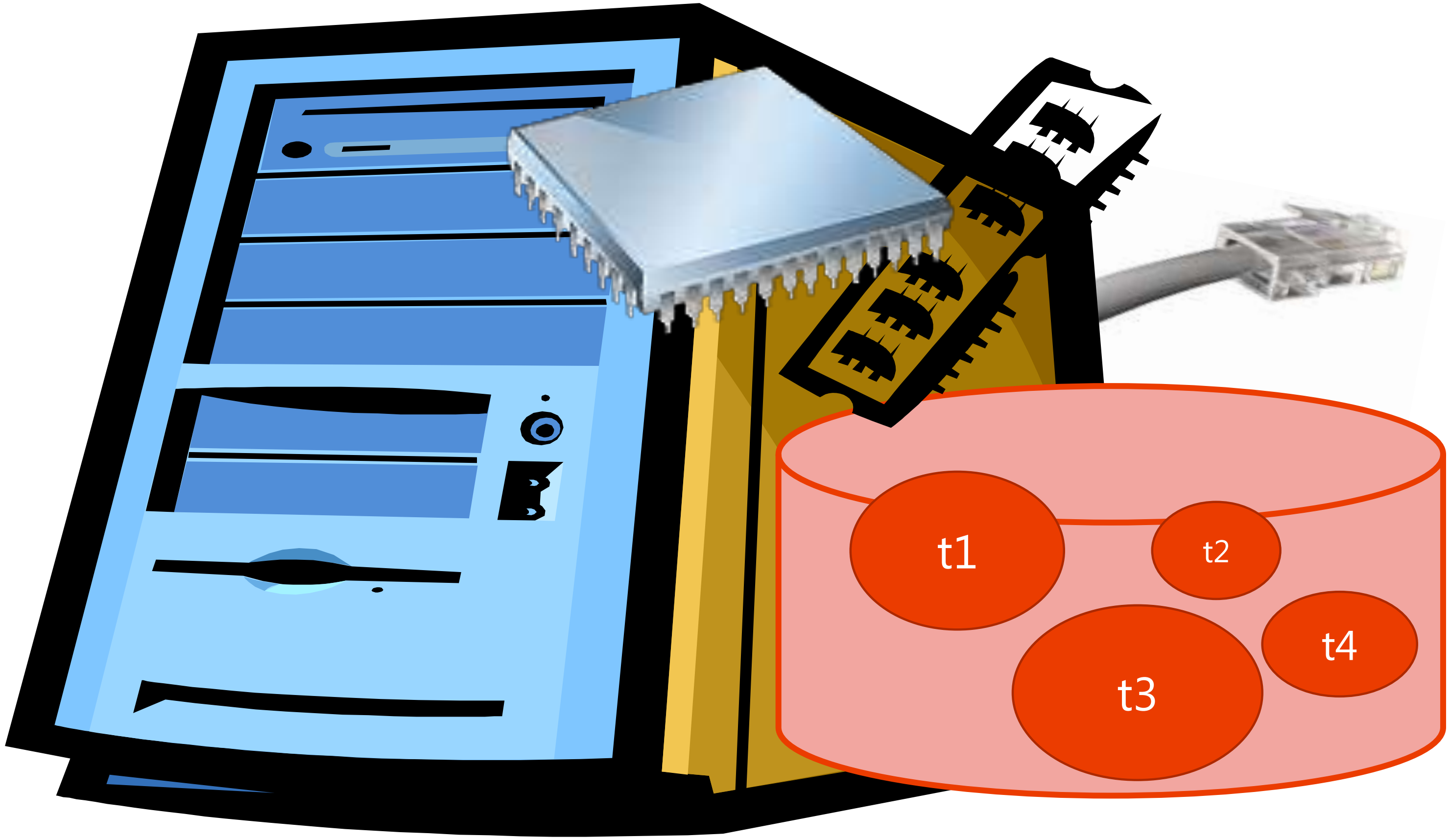
Finding the Balance

Tenant's view

Provider's view

Contention for Resources

Resources are shared, finite, and valuable



Enable "Performance" in a Shared Environment

System needs to isolate the tenants to provide performance when finite resources are shared.

Mechanisms to Enforce Isolation

Hard

Static Provisioning

Resource Allocation
(Dynamic Provisioning)

Soft

Smart Placement

(Admission Control)

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Hard Isolation

"Keeping your word about resource sharing"

SQLVM [CIDR 2013, SIGMOD 2013, VLDB 2014]

Focus

- Embedding resource allocation in DBMS kernel.
- How to share critical resources required by DB.
- How to understand resource allocation.

Key Contributions

- Fine grain resource scheduling (CPU, Memory, I/O).
- Metering to audit resource promise.

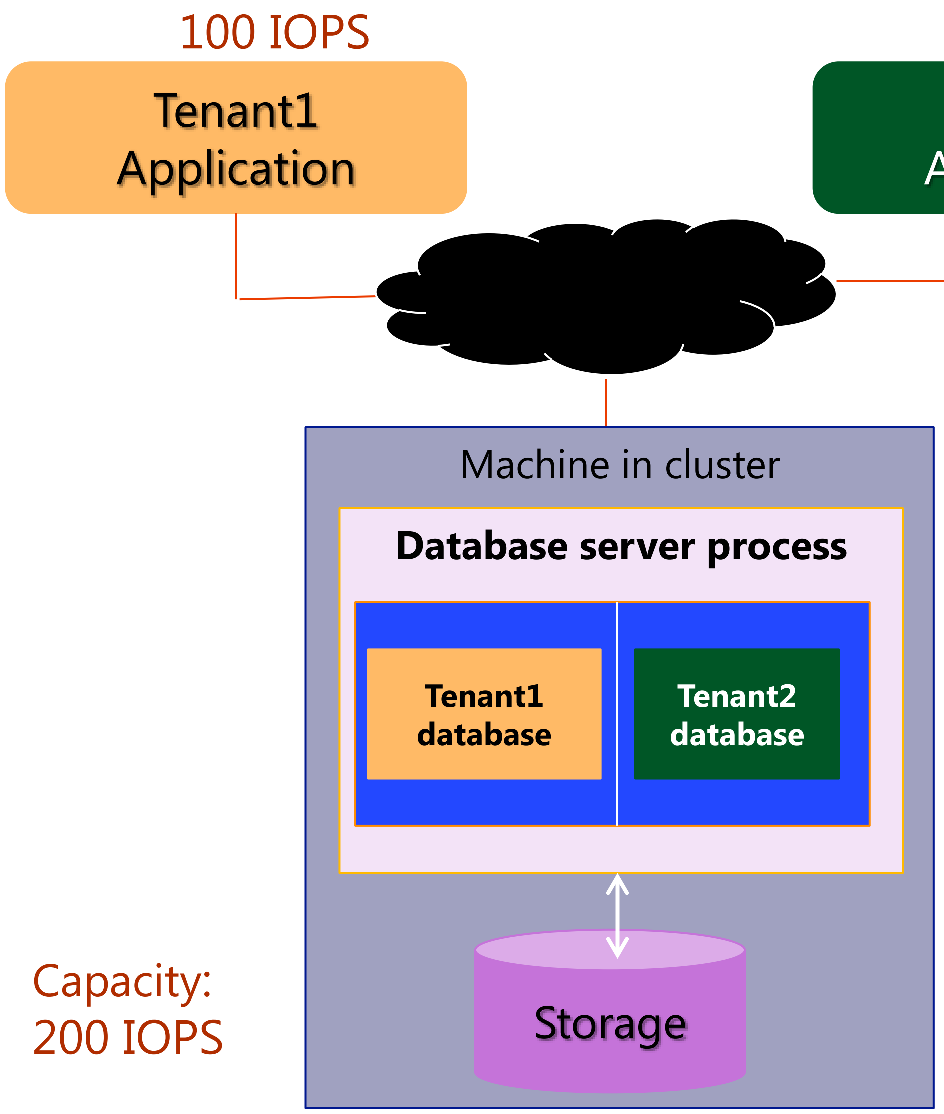
SQLVM Motivation

Query level SLOs are hard.

SELECT Product, SUM(Sales) as TotalSales
FROM FactSales F **JOIN** DimProduct P JOIN DimStates S
ON F.ProdID = P.ProdID and F.StateId = S.StateId
WHERE State = ~~'Vermont'~~ 'California'
GROUP BY Product

Ad-hoc queries add to the challenge.

Resource Governance Mechanism



Tenant is promised reservation of DBMS resources

- "VM inside SQL process"
- CPU utilization, IOPS, Memory, …

Resource governance

- Fine-grained resource sharing
- Novel mechanisms

Metering (auditing)

- Monitor actual and promised metrics for tenant
- Determine violations

Resource Allocation

CPU

Reservation: CPU utilization (e.g. 10%) for running or runnable tasks

Memory (Buffer Pool)

Reservation: Hit Ratio of workload for given memory size (e.g. 1GB)

Disk I/O: Shaping Traffic

50 IOPS $\Rightarrow$ one I/O every 20 msec **issued**

I/O request tagged with deadline. Put into queue

Issue I/Os whose deadline has arrived

Challenges

Metering and auditing resources.

Multi-core CPU scheduling.

Multiple volumes

Indirect and direct work.

Soft Isolation

"Smart placement to mitigate resource contention"

DaaS: challenges (and agenda)

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- Migration
- Performance Isolation ✓

Common Patterns

Understand workloads

- Fixed, Profiled, or Learned
- Isolated vs Consolidated

How workloads combine

- Provided function (oracle)
- Models
- Observations

Find placement

- Incremental
- Bin-packing
- Optimization

Metrics

- Robustness
- Costs (SLA, Operating)
- Performance (TPS, Latency)

Towards Multi-Tenant Performance SLOs

Willis Lang, Srinath Shankar, Jignesh M. Patel, Ajay Kallan
Univ. of Wisconsin and MS Gray Systems Lab

ICDE 2012

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Towards Multi-Tenant Performance SLOs

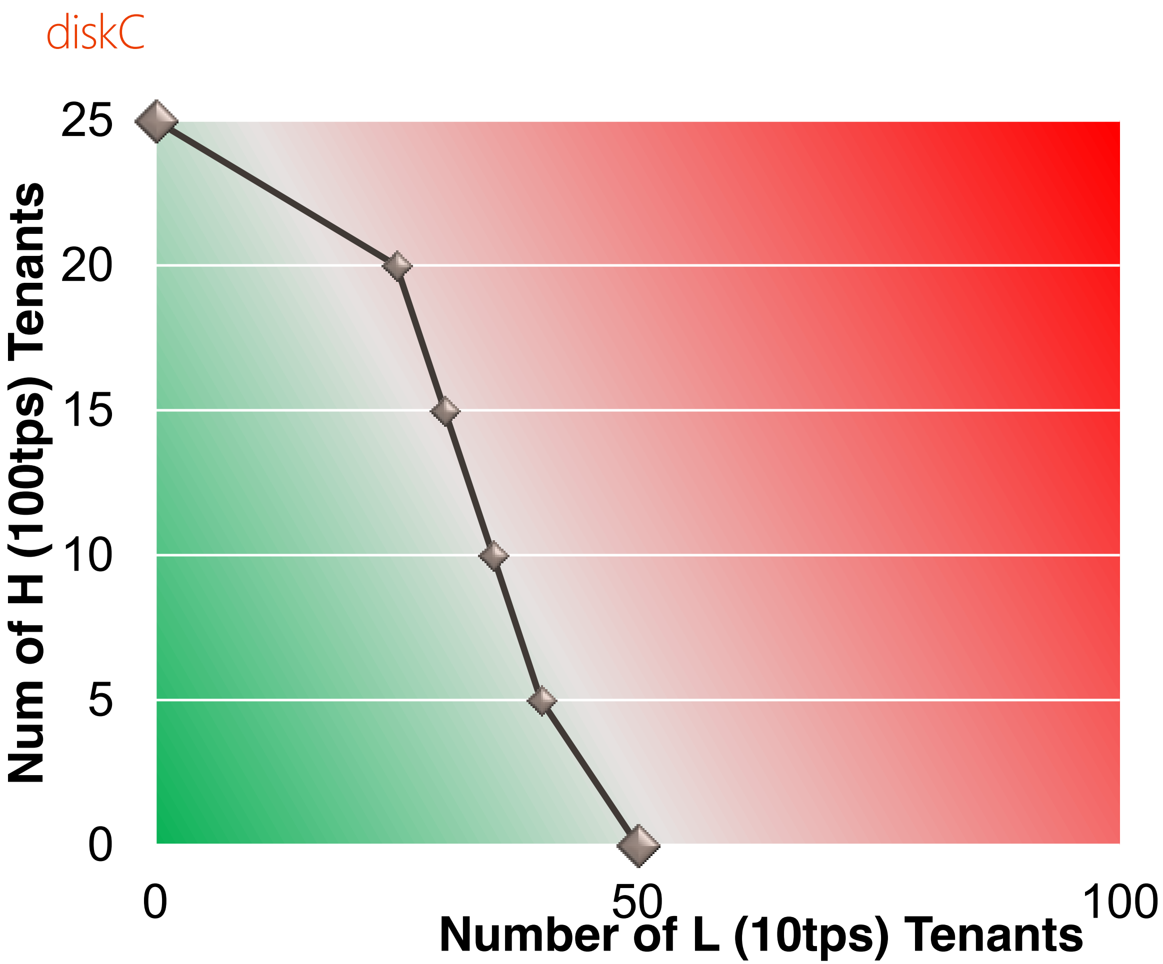
Focus

- Different hardware configurations (SKU)
- Multiple tenant **performance SLO** classes
- Place to meet SLOs and minimize costs

Key Contributions

- Cost aware server consolidation
- Tenant placement optimization framework

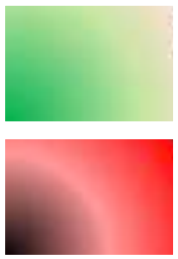
Heterogeneous SLO Characterization



Benchmark server to find max degree multi-tenancy for perf objectives

Systematically reduce ‘H’ tenants, steadily increase ‘L’ tenant scheduling until a perf objective fails

Server characterizing function:



Both perf objectives met

Some perf objective fails

Slide by Lang et al.

Approach

Assumption

In memory tenant addition is mainly linear.

Solution

One DB instance per SLO throughput class.

(Balancing buffer pool sharing)

Discover frontier

Use solver for ILP formulation to minimizes costs

RTP: Robust Tenant Placement for Elastic In-Memory DB Clusters

Jan Schaffner, Tim Januschowski, Megan Kercher, Tim Kraska,
Hasso Plattner, Michael J. Franklin, Dean Jacobs

Hasso Plattner, SAP, UC Berkeley, Brown University

SIGMOD 2013

Common Patterns

Understand workloads

- Fixed, Profiled, or Learned
- Isolated vs Consolidated

How workloads combine

- Provided function (oracle)
- Models
- Observations

Find placement

- Incremental
- Bin-packing
- Optimization

Metrics

- Robustness
- Costs (SLA, Operating)
- Performance (TPS, Latency)

Robust Tenant Placement

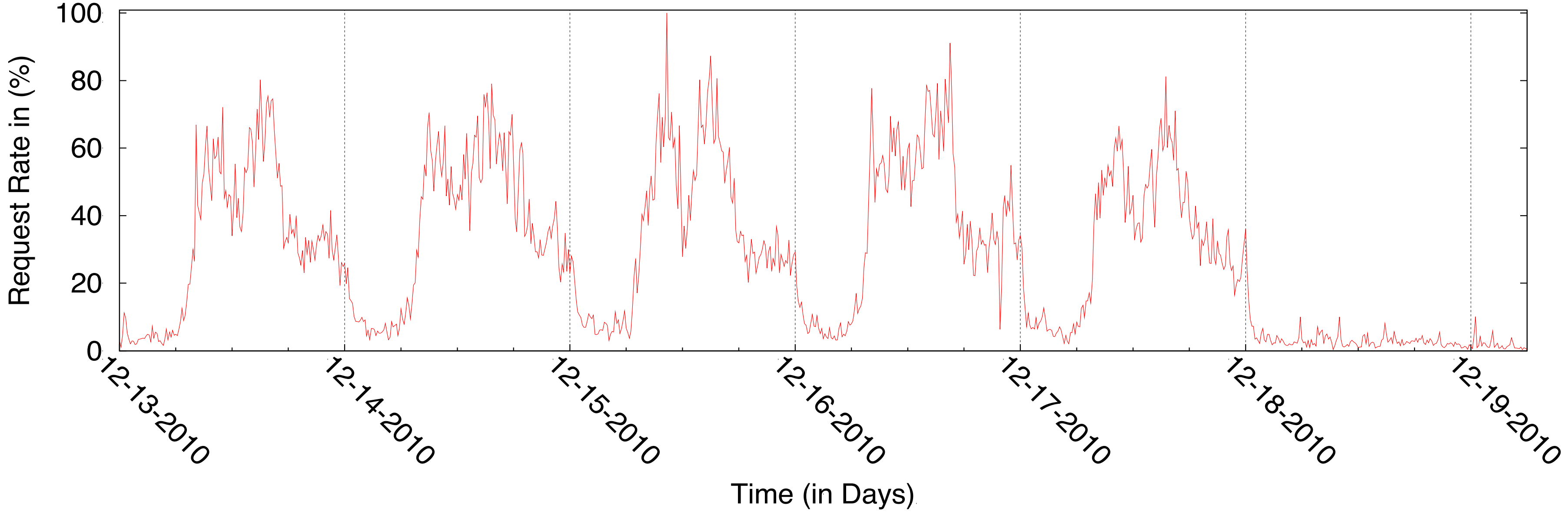
Focus

- In memory databases with **temporal changes** / etheral DBs
- Minimize servers while being **robust** to failures
- **Replication** with ability to redirect workload

Key Contributions

- Incremental algorithms to reduce total costs of ownership
- Maintain replication and respect server load.
- Migration and existing placement aware solution

Workloads



Workloads are diurnal and short lived bursty tenants.

Workload resource consumption. is univariate and additive

Read heavy workloads

Placing Tenants

Robust to failure (interleaving tenants over bin packing)

Maintain replication

Migration capacity

Solutions

Greedy Heuristics

Meta-heuristics

Exact Solutions

Static and incremental solutions.

Framework

Incremental algorithms follows these steps:

1. Delete un-needed replicas
2. Ensure migration flexibility
3. Create missing replicas
4. Fix overloaded servers
5. Reduce number of active servers
6. Minimize max load

PMAX: Tenant Placement in Multitenant Databases for Profit Maximization

Ziyang Liu, Hakan Hacıgümüş, Hyun Jin Moon,
Yun Chi, and Wang-Pin Hsiung

NEC Laboratories America

EDBT 2013

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PMAX

Focus

Latency response SLOs

Workloads are not fixed and vary, history is not available

Profit maximization

Key Contributions

Cost focused placement solution

Bounded approximation algorithms & dynamic prog. solution

Common Patterns

Understand workloads

- Varied arrival rate
- Provided query SLA (over
- Load = resp. time / arrival
- Load > 1 = missed SLA

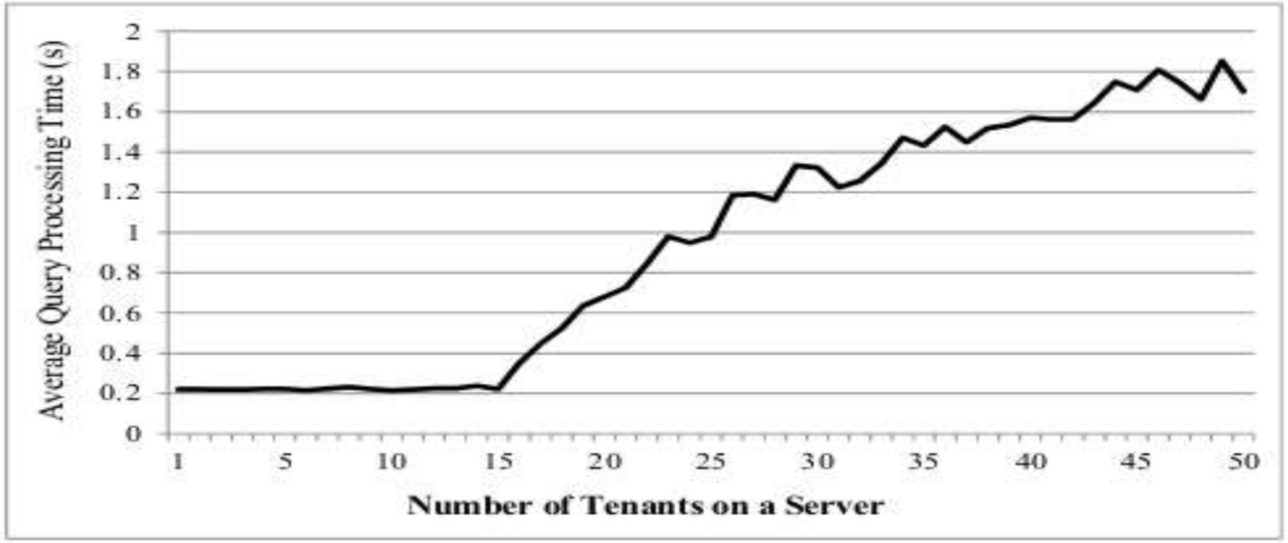

Figure 3: Relationship between Average TPC-W Query Processing Time and Number of Tenants on a Server

How workloads combine

- Server load = sum tenants load * tenant load factor

Placement Formulation

Each server has a operating costs.

Place tenants to minimize costs (occasional violations OK).

Two problem formulations:

- Uniform: Fixed arrival rate and SLA
- General: Varied arrival and query based SLA
- Both reduced to NP-hard

Solution

Best fit heuristic is sub-optimal

Encourage new servers

Use normalized SLA ordering of tenants

Approximation and DP solution

DaaS: challenges (and agenda)

- Multi-tenancy Architectures ✓
- SLA/SLO ✓
  - Definition
  - Enforcement
- High Availability ✓
  - Replication
  - Fault tolerance
- Partitioning ✓
- (security/privacy)

- Workload Characterization
  - Estimation / Prediction
  - Resource Attribution
  - What if analysis
- Resource Management
  - Allocation / Balancing
  - Tenant Placement
  - Admission Control
- Migration
- Performance Isolation ✓

Workload-Aware Database Monitoring and Consolidation

Carlo Curino, Evan P.C. Jones, Samuel Madden, and Hari Balakrishnan

MIT

SIGMOD 2011

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Kairos

Focus

- Modeling resource consumption of OLTP workloads
- Consolidate workloads

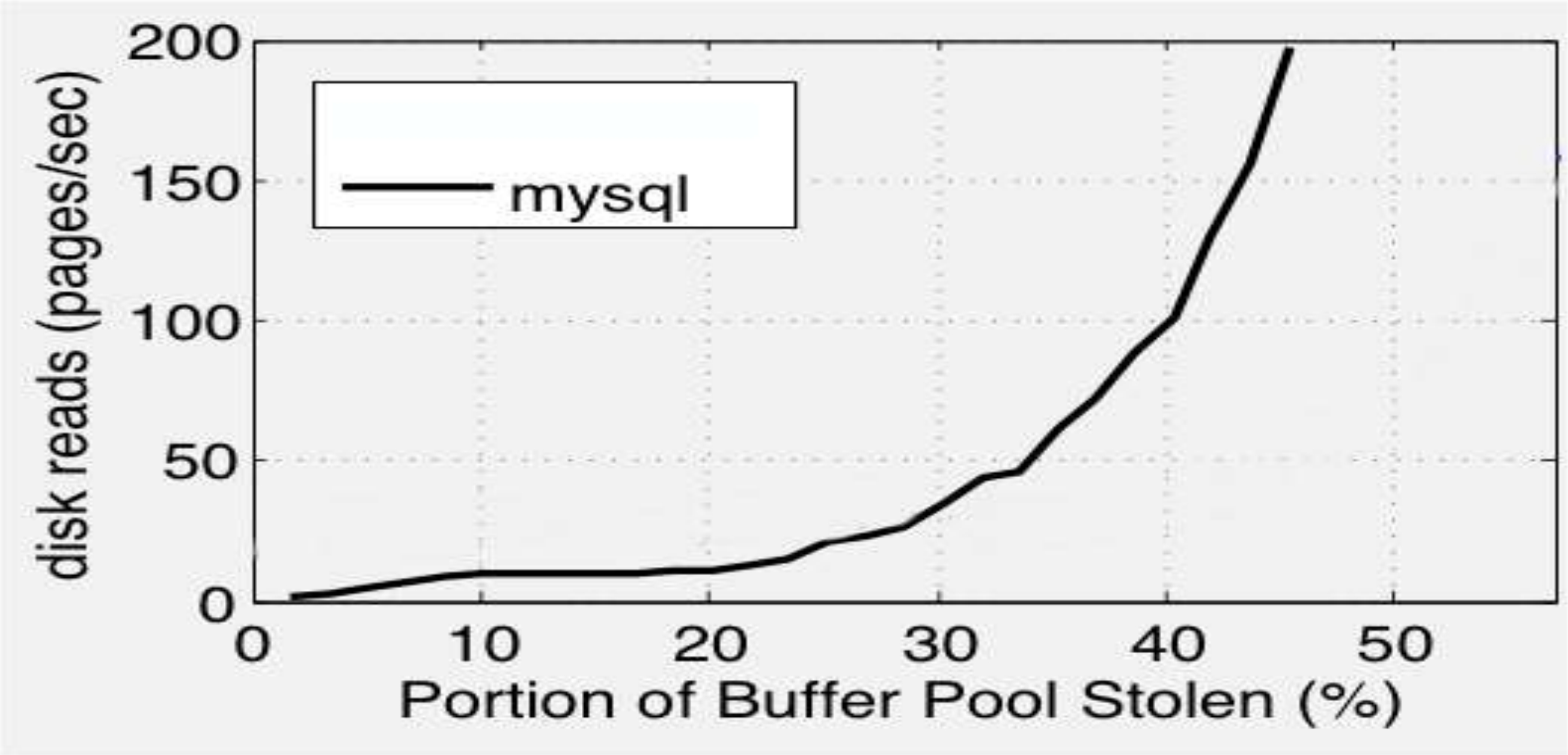
Key Contributions

- Method to determine **active working set size**
- Model disk I/O for consolidation
- Find balanced consolidation plan.

Buffer Pool Gauging for RAM

Databases are greedy

Use ballooning to ID active working set size



953 MB Bufferpool, on TPC-C 5W (120-150 MB/WH)

Slide by Sam Madden

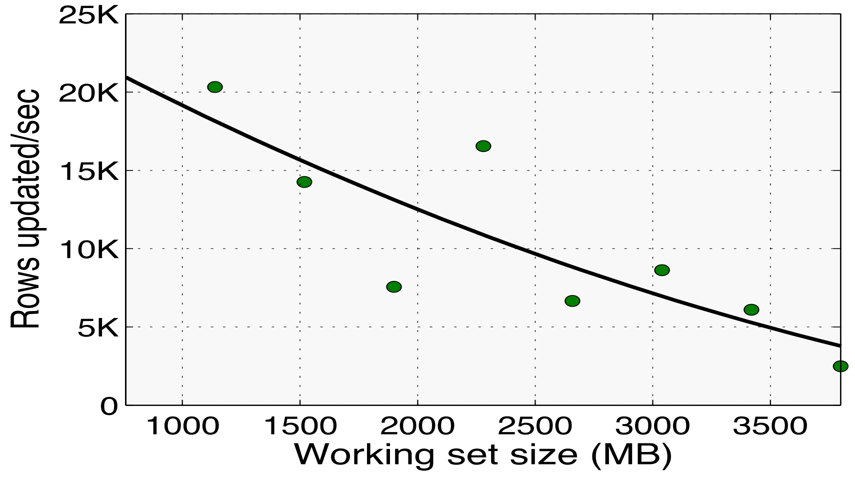
Disk Model

With working set in RAM:

I/O is flushing and txn logs

Regardless of transaction type, max update throughput of a disk depends primarily on database working set size.

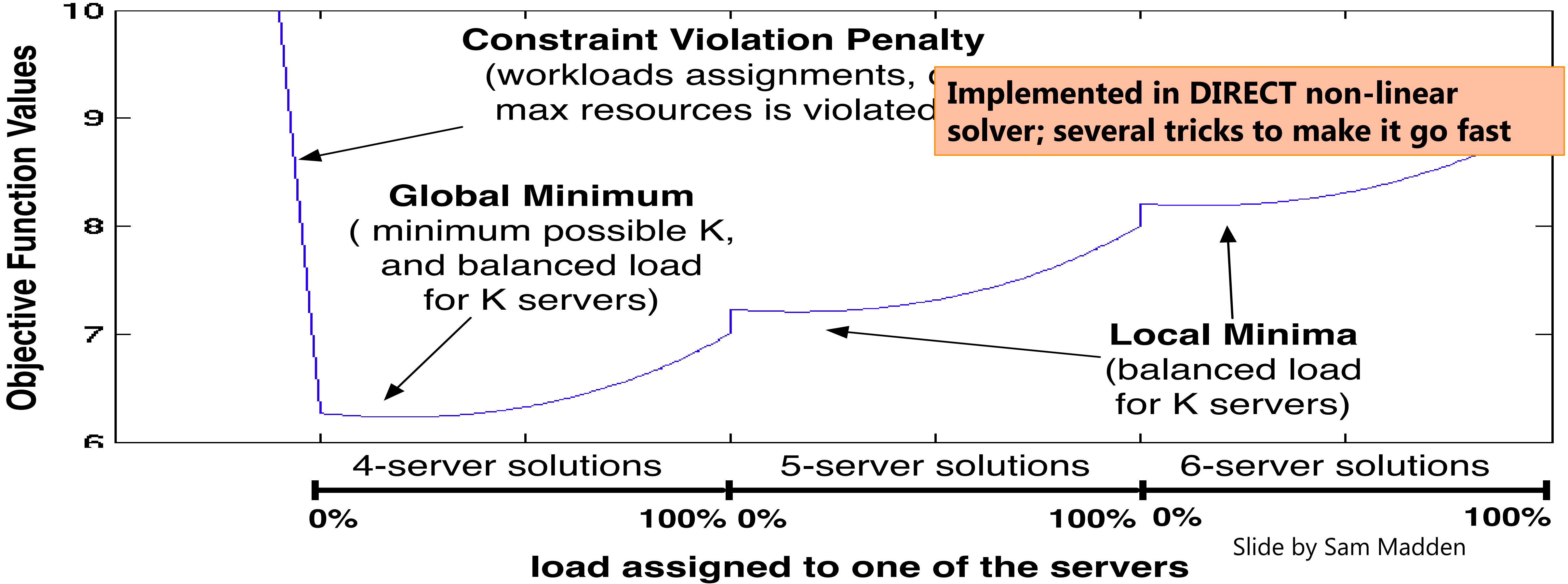
Adding workload metrics holds.



Node Assignment via Optimization

Goal: minimize required machines (leaving headroom), balance load

Problem modeled as:
Mixed-integer non-linear optimization problem



Implemented in DIRECT non-linear solver; several tricks to make it go fast

Slide by Sam Madden

DaaS: challenges (and agenda)

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- Migration
- Performance Isolation ✓

Performance and resource modeling in highly-concurrent OLTP workloads

Barzan Mozafari, Carlo Curino, Alekh Jindal, Samuel Madden

MIT, MS CSIL

SIGMOD 2013

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DBSeer

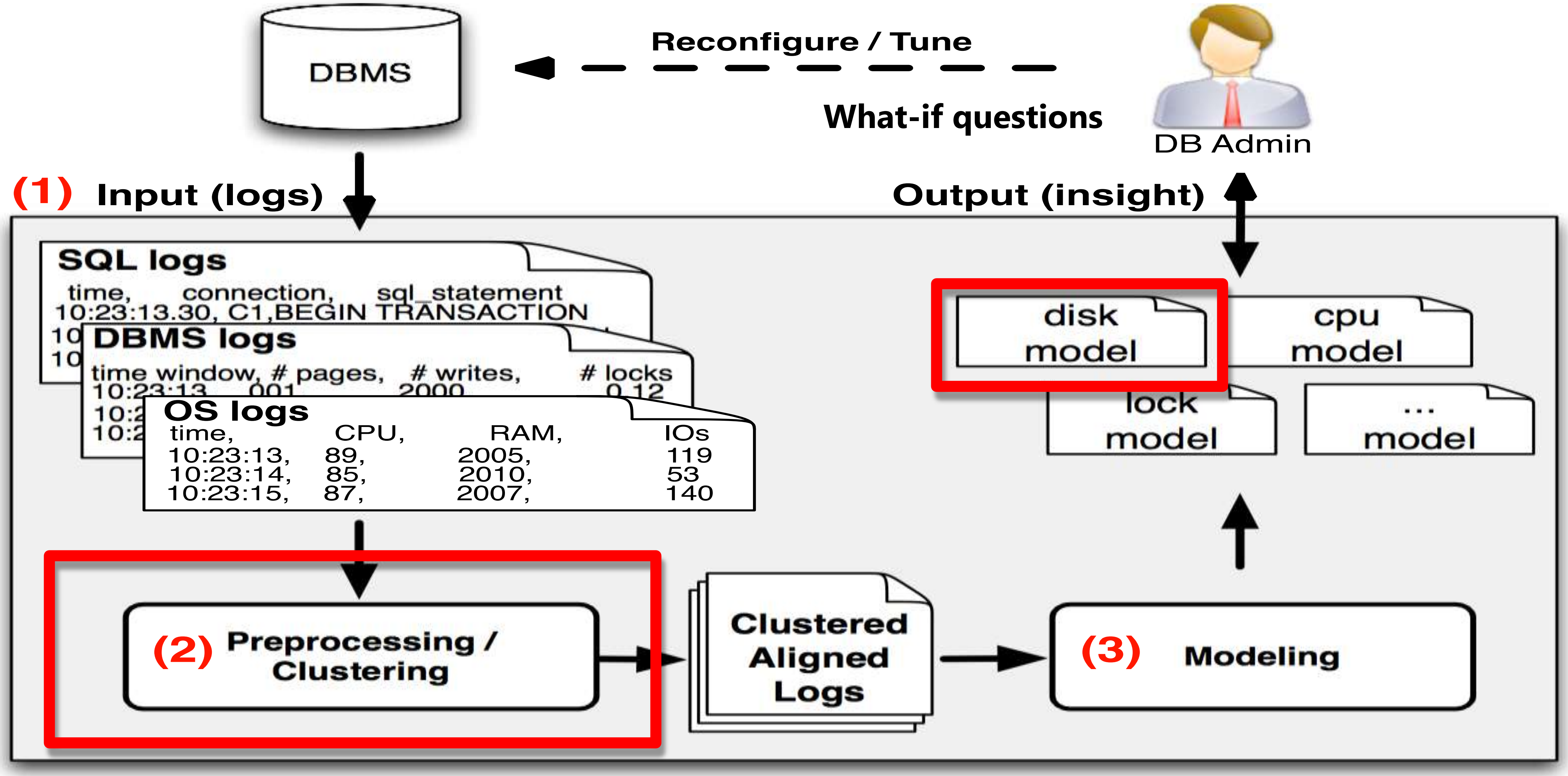
Focus

- Attribute resource consumption to txn classes (and tenants)
- Attribute at runtime in consolidated process
- Build models of various DB resources

Key Contributions

- Models for disk I/O, locks, throughput, etc
- Attribute resources to tenants.
- Ability for DBAs to play what-if

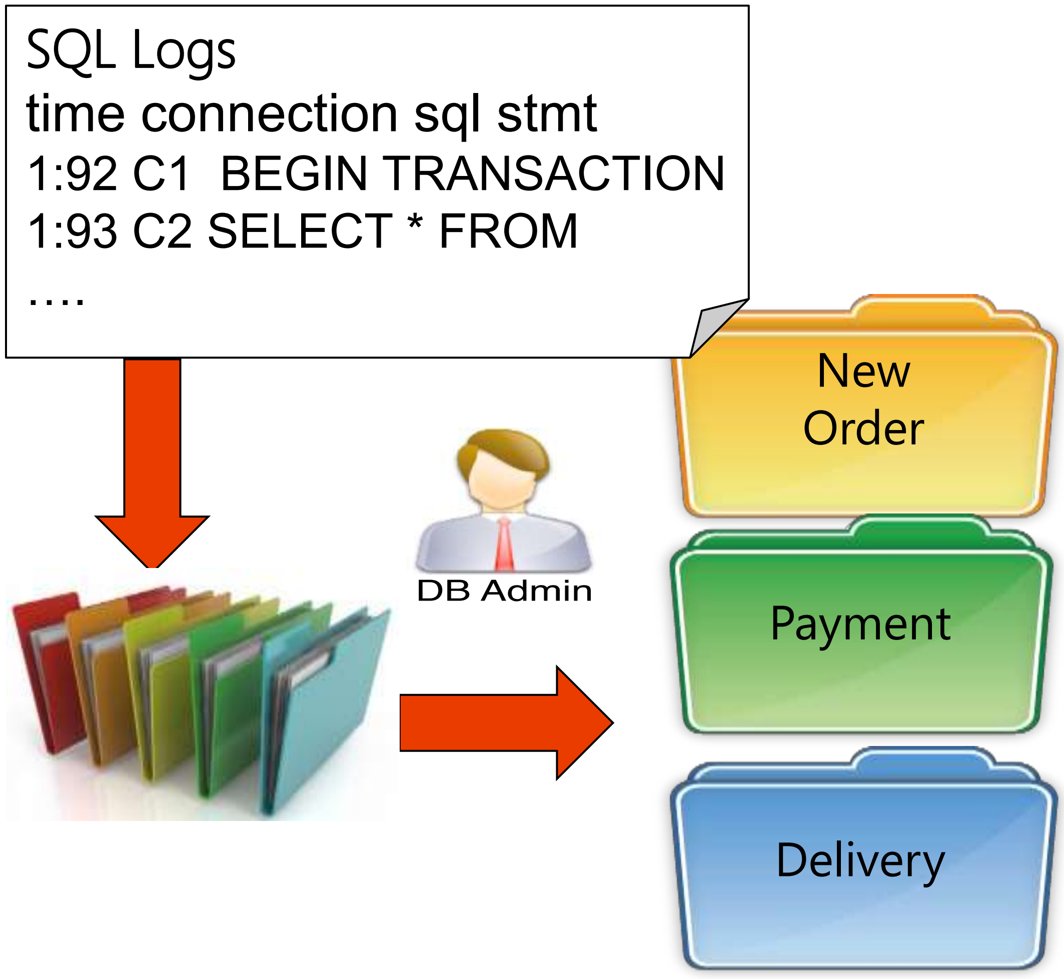
DBSeer From 10000 ft

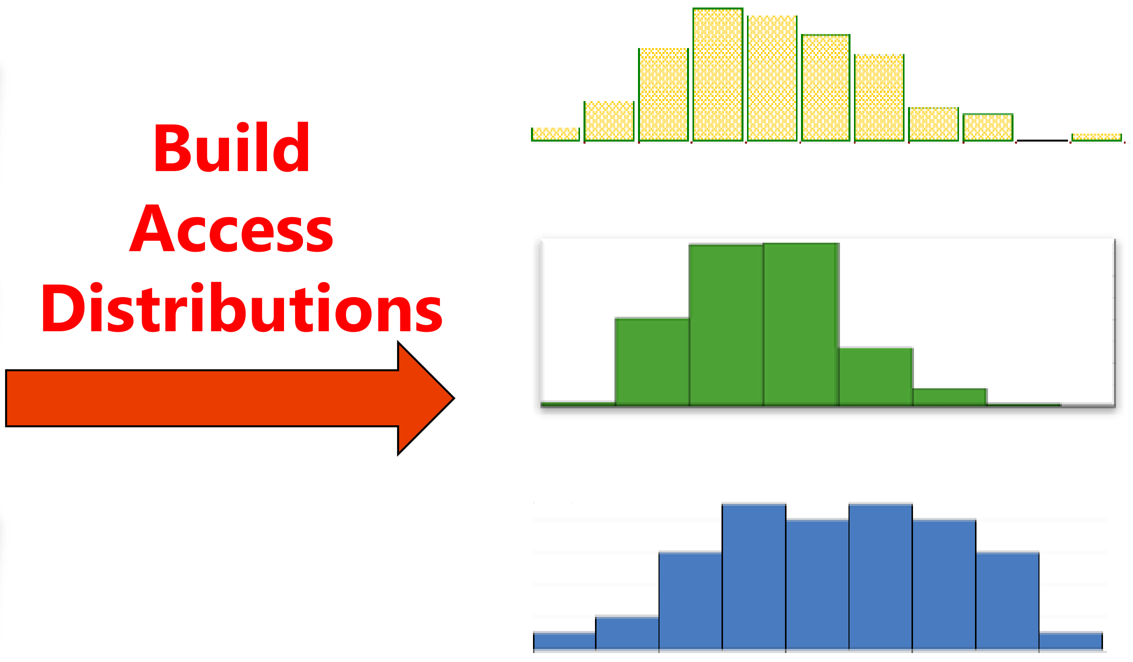


Transaction Clustering

Problem: Different transaction have different access patterns

1. Extract features of each transaction
   - number of rows read/written to each table
2. Run DBSCAN clustering algorithm





Predicting Disk I/O

Disk Reads = Cache miss rate * # logical reads

Disk Writes = log IO + data IO

- **Log IO (sequential):** redo logs
- **Data IO (random):** dirty pages
  - due to log reclamation
  - due to page evictions (buffer pool misses)

Key Observation:

- # dirty pages flushed = # new pages getting dirtied
- **Predict # of dirty pages**

Other Components of DBSeer

- Clustering transactions
- Disk Writes
- RAM/Disk Reads
  - Predicting expected cache-miss rate
- Lock Contention
  - Queuing theory techniques
- Network, CPU, Logical I/O, Logging
  - Linear regression
- Max Throughput
  - Finding the bottleneck resource

DaaS: challenges (and agenda)

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  - Resource Attribution ✓
  - What if analysis ✓
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  - Admission Control
- Migration
- Performance Isolation ✓

Characterizing tenant behavior for placement and crisis mitigation in multitenant DBMSs

Aaron J. Elmore, Sudipto Das, Alexander Pucher, Divyakant Agrawal, Amr El Abbadi, Xifeng Yan

UC Santa Barbara, MSR

SIGMOD 2013

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- Bin-packing
- <u>Optimization</u>

Metrics

- Robustness
- Costs (<u>SLA</u>, Operating)
- Performance (TPS, <u>Latency</u>)

Pythia

Focus

Tenant workloads are unknown, disk-based, and dynamic

Use supervised learning to model tenants and colocation

Leverage models to resolve performance crisis

Key Contributions

Method for empirically learning how tenant classes colocate

End to end framework for tenant placement

Tenant Model

Want to construct a **tenant model** which given a vector of database attributes provides a **tenant class** (or label).

Tenant based on database agnostic attributes

(TPS, cache hit %, buffer pool size, write %, etc)

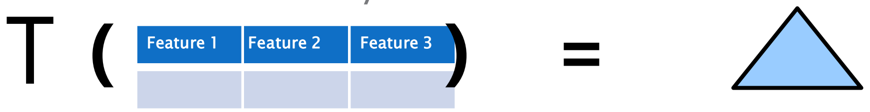
Easily available and available after consolidation

Correlates to tenants' behavior and performance requirements

Describe Resource Consumption

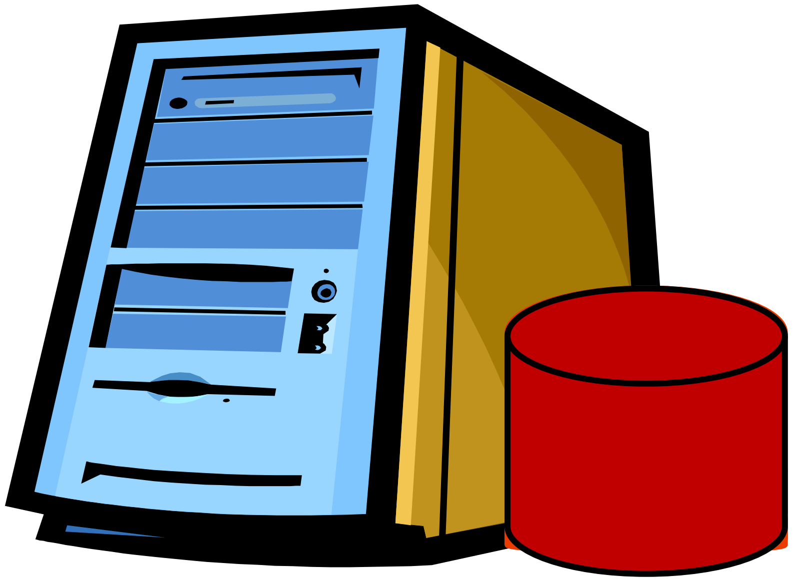
Tenant labels should describe resource consumption.
For example, we are concerned with: Disk and CPU
Use colored shapes as example classes:

Train a function T : set of tenant / DB attributes → class



Learn which classes colocate well

Want to see how a **node** is performing



Under ✓+

Good ✓

Over ✗

Boundaries set by administrator.

Uses resources and latency SLOs.

Control over consolidation.

Incrementally learned through observation

Things Don't Always Go To Plan

Single tenant in percentile latency causes a node violation.

Use **node model** to identify set of tenants to remove and identify destinations to receive tenants.

How to identify which tenants and destination nodes?

Searching for a solution

Implemented as a hill-climbing algorithm

Each step is a migration

Evaluate the sum of: each nodes "over"-ness * # tenants

DaaS: challenges (and agenda)

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Migration for Load Balancing

Migration Forms

Want to move a database between servers

Naïve: *Stop-and-copy*

Improvement: *Flush-and-copy*

Replication based: *Synchronous*

Ideal: *Live Migration*

Migration Goals

Downtime

Service Interruption

Migration Overhead

Time to Complete

Albatross

[Das et al. VLDB 2011]

Focus

Live migration in a shared storage transactional DB

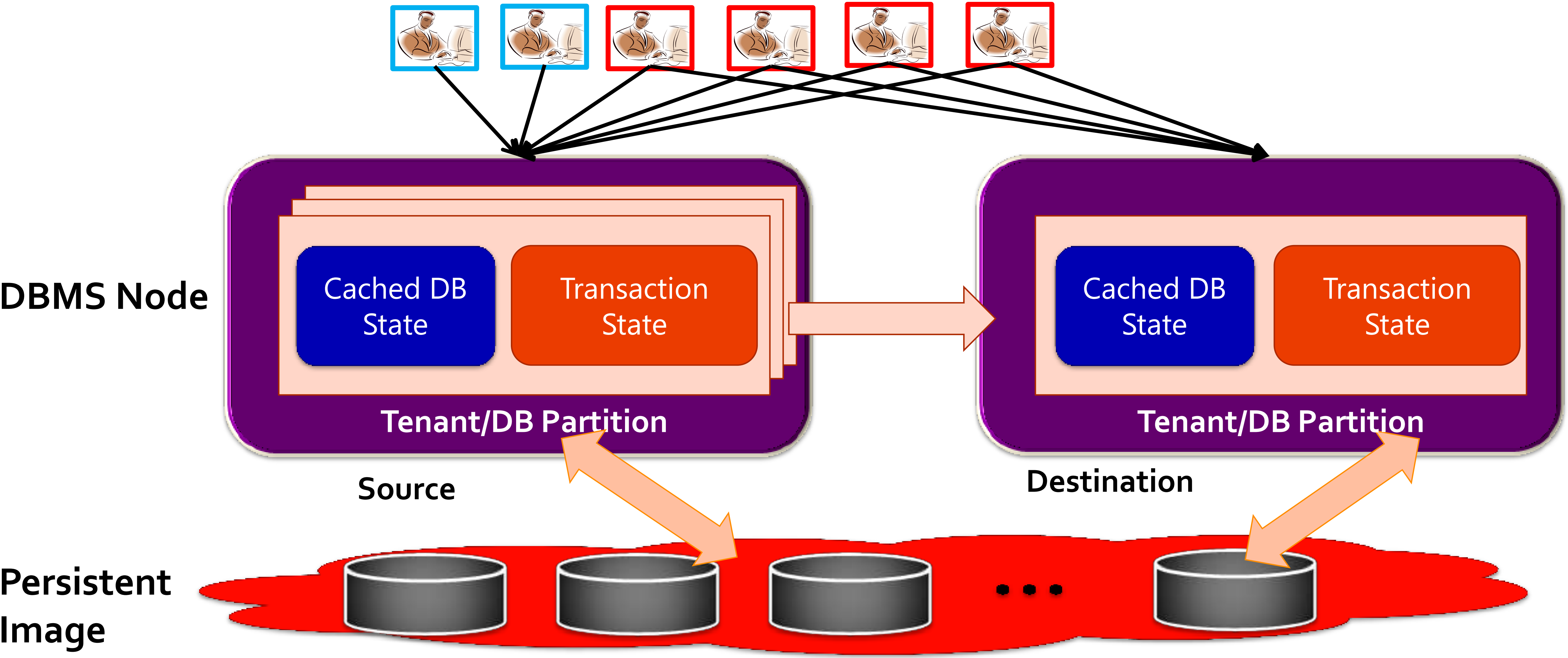
Migration TM state and cache

Key Contributions

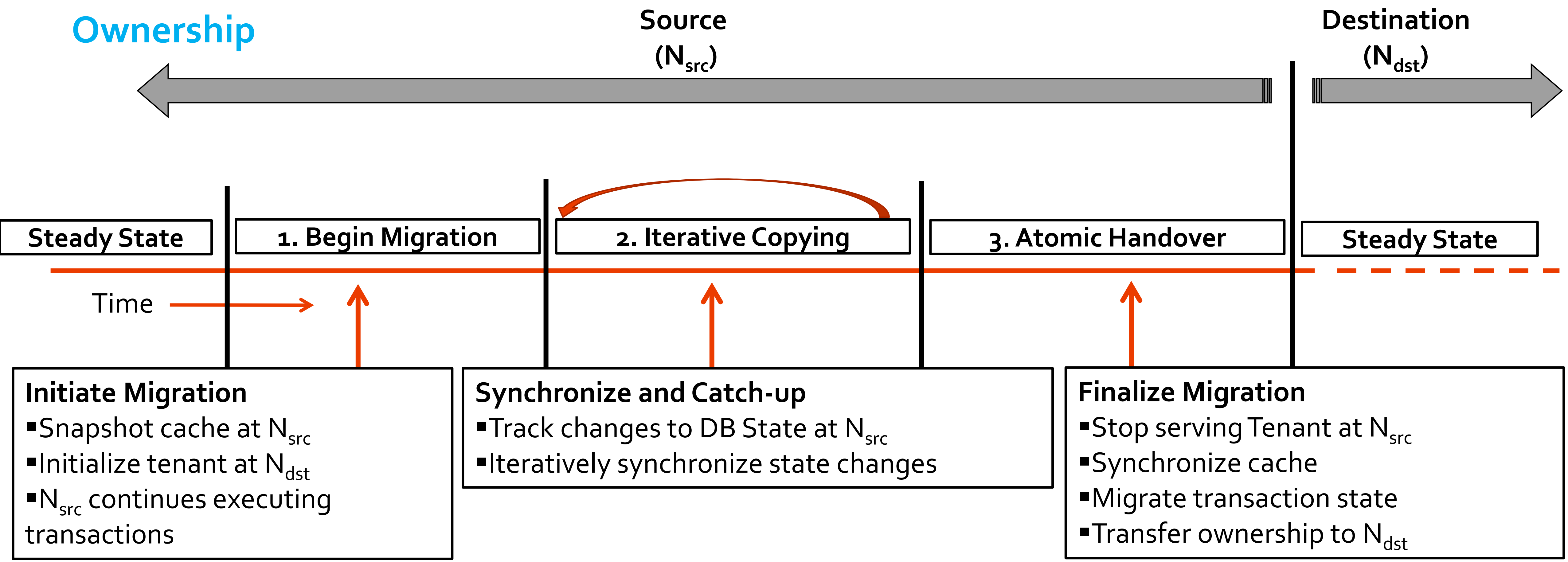
First live migration for shared storage.

Minimal strain on destination

Live Migration for Shared Storage



Albatross Live Migration



Zephyr

[Elmore et al. SIGMOD 2011]

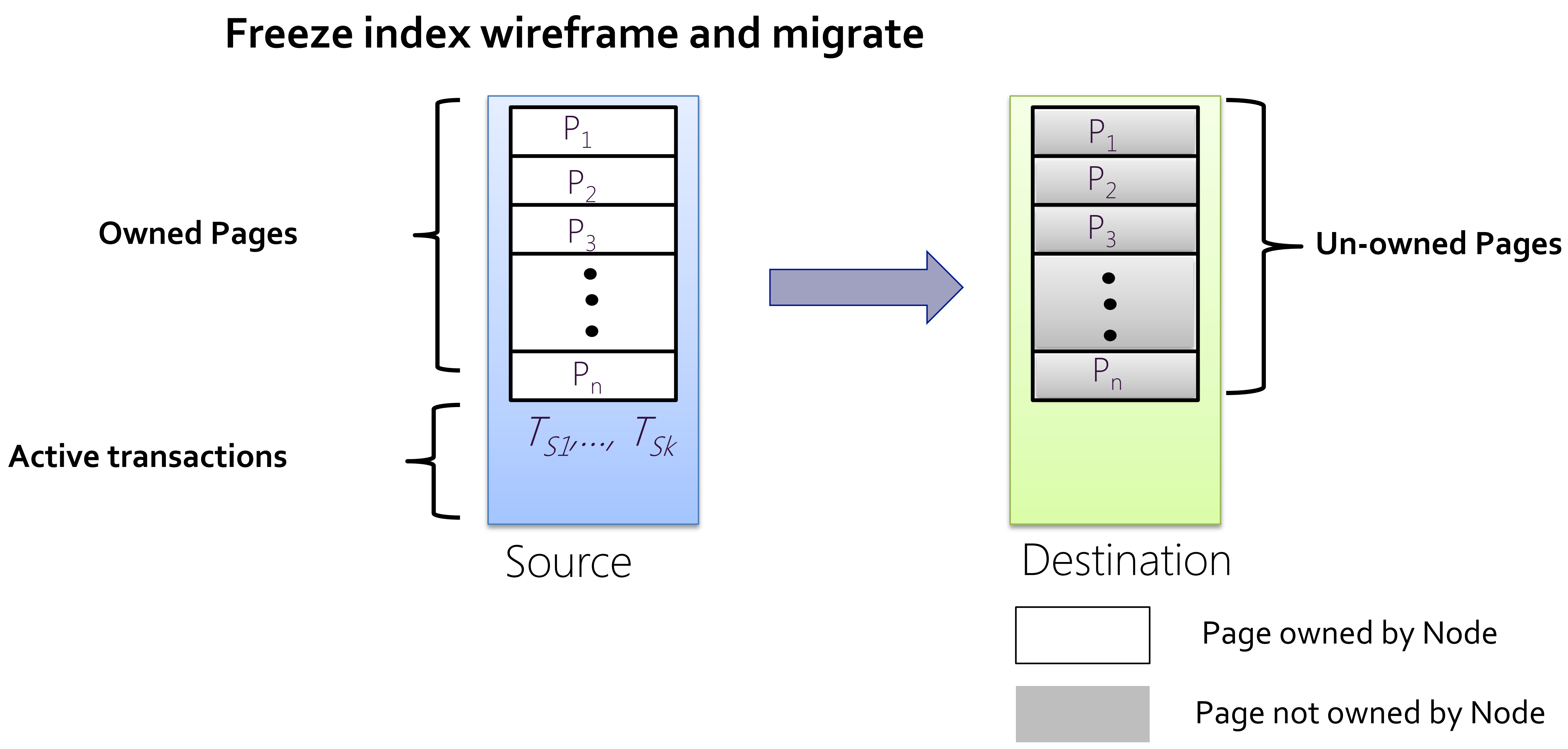
Focus

- Live migration in a shared nothing transactional DB (H2)
- No heavy-weight synchronization protocols or replication.
- No downtime, some aborted transactions.

Key Contributions

- First live migration for shared nothing DBMS.
- Minimal strain on source (scale up)

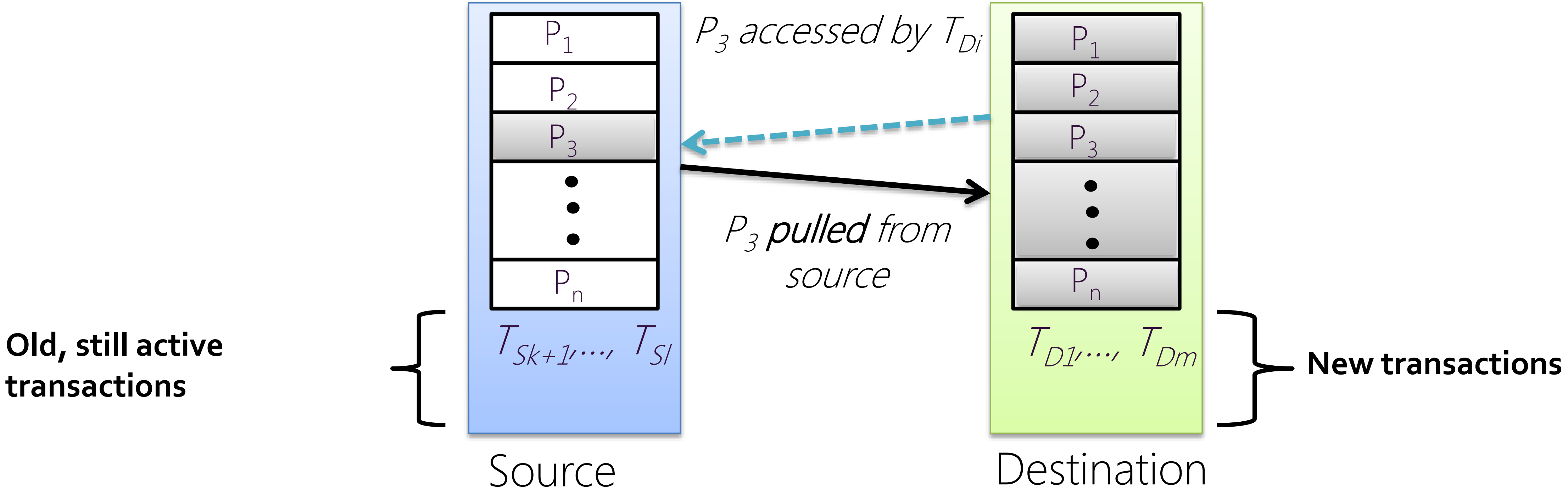
Init Mode



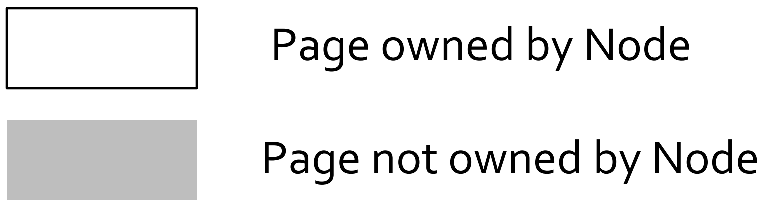
Freeze index wireframe and migrate
Owned Pages
Active transactions
P1
P2
P3
Pn
TS1,…, TSk
Source
P1
P2
P3
Pn
Un-owned Pages
Destination
Page owned by Node
Page not owned by Node

Dual Mode

Requests for un-owned pages can block

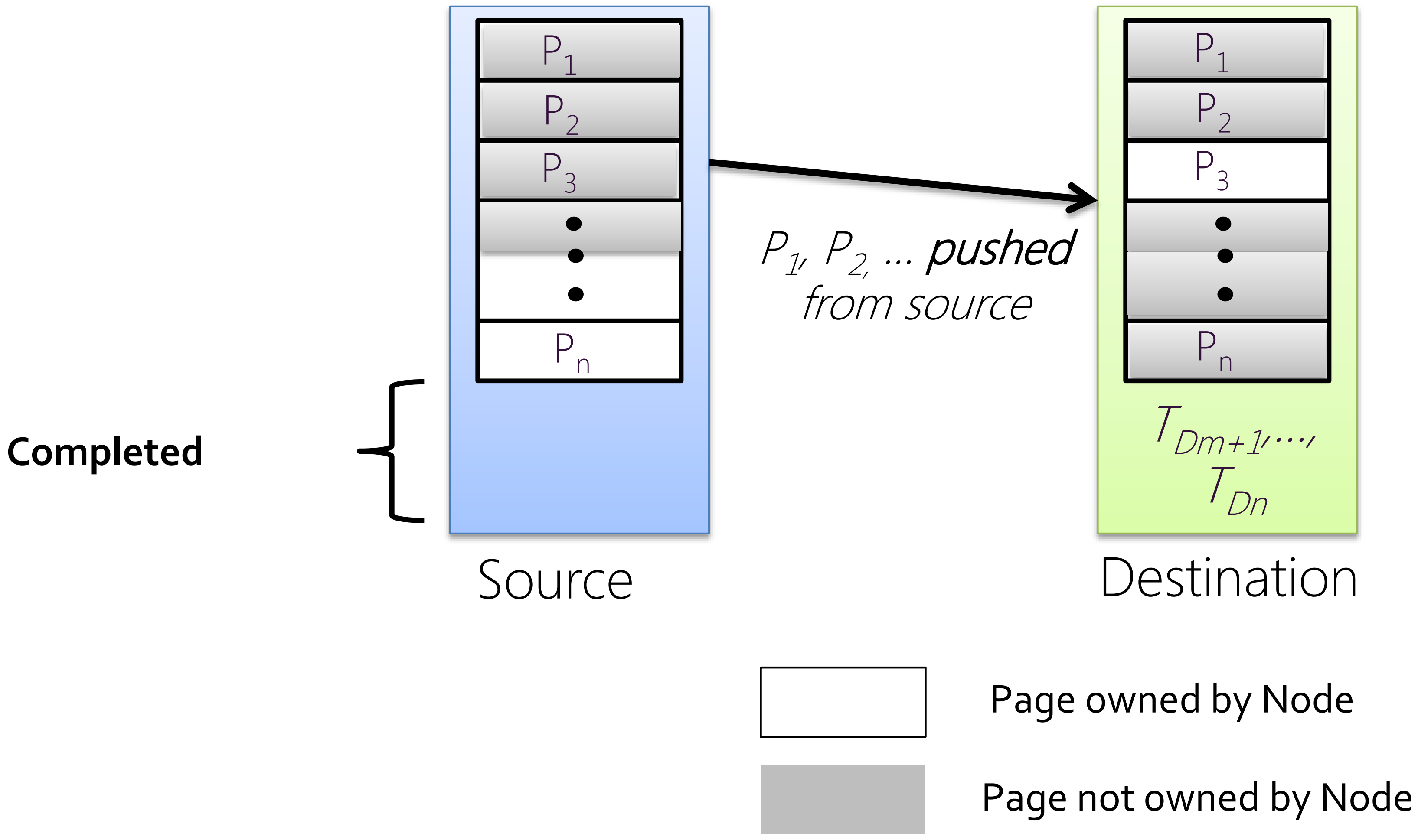


Index wireframes remain frozen



Finish Mode

Pages can be pulled by the destination, if needed



"Cut Me Some Slack": Latency-Aware Live Migration for Databases [Barker et al. EDBT 2012]

Focus

Interference aware live migration

Key Contributions

Throttles migration to minimize impact

Implementation with no internal modification

Slacker Approach

Uses hot backup to migrate

Snapshot, Recover, Delta Shipping, & Handover

Throttle using a linux pipe limiter & piping backup

Use a PID controller (feedback loop on latency)

ProRea – Live Database Migration for Multi-tenant RDBMS with Snapshot Isolation [Schiller et al. EDBT 2013]

Focus

Overcome some Zephyr shortcomings

Key Contributions

A proactive and reactive live migration

ProRea - Approach

Instead of 2PL based on SI

Proactively migrates hot pages

Reduced aborts from Zephyr

Implemented in PostgreSQL

In Closing

Many Other Issues

Pricing

Replication

- Swapping instead of migration [SWAT @ EDBT 2013]

Security / Privacy

Admission Control / Query Scheduling

Future Challenges

- Additional resource isolation controls
    - Query processing, buffer management, etc
- SLOs / SLAs
    - Workload or resource based
    - Multi-user (application, data scientist, developer, C-level)
- Data sharing
- Better workloads
- Analytics

Thanks!