Realizing value in shared compute infrastructures

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Doctoral thesis defense

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Nov. 18th, 2022

Carnegie Mellon
Parallel Data Laboratory

Talk outline

- Shared cluster environments + thesis statement
- 2 case studies: specializing application frameworks
- 2 case studies: from perspective of cluster operators
- Conclusion

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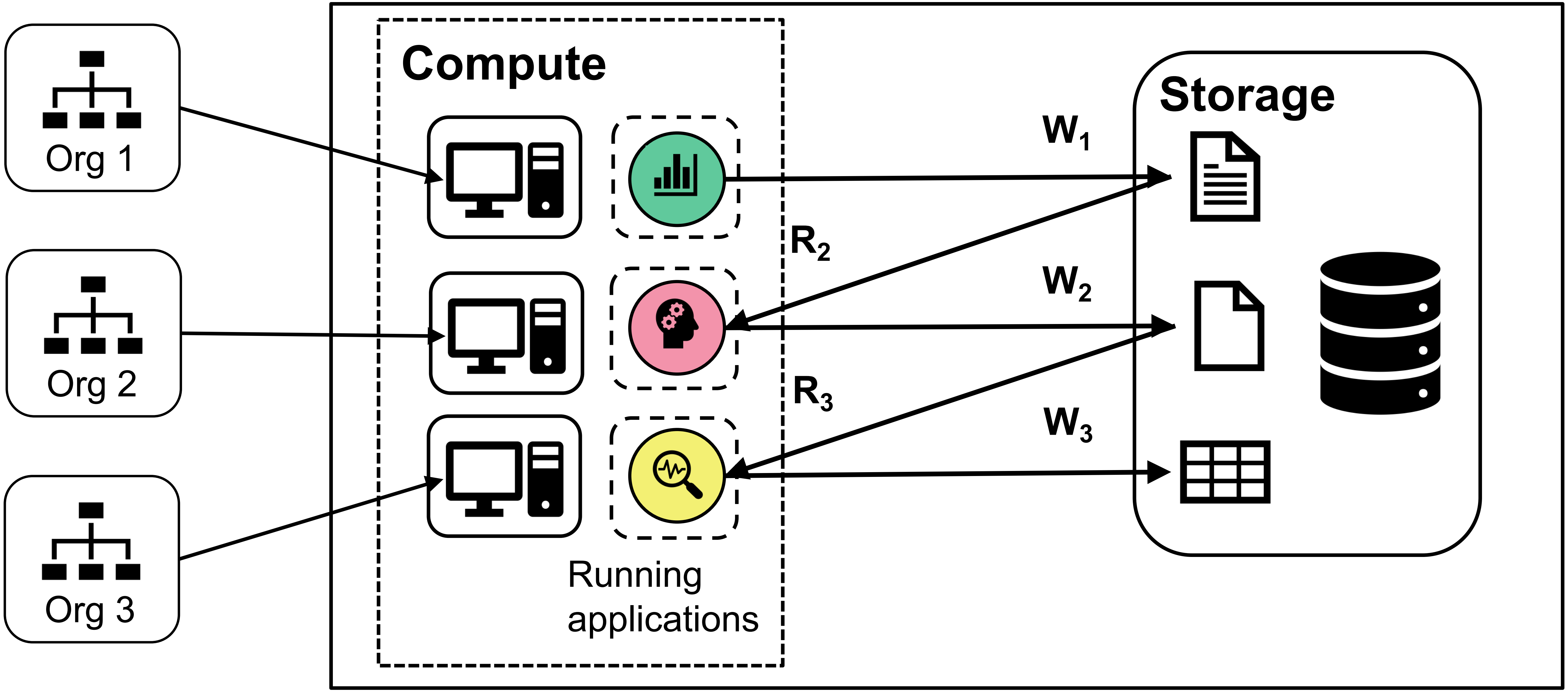
Shared cluster environments

- Highly heterogeneous resources and applications
  - Many users from various groups and organizations
  - Time varying load
- Examples of shared cluster environments:
  - Public clouds (AWS, Azure, GCE)
  - Private clouds (MS Cosmos, Google Borg)

Example: Shared cluster environment



User goals in shared clusters

- **Users:** Run applications in shared environment
  - Goal 1: Meet application business requirements
  - Goal 2: Minimize cost of meeting requirements
- Challenges:
  - Resource heterogeneity
  - Wide variety of pricing mechanisms

Cluster operator goals in shared clusters

- **Cluster operators:** Maximize profit & satisfy users
  - Goal 1: Prioritize resource allocation to applications
    - Using some notion of "user value"
  - Goal 2: Maximize "profit" = "value" achieved - costs
- Challenges:
  - Resource heterogeneity and availability
  - Hidden user values and performance requirements
  - Cluster capacity + cost management

Thesis statement

Value-realized in shared data environments can be improved both by value- and dependency-aware resource management systems from cluster operators and by cost- and heterogeneity-aware applications from users.

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Application-specific resource acquisition: Case studies

1. Elastic web services
   - Spot-dancing for elastic services with latency SLOs
   - Tributary [USENIX ATC 2018]
2. General containerized batch task scheduling
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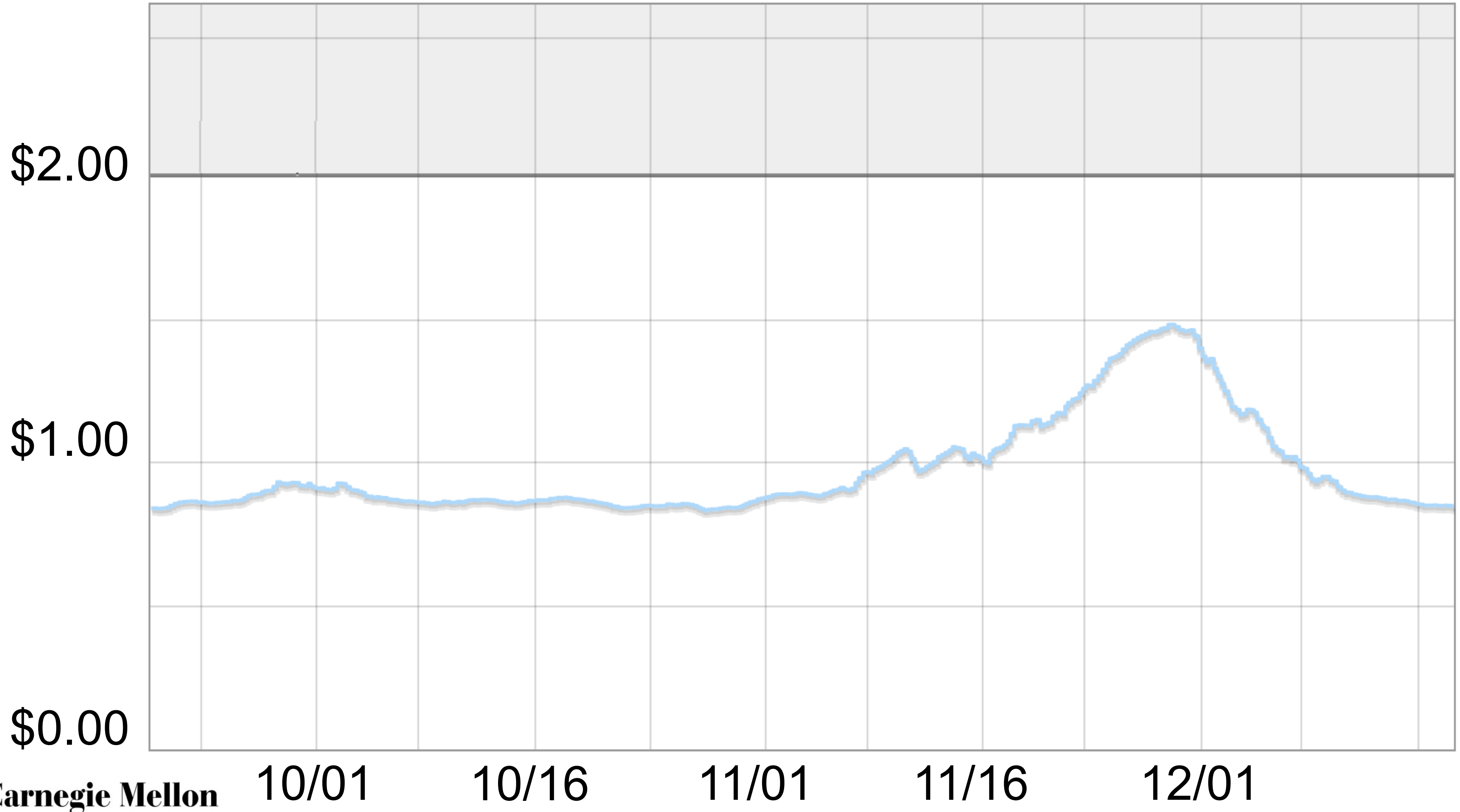
More background: Public clouds

- Public clouds offer a variety of resources
  - e.g., varying compute capacity, storage, HW accelerators
- Under different types of contracts
  - e.g., reliable, transient, and burst
- Difficult for users to choose resources cost-effectively!

Achieve user value through:
Application-specific, cost-aware resource acquisition

Transient/spot instances in AWS

Adv: Often > 50% cheaper vs on-demand, *refund if revoked in 1st hr*



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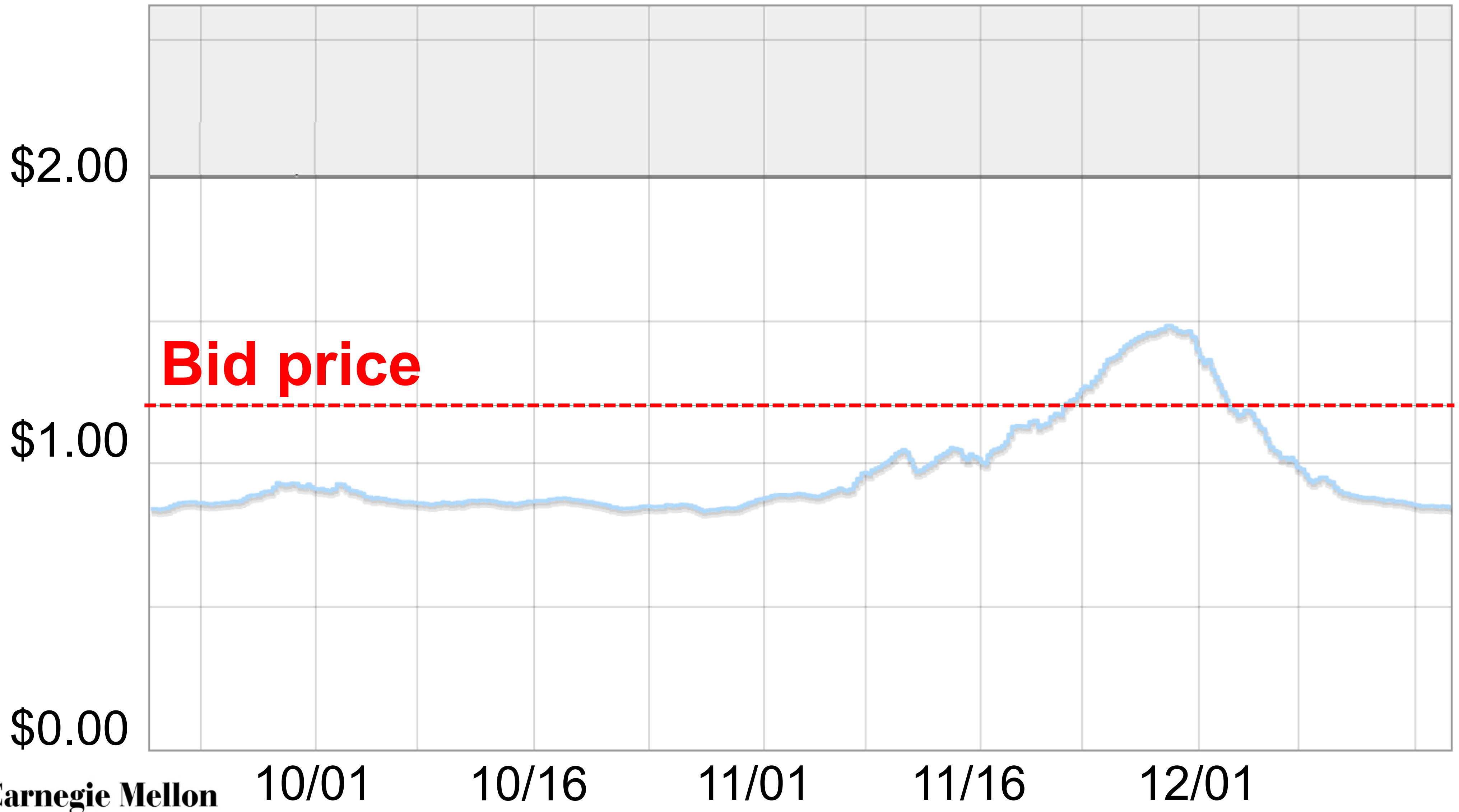

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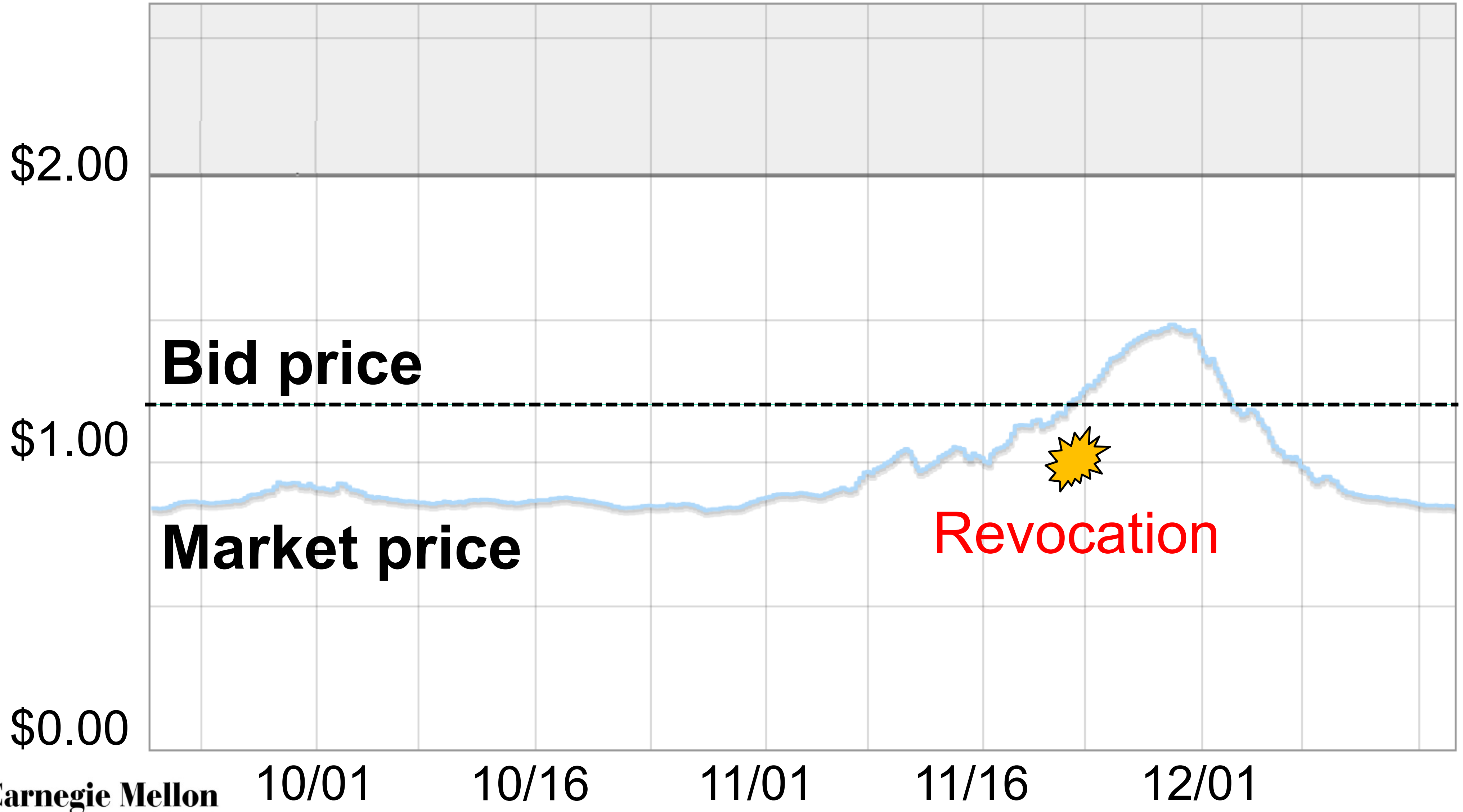

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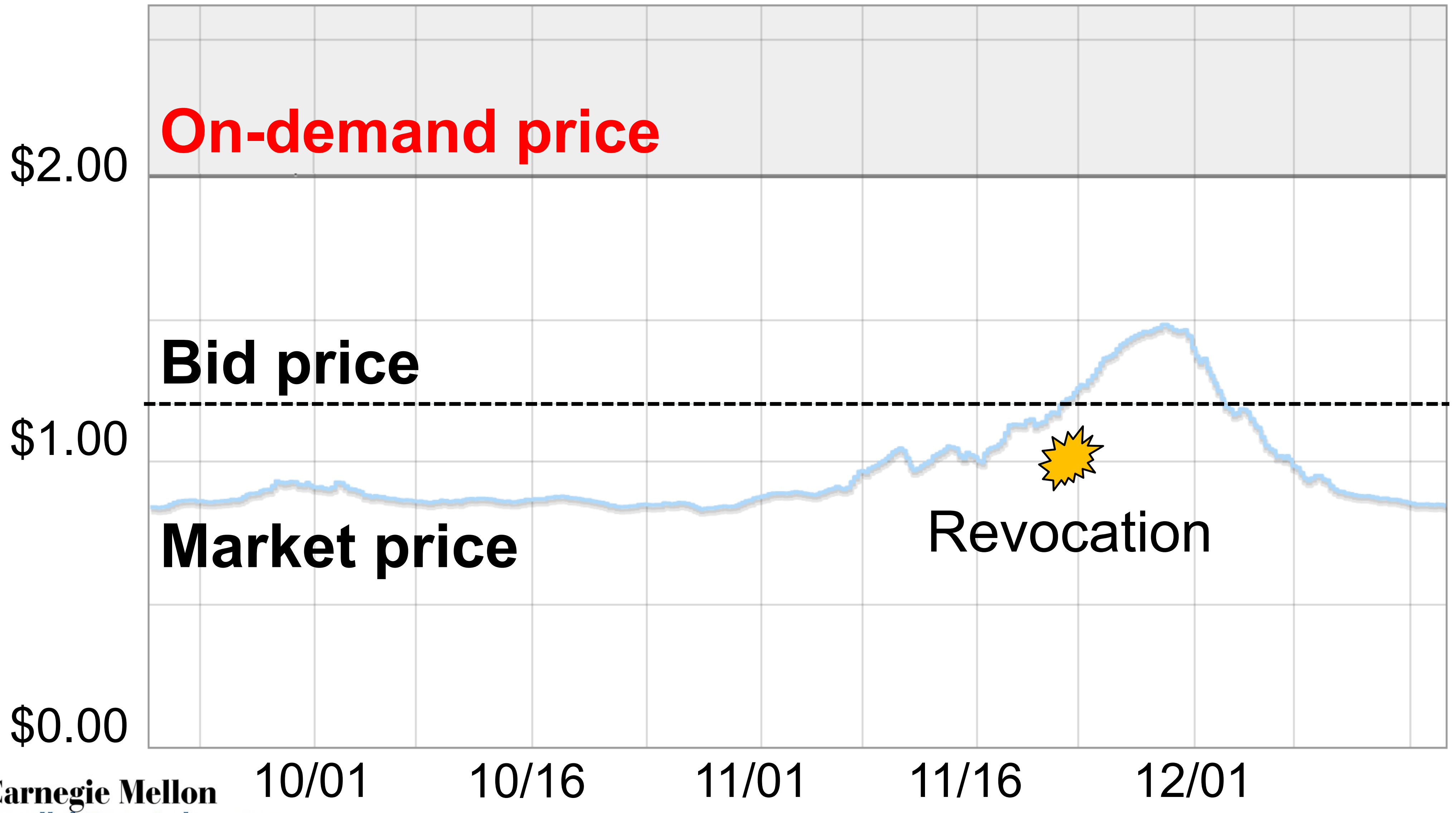

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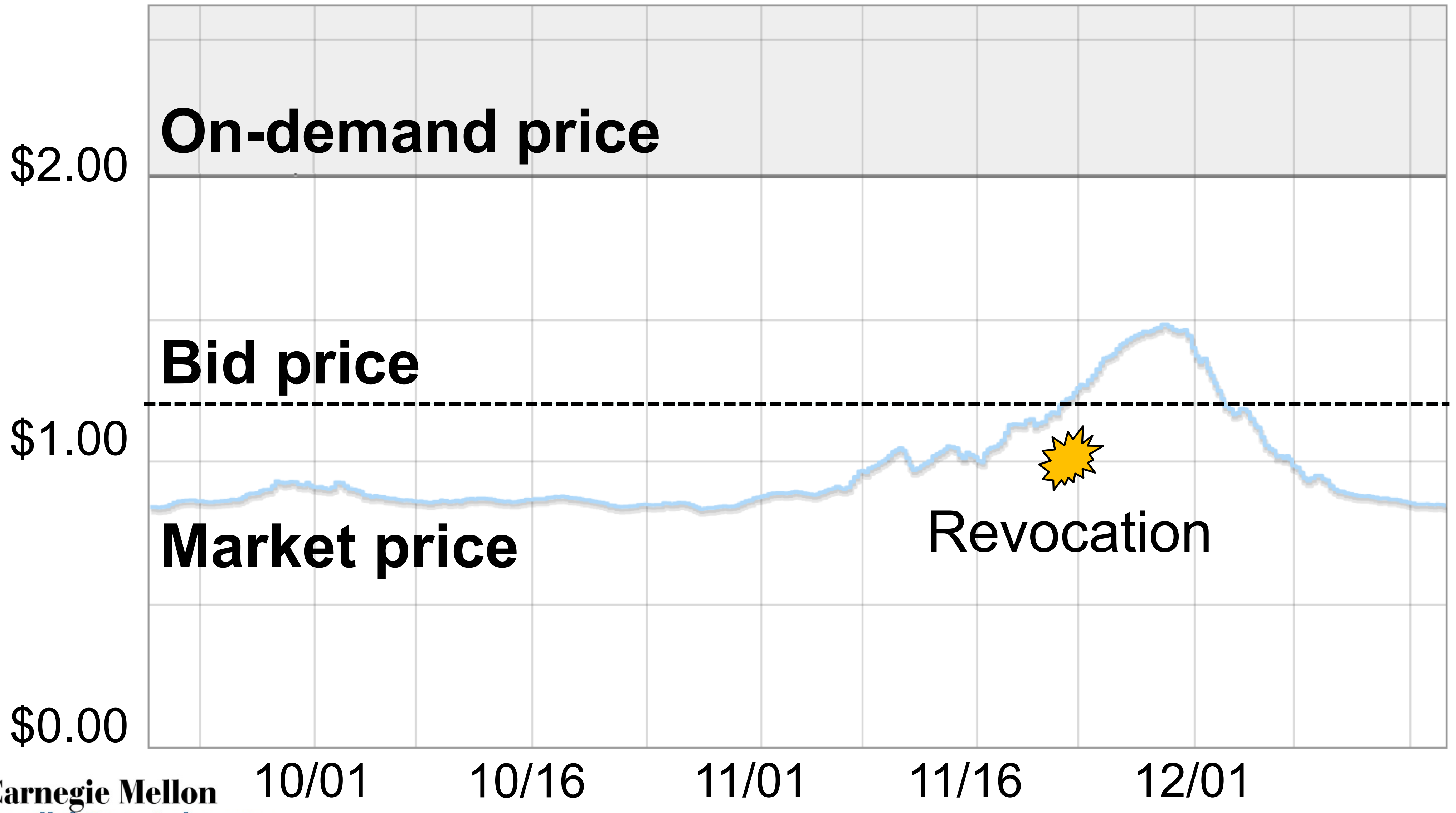

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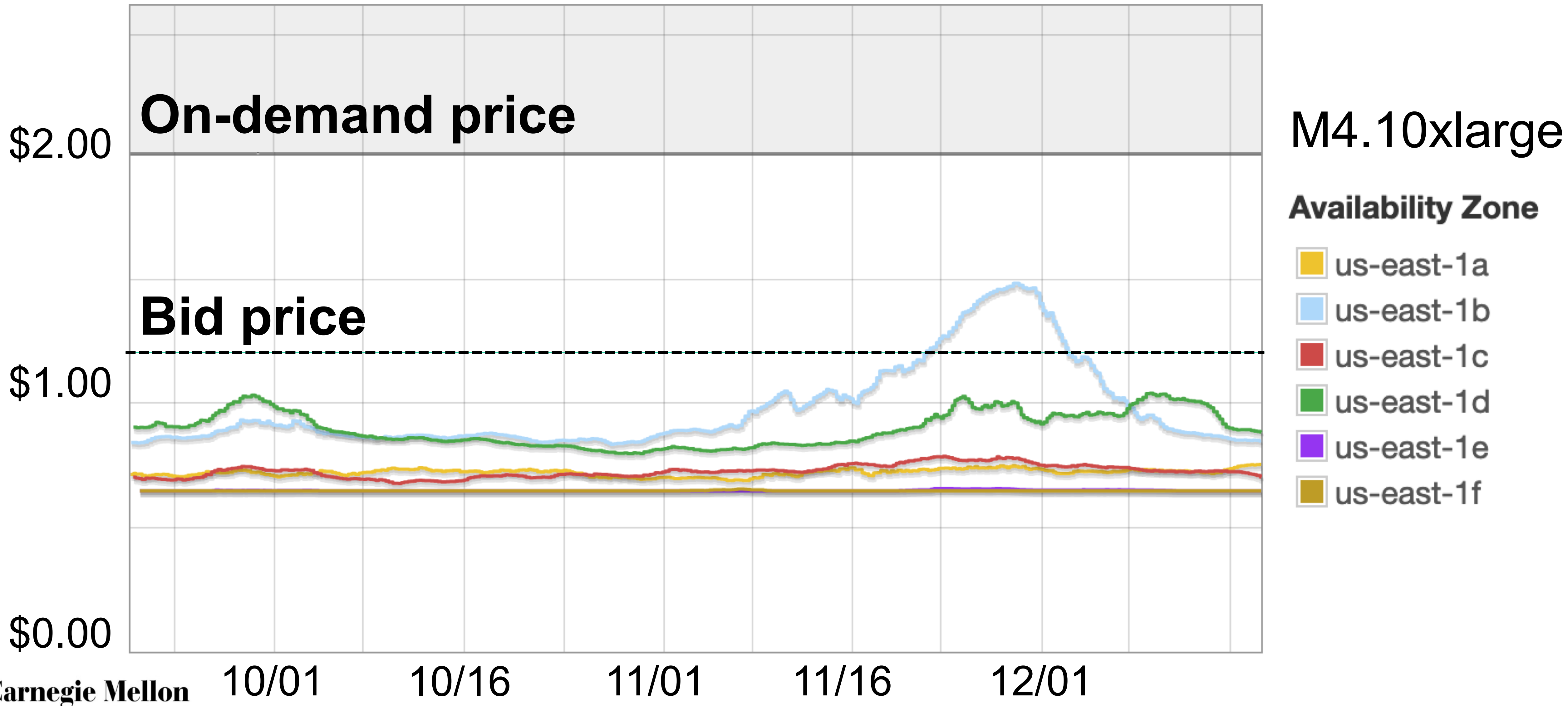

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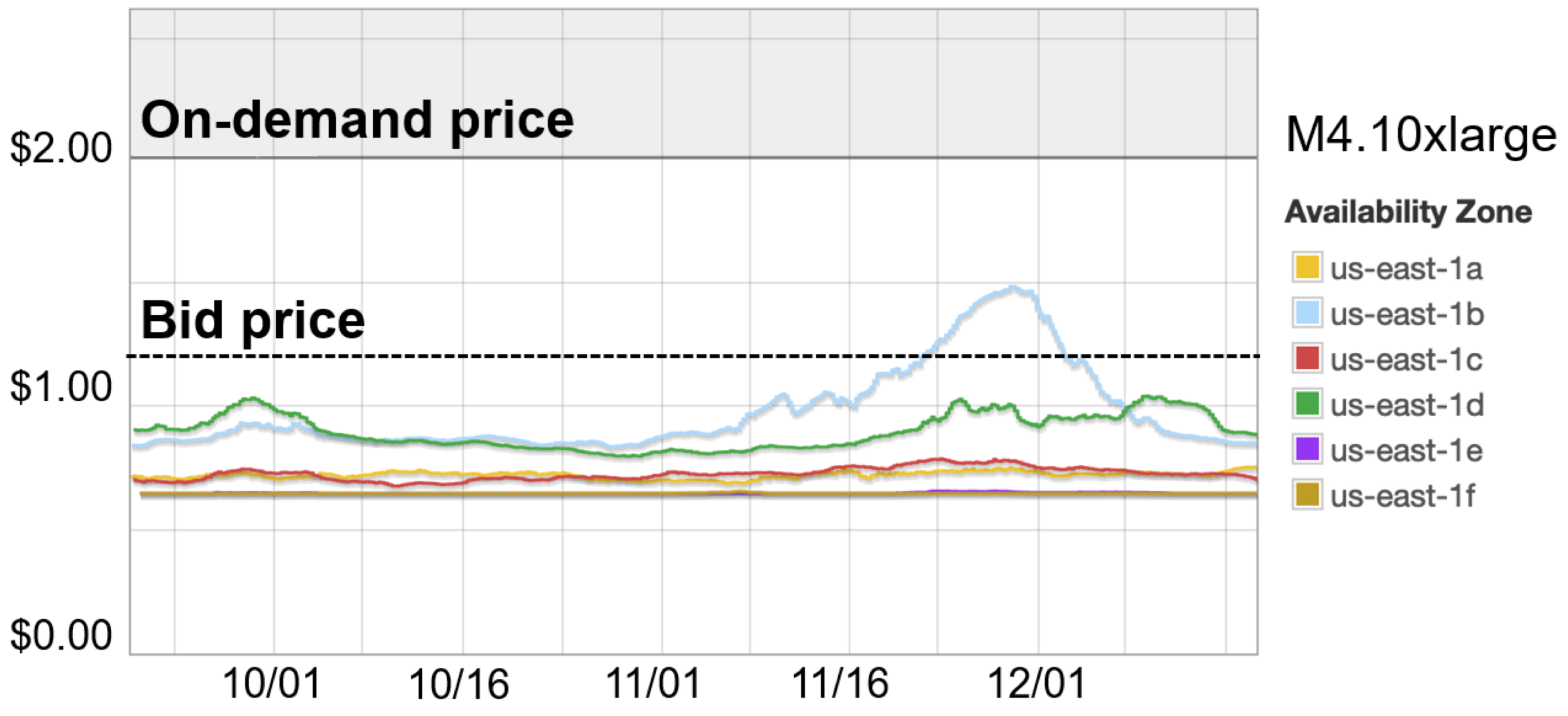
Elastic web services & spot instances

- Elastic web services
  - Manage a pool of VMs to serve client requests
  - Need to meet latency SLOs (e.g., request within X ms)
  - Stateless services (Tributary's focus) allow quick scaling
- Spot instances *cheaper but riskier* than on-demand:
  - Instances can be revoked, leading to missed SLOs

Tributary embraces risk associated w/ spot instances to achieve lower cost while meeting SLOs

Exploiting spot resources

- Naïve selection of spot → bulk revocations
  - Large alloc of low cost → low # of VMs left if price spikes
- Observation: Spot market prices not too correlated

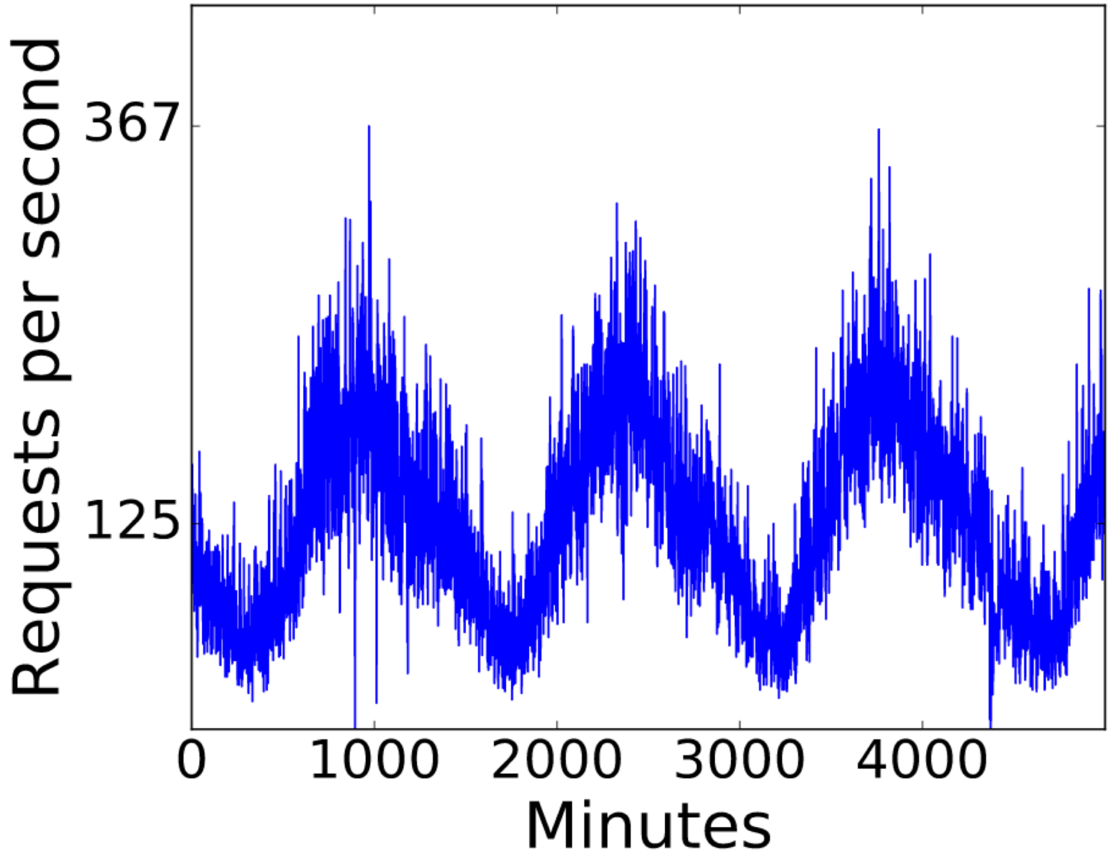


Tributary strategy

- Selects resources from multiple spot markets
  - Exploit pricing low or non-correlation
- Uses different bids within the same spot market
  - Higher/lower bid → less risk/more partial-hours
- ML-based prob model → extra resources acquired
  - Added benefit: soaks up unexpected spikes in requests
- Expected cost w.r.t. SLO
  - Cost offset by lower cost VMs and free partial hours

Tributary experimental setup

- 4 real world internet traces
  - Show Clarknet
- Compare vs 3 systems
  - AWS AutoScale shown
- AWS AutoScale:
  - Acquires lowest cost
  - Bid on-demand price



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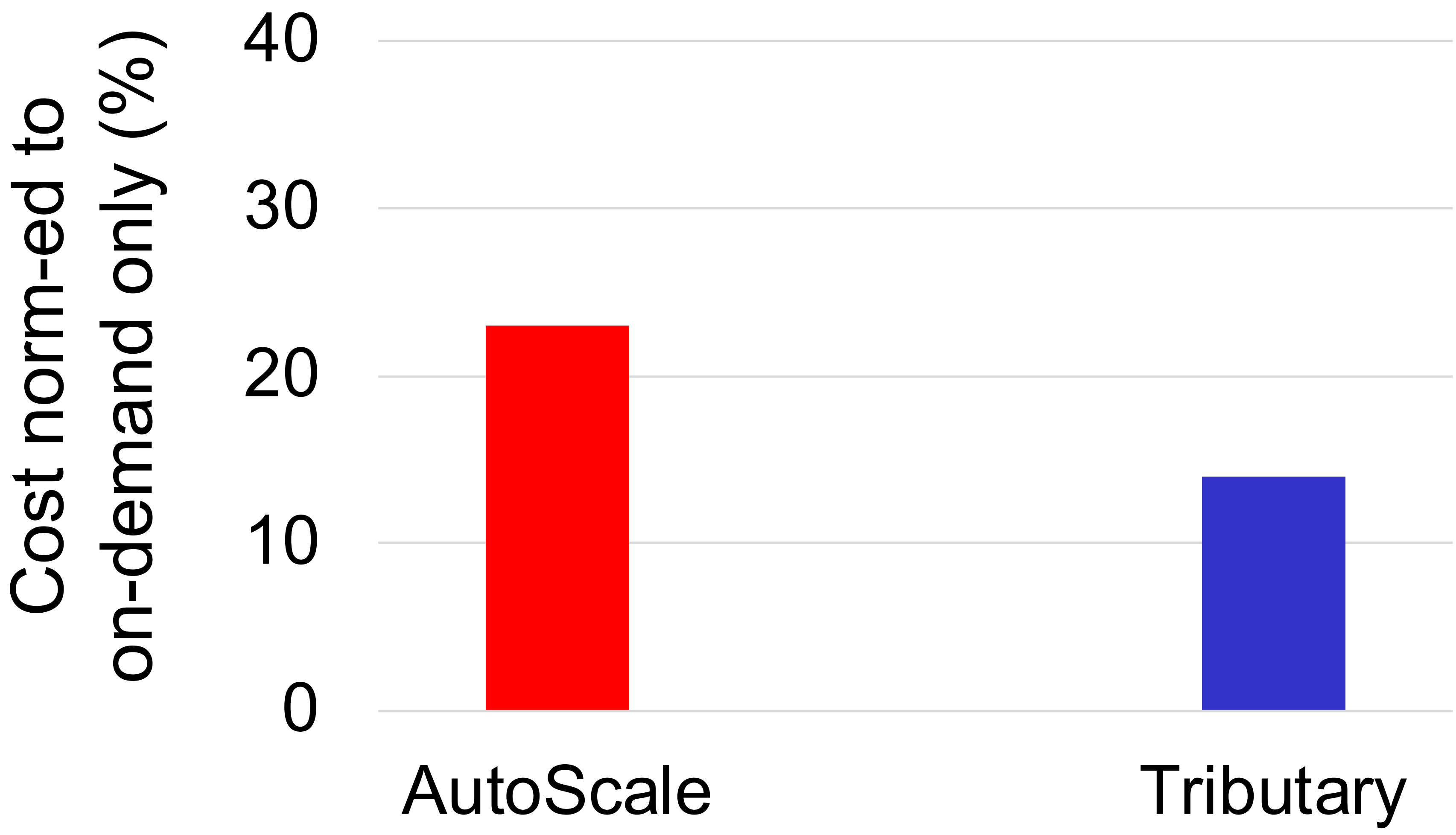
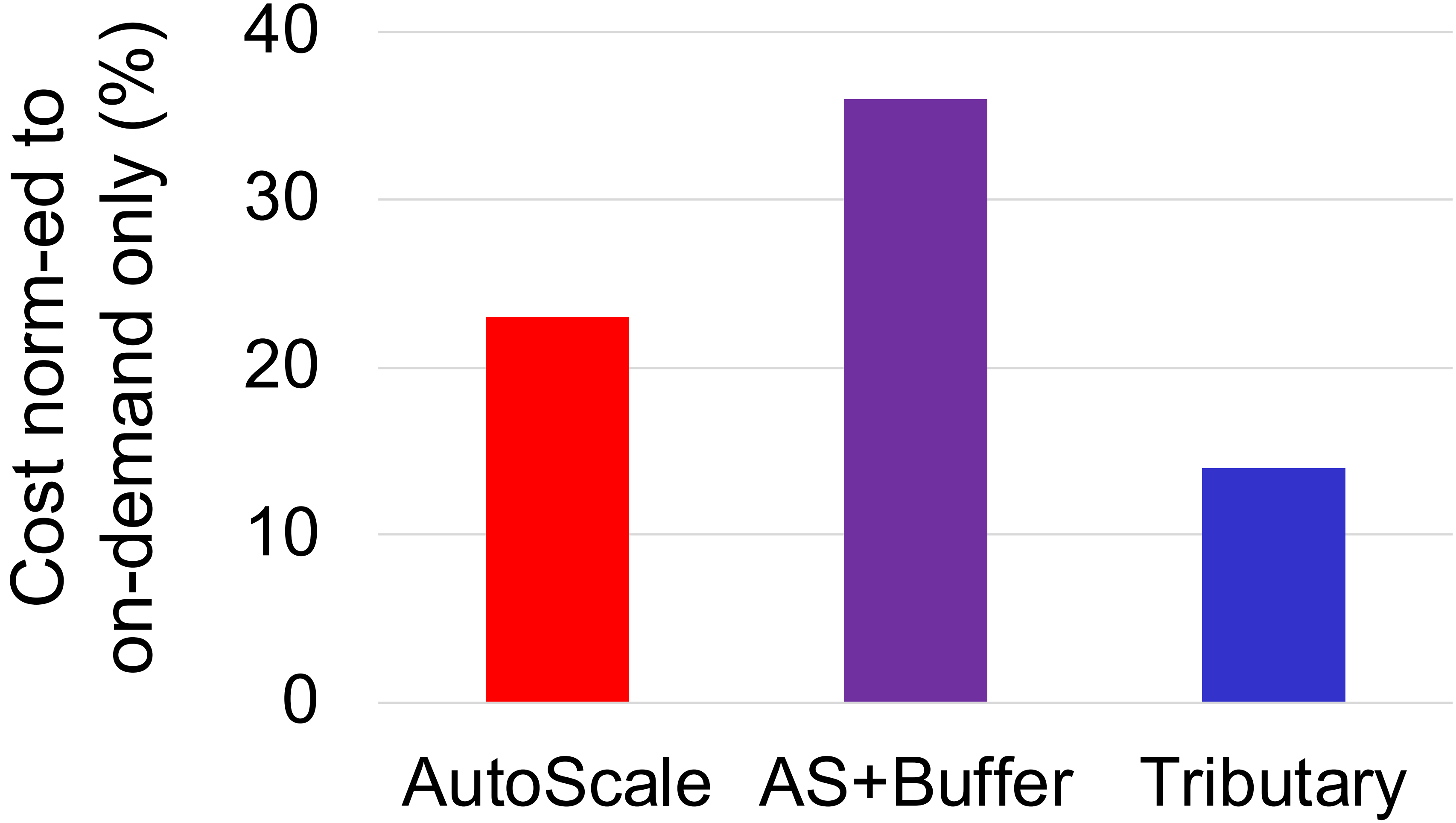
Tributary experimental results

- Tributary 40% lower cost, 60% less reqs violating SLO



Tributary experimental results

- Tributary 40% lower cost, 60% less reqs violating SLO
- AutoScale costs 60% more vs Tributary to match SLO attained



Tributary takeaway

- Diversified resource pools mitigate revocation risk
  - Prob model → diverse + extra resources → SLO attained
  - Considering expected cost + partial-hours → lower cost
- Reduces cost vs compared systems

Application-specific resource acquisition: Case studies

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Background and motivation

- Virtual cluster (VC) scheduling:
  - Schedule containerized batch tasks on to rented VMs
  - Different from traditional cluster scheduling:
    - Add/remove VMs any time → dynamically sized
    - VC can be highly heterogeneous

Diverse offerings + VC elasticity to lower cost of executing batch workloads

Stratus

- Stratus: Sched middleware that sizes VC + place tasks
- Goal: Lower cost of executing batch workloads
- Key: Wasted resource-time is wasted money
  - VMs should be highly utilized while rented
  - Use cost-efficient resources

Runtime binning: Pack tasks of similar runtime on to VM

Aligning runtimes: Runtime binning

- Runtime bins: *Logical* groups of tasks and VMs
- Idea: Tasks w/ similar predicted run times on same VM
  - Pluggable task run time predictor
  - VM highly utilized while rented → high tasks per dollar

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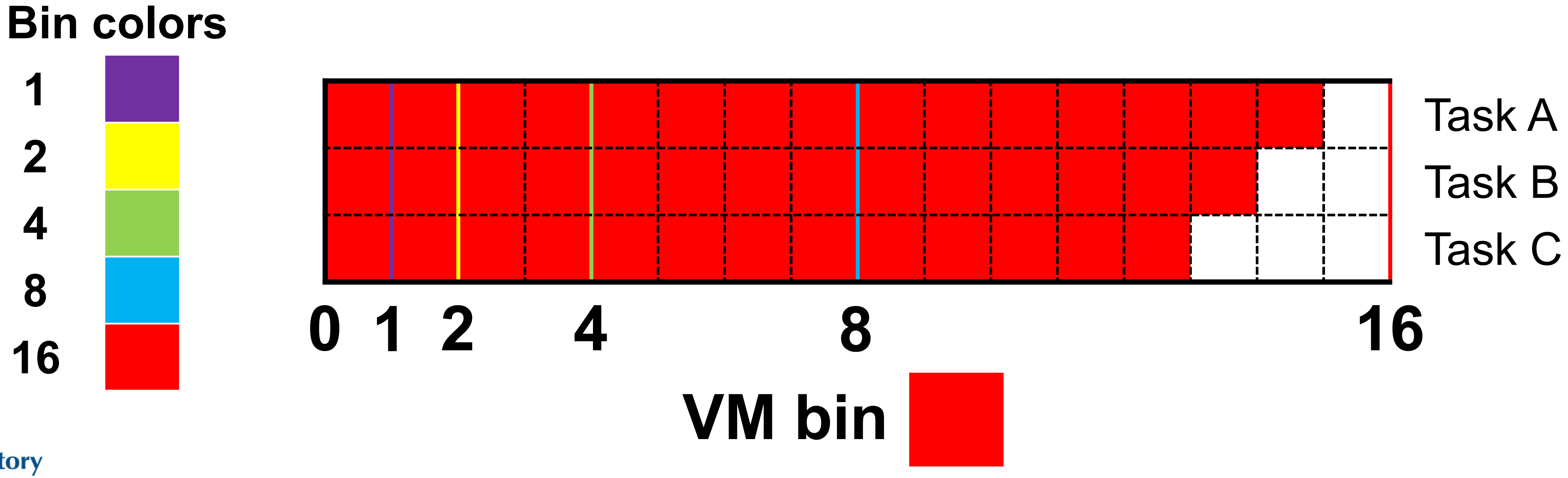

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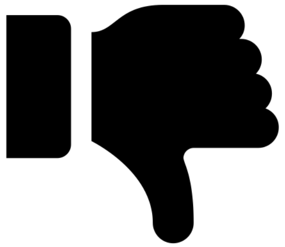
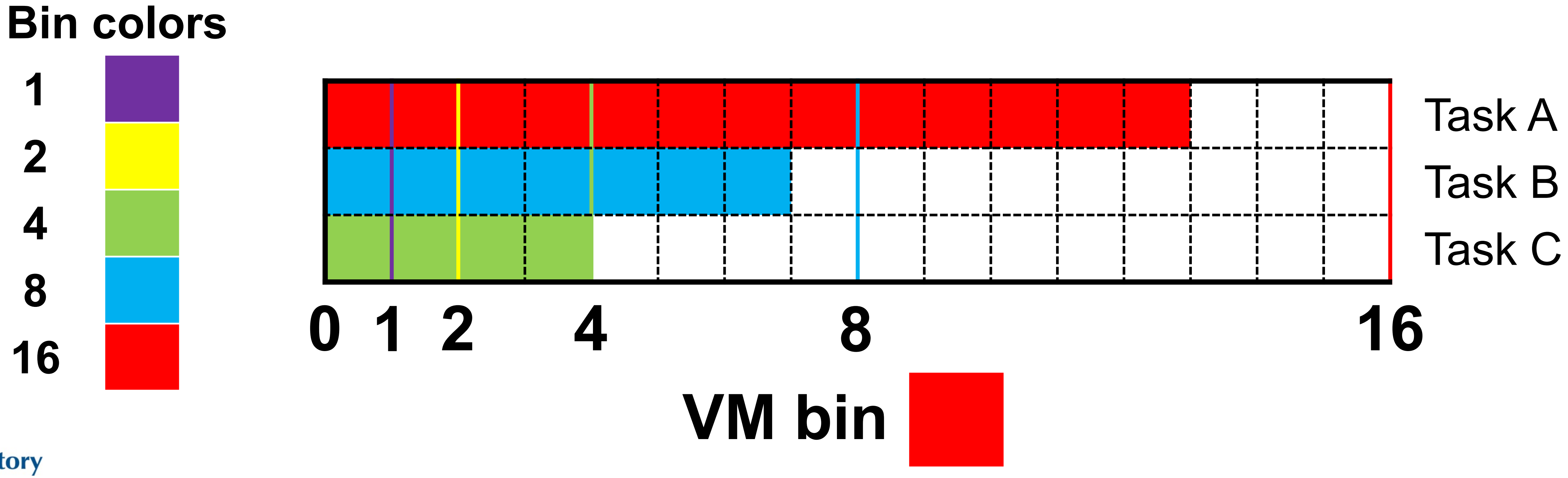


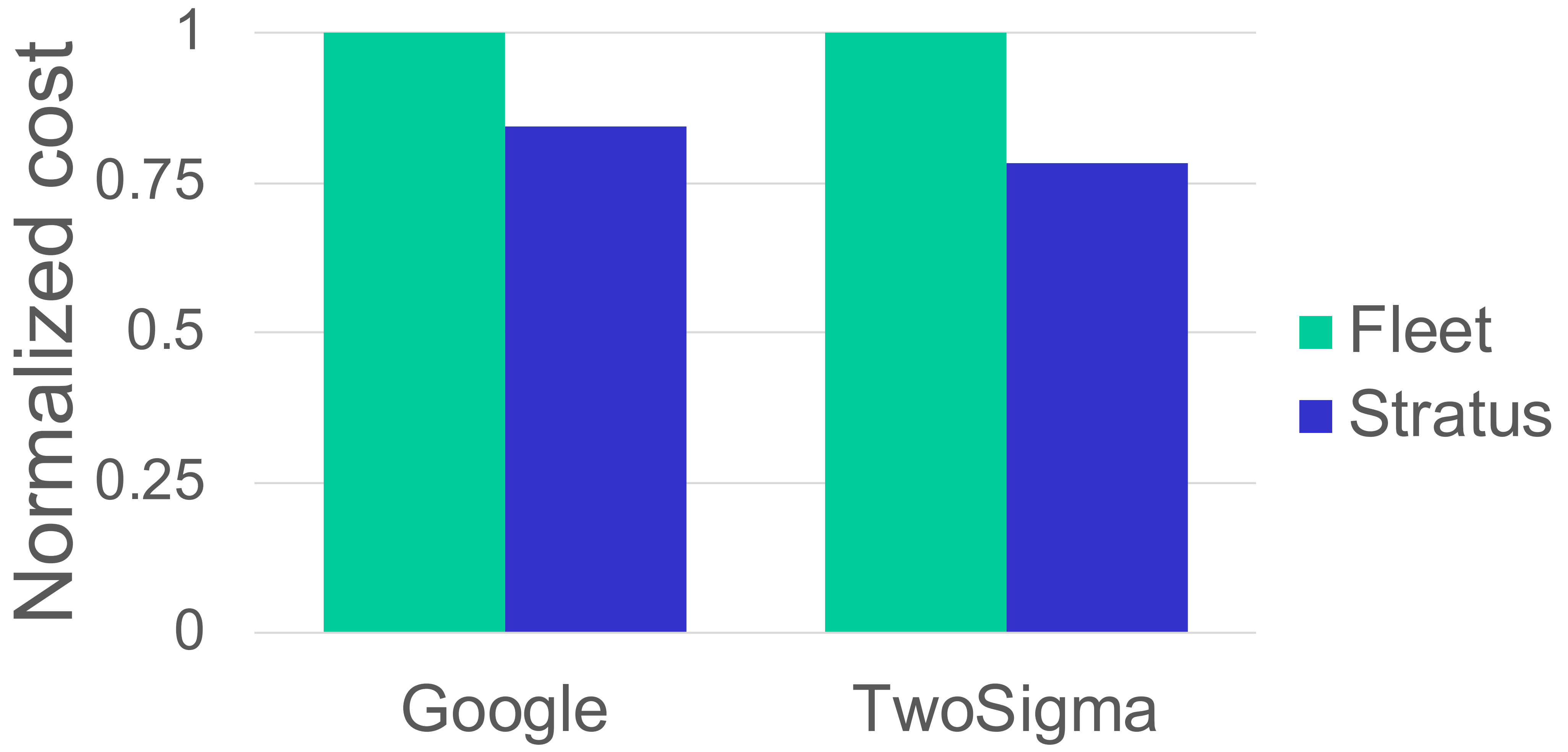


Experimental setup

- Simulation-based experiments
  - Google and Two-Sigma cluster traces
- Focus on batch analytics jobs
- Spot market traces for dynamically priced VMs
  - Always bid on-demand price – little to no preemptions
- Compare against Fleet: SpotFleet + ECS (AWS)
  - SpotFleet: Scaling based on policies
  - ECS: Packing containers on to VMs

Stratus vs Fleet

- Fleet: SpotFleet + ECS (Amazon offerings)
- Stratus reduces cost by 17% (Google) and 22% (TwoSigma)



Stratus takeaway

- Runtime binning → high VM utilization during rental
- Simultaneous consideration of scaling, packing, and cost-per-resource leads to reduced cost

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Cluster-operator resource management: Case studies

1. Scheduling to increase attained utility in cluster
   - Unearthing inter-job dependencies for better scheduling
   - Wing [USENIX OSDI 2020]
2. Load-shifting to reduce cluster operation costs
   - Reducing costs with dependency-informed load-shifting
   - Talon [Submission-prep]

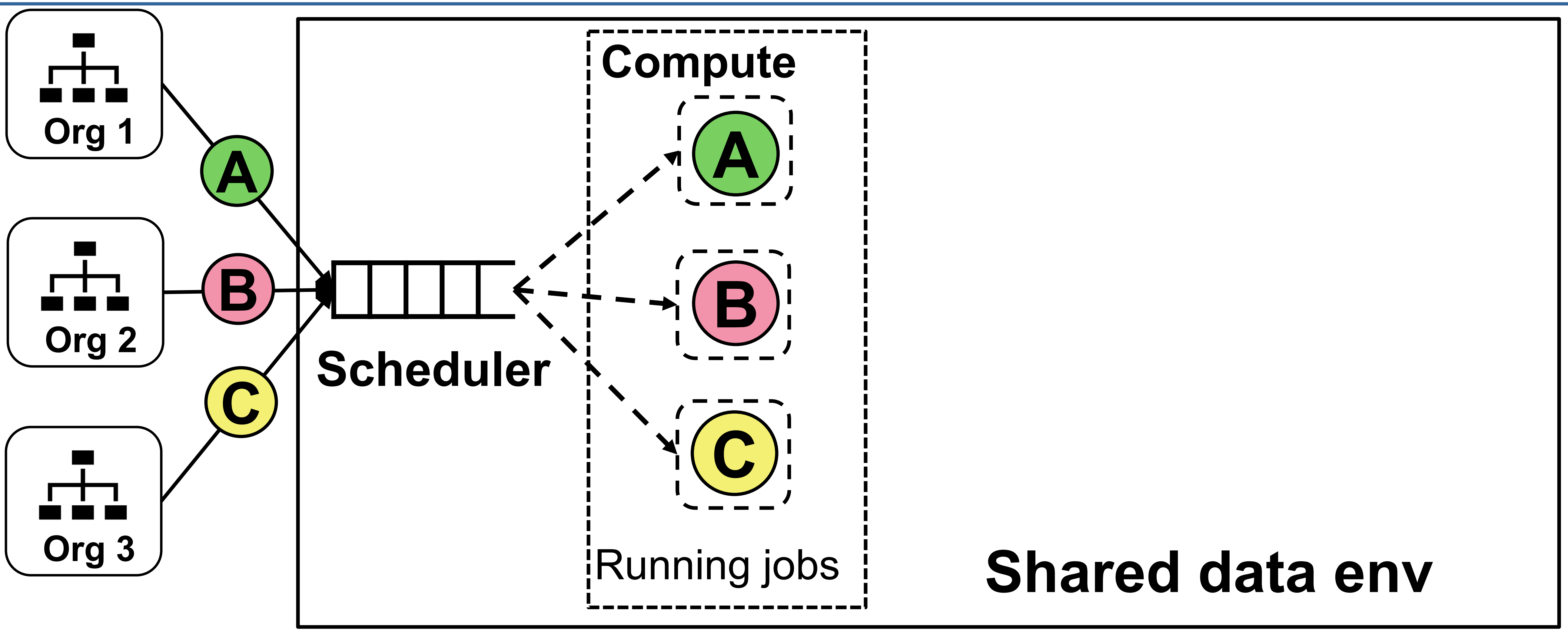
Background: Cosmos

- Microsoft's internal data analytics platform
- Multiple multi-tenant clusters
  - Tens of thousands of nodes each
  - Shared by many teams and orgs
  - Primarily SCOPE jobs
    - Batch analytics jobs similar to Spark/MapReduce
    - 80% resource-time

Background: Inter-job dependencies

- Inter-job dependencies:
  - Occur when job dep on output of earlier job as input
  - Pervade shared envs, but ignored in resource mgmt
- GDPR enables inter-job dependency analysis
  - Untapped opportunities
  - Wing (discussed later) first to analyze in large cluster
    - Forms basis of next two case studies

Shared data environments



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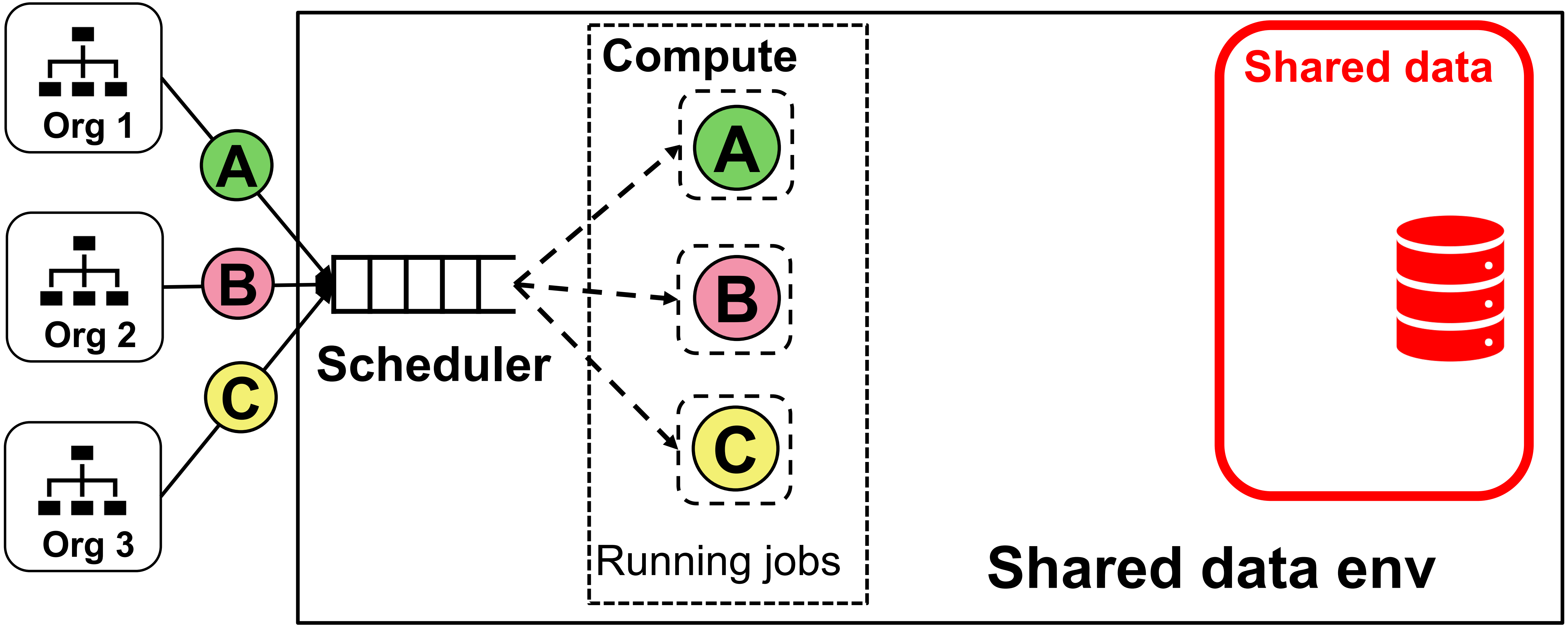

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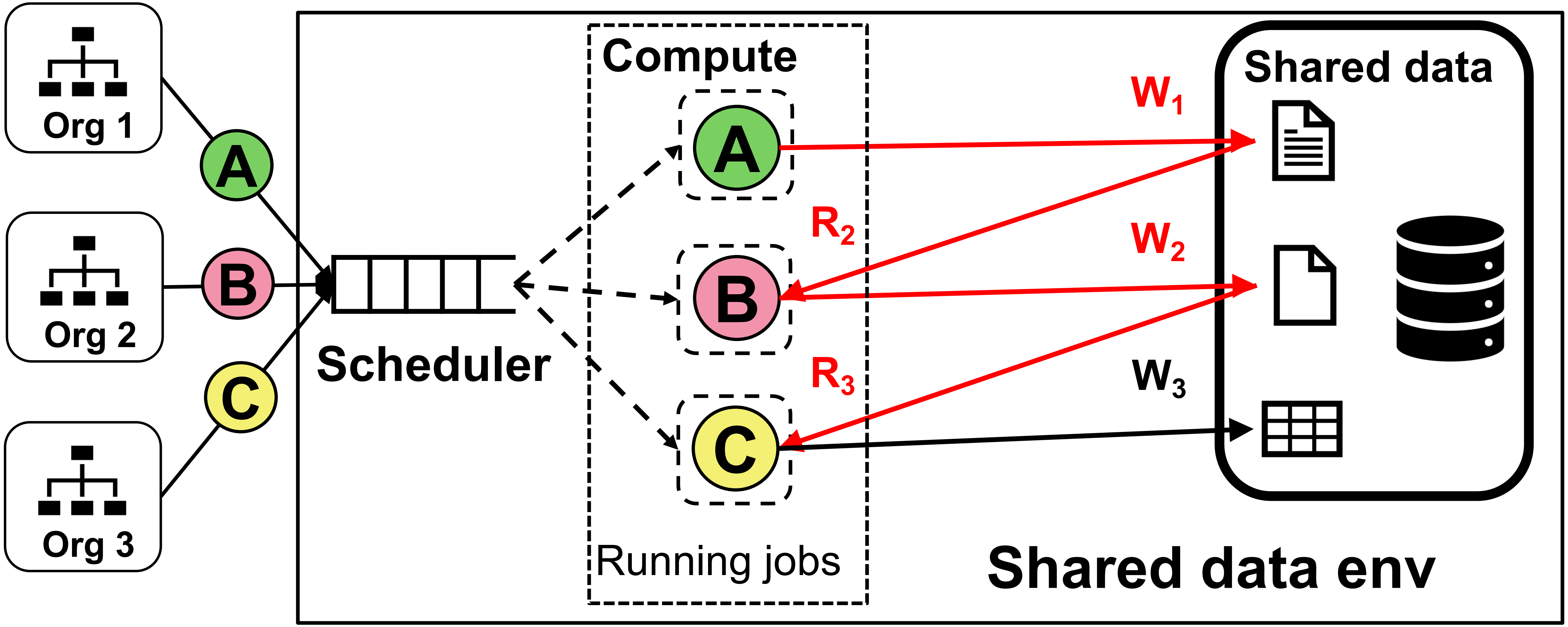


C depends on B depends on A

Data from a Cosmos cluster

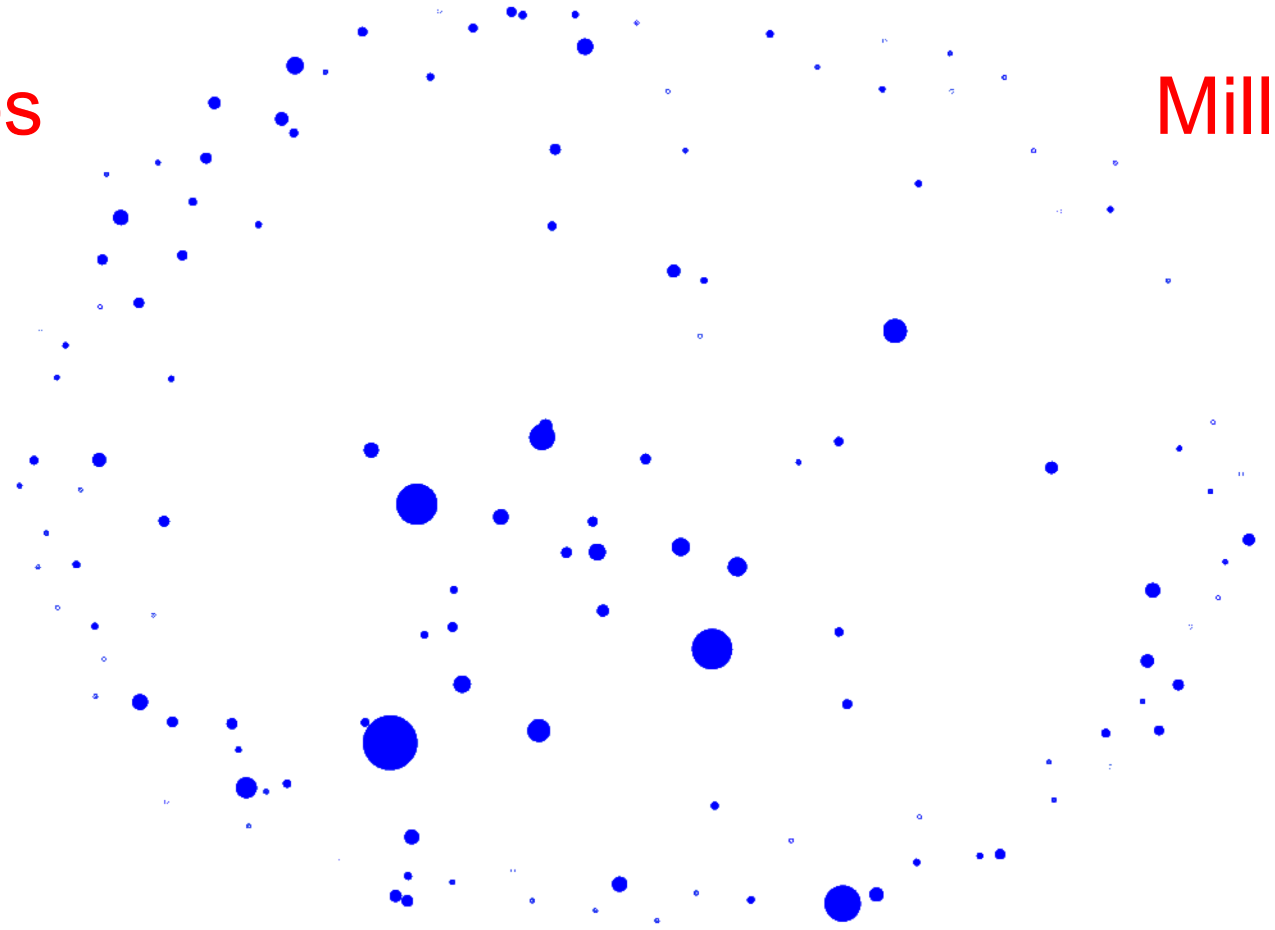
100s of hierarchical queues (teams)

40k+ daily jobs

Millions of daily tasks

50k+ servers

TBs of job + data prov logs daily



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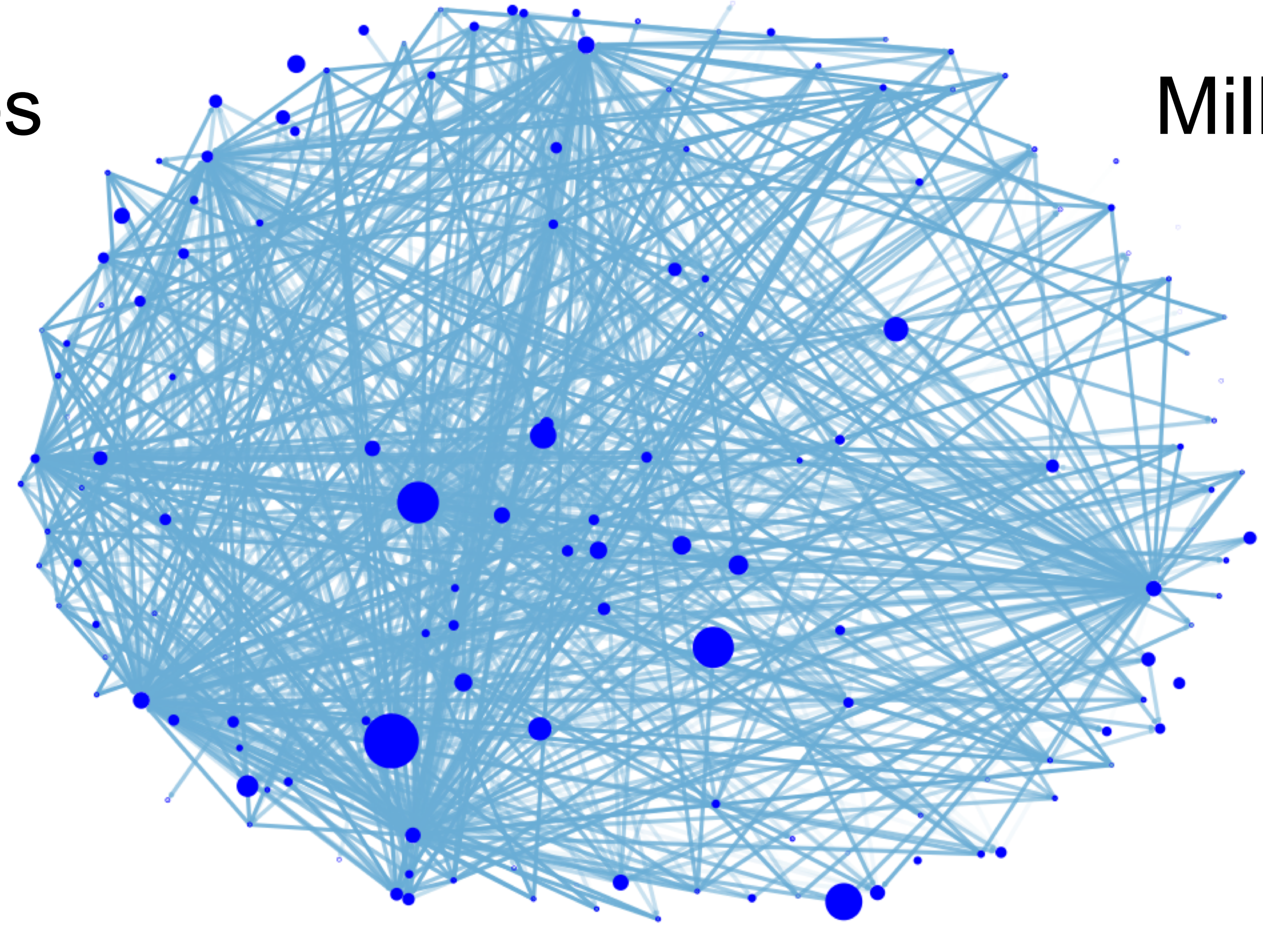

160k+ daily inter-job dependencies

68% jobs recurring

95% of queues inter-dependent

80% jobs depend on other jobs

Cluster-operator resource scheduling: Case studies

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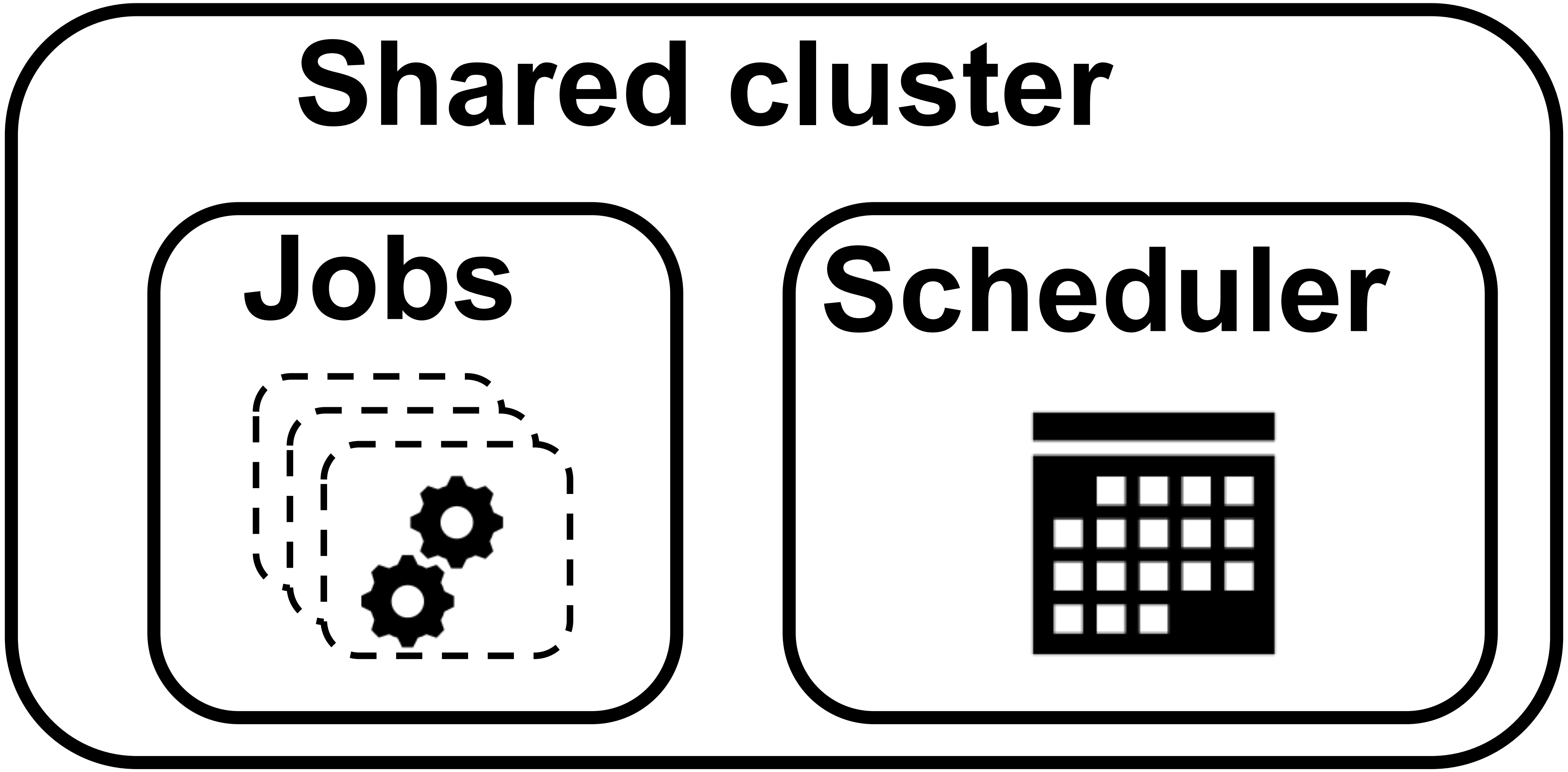
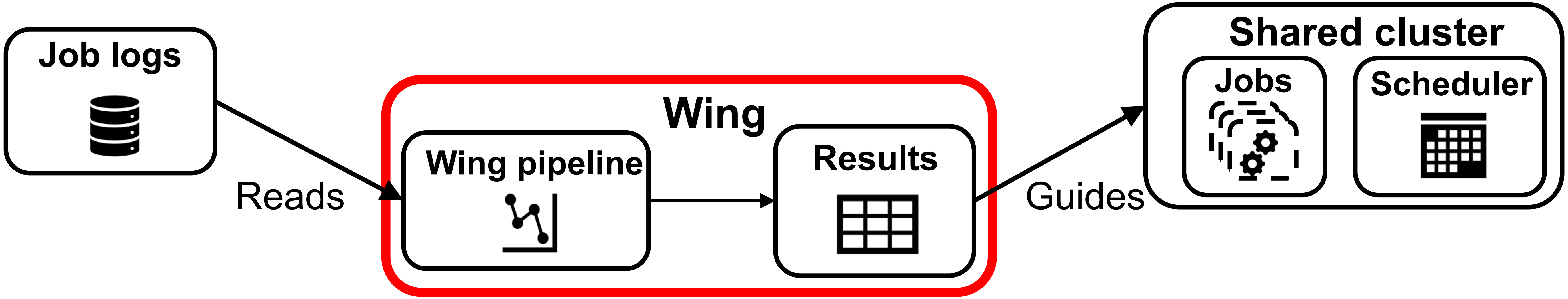
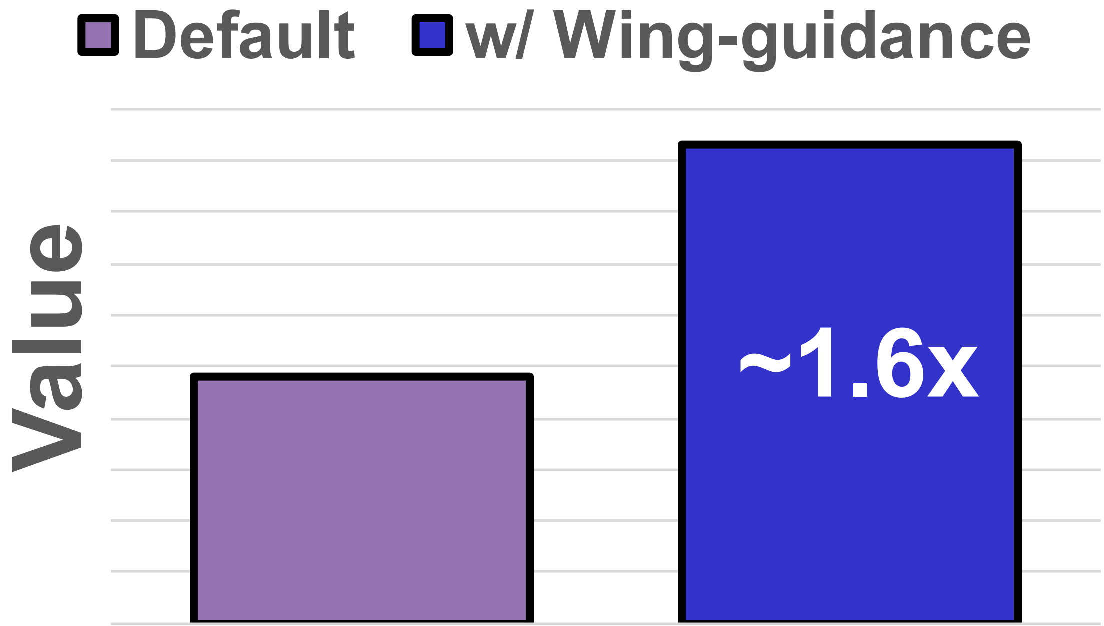
Wing summary



Wing summary





Wing: Scheduling for value with inter-job dependencies

Problems when not considering deps

Inter-job dependencies pervade data envs, but are ignored in resource management

Problems when not considering deps

Inter-job dependencies pervade data envs, but are ignored in resource management

↓

Missed deadlines, wasted resources, and untapped opportunities

We can fix this, with recurring and predictable inter-job dependencies

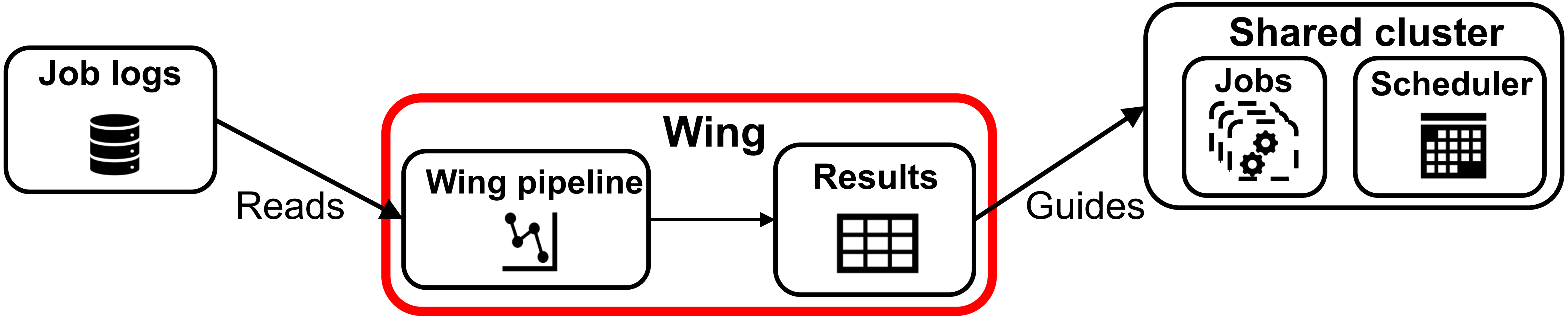
Towards addressing inter-job deps

Wing

Discovers + analyzes inter-job dependencies from data provenance

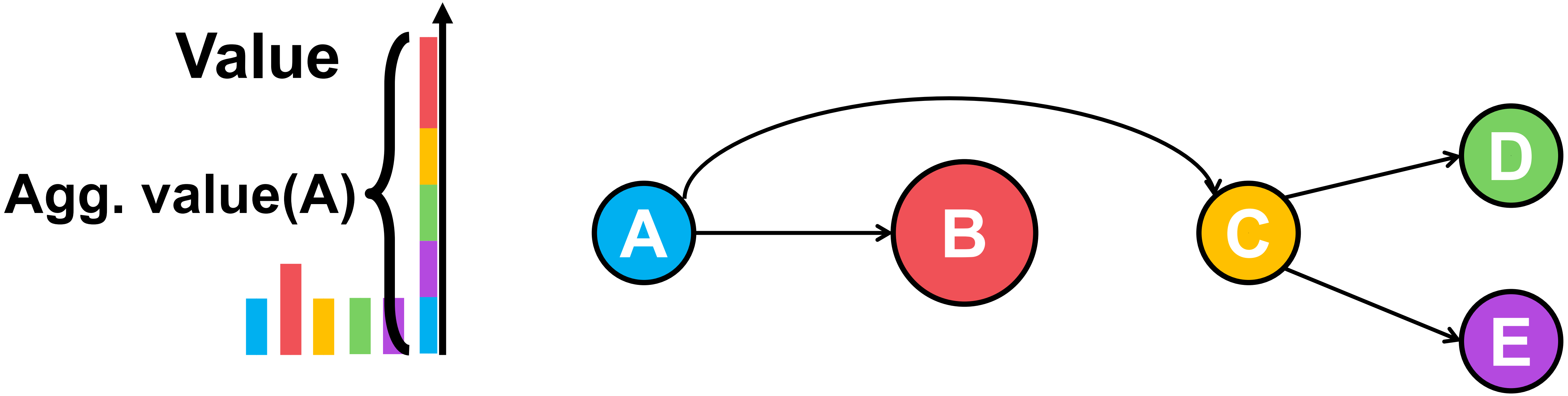
Scheduling with Wing guidance

Scheduling that prioritizes the most value-impactful jobs, informed with historical recurring inter-job dependencies



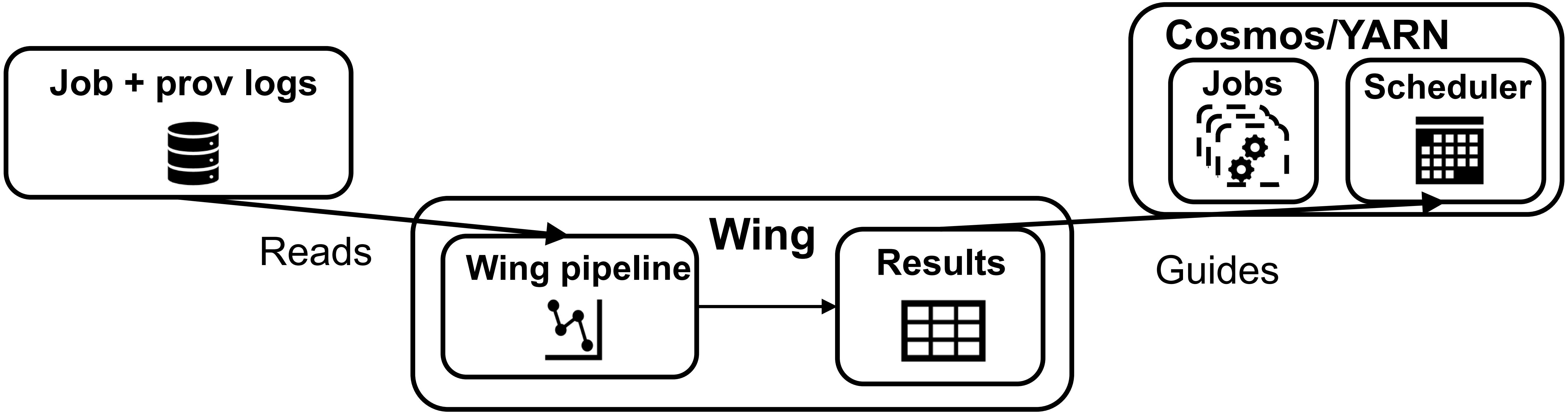
Job value & inter-job dependencies

- Failing/finishing jobs late can impact downstream jobs
- Wing analyzes the aggregate value (impact) of jobs



Wing-Agg: Wing-guided scheduling

- **Goal of value scheduling**: Achieve most value given workload
- **Wing-Agg**: YARN's prio-based sched + Wing-guidance
  - Prioritize recurring jobs with high aggregate value efficiency

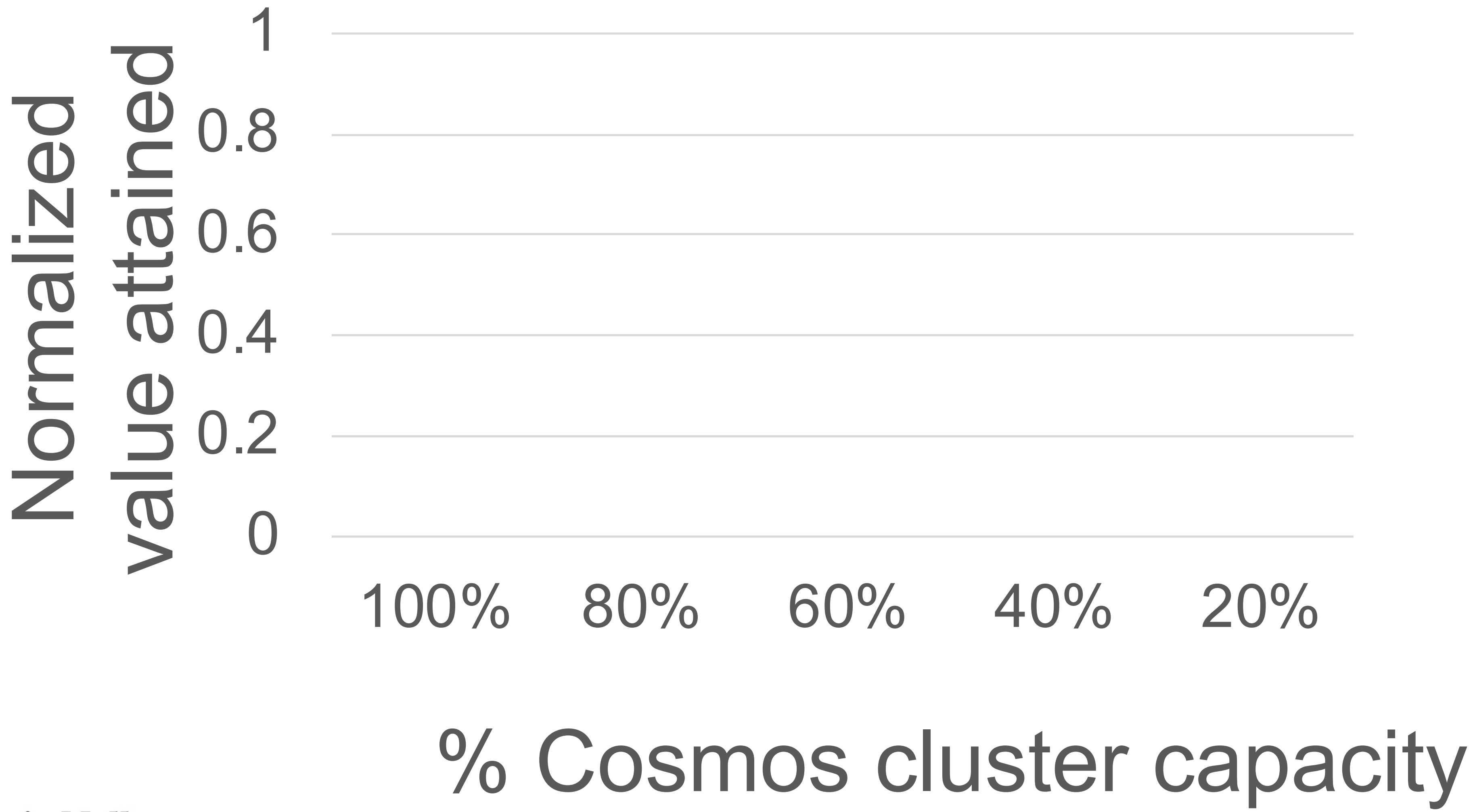


Experimental setup

- Trace-driven simulations on real cluster traces
  - Preserves inter-job dependencies and properties
- Goal: Attain more value from the same workload
  - Value metric: Total file output downloads attained
- Experiments at various cluster sizes (capacities)
  - To simulate resource-constrained clusters

Value-attainment

- **Wing-Agg**: Prio as historical **agg** value / **agg** compute



Value-attainment

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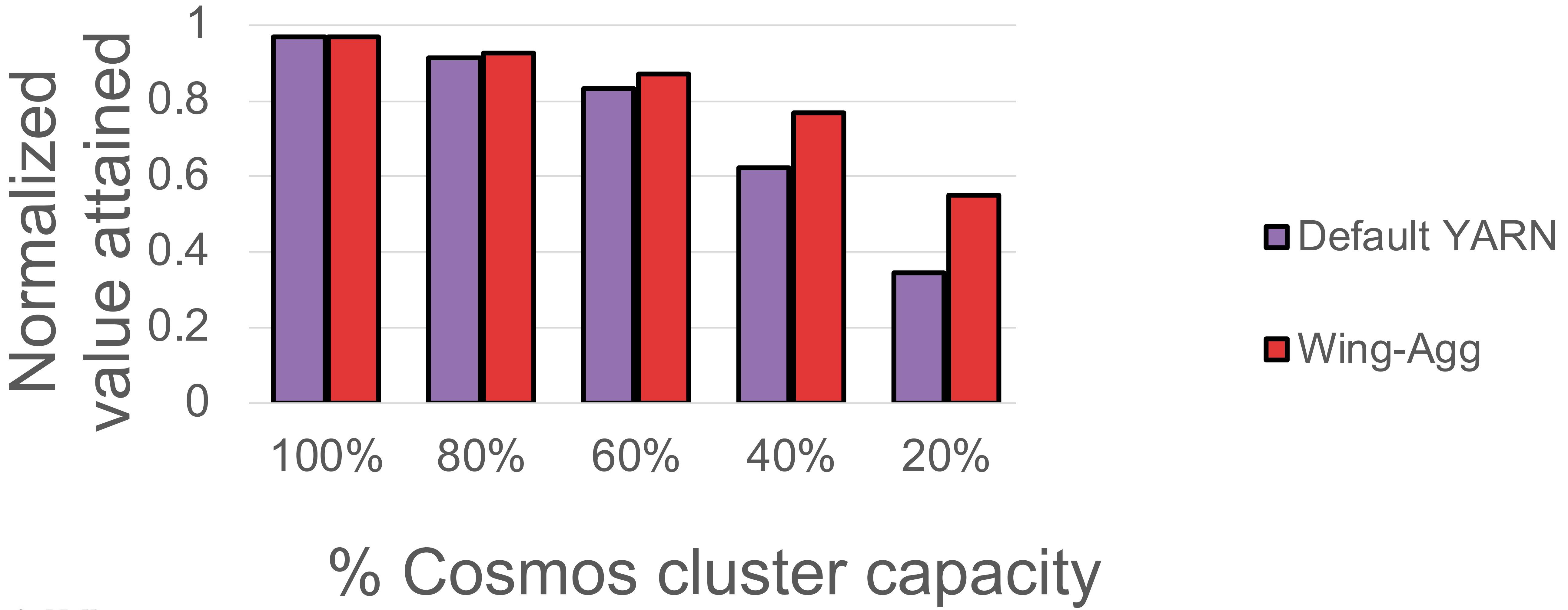

Wing takeaways

- Inter-job dependencies prevalent in real clusters
  - But, can be predictable with recurrence
- Inter-job dependencies need to be addressed
  - To ensure jobs meet their deadlines, reduce resource wastage, and improve value attained in shared clusters

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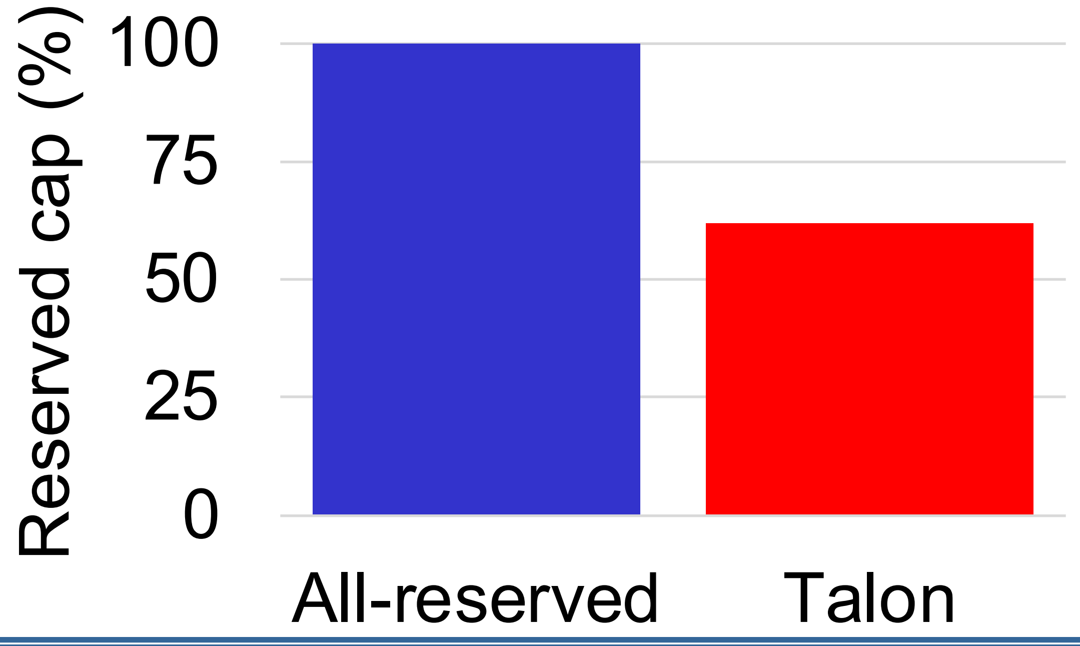
Talon summary

- Talon: Workflow mgr that reduces cluster op cost by reducing expensive locked-in reserved capacity
  1. Load-shift workload off-peak using inter-job deps
  2. Exploiting low-cost *transient resources*
     – Reduce preemption impact w/ load-shifting

Reduces reserved resources by 38% with minimal deadline violations

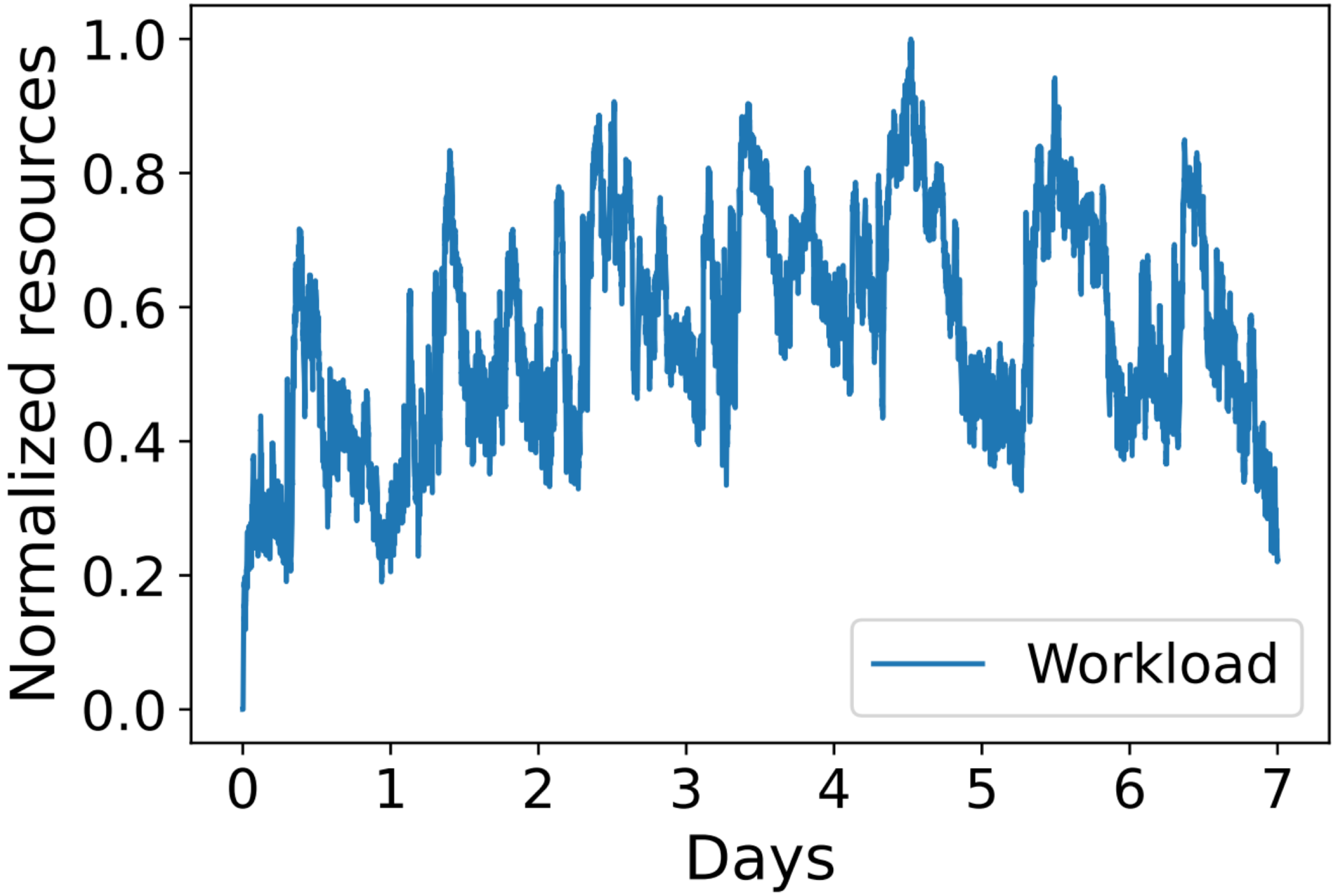


Background

- Resource types common in shared clusters:
  - Reserved: Long-term committed
    - Expensive and inflexible (locked-in long-term)
    - On-prem/reserved instances/guaranteed cap in cluster
  - Transient: Low-priority, intermittently-available
    - Lower cost, no lock in, but preemption/revocation risk
    - Spot instances/opportunistic cap in cluster
- Load-shift jobs: Change when job is run

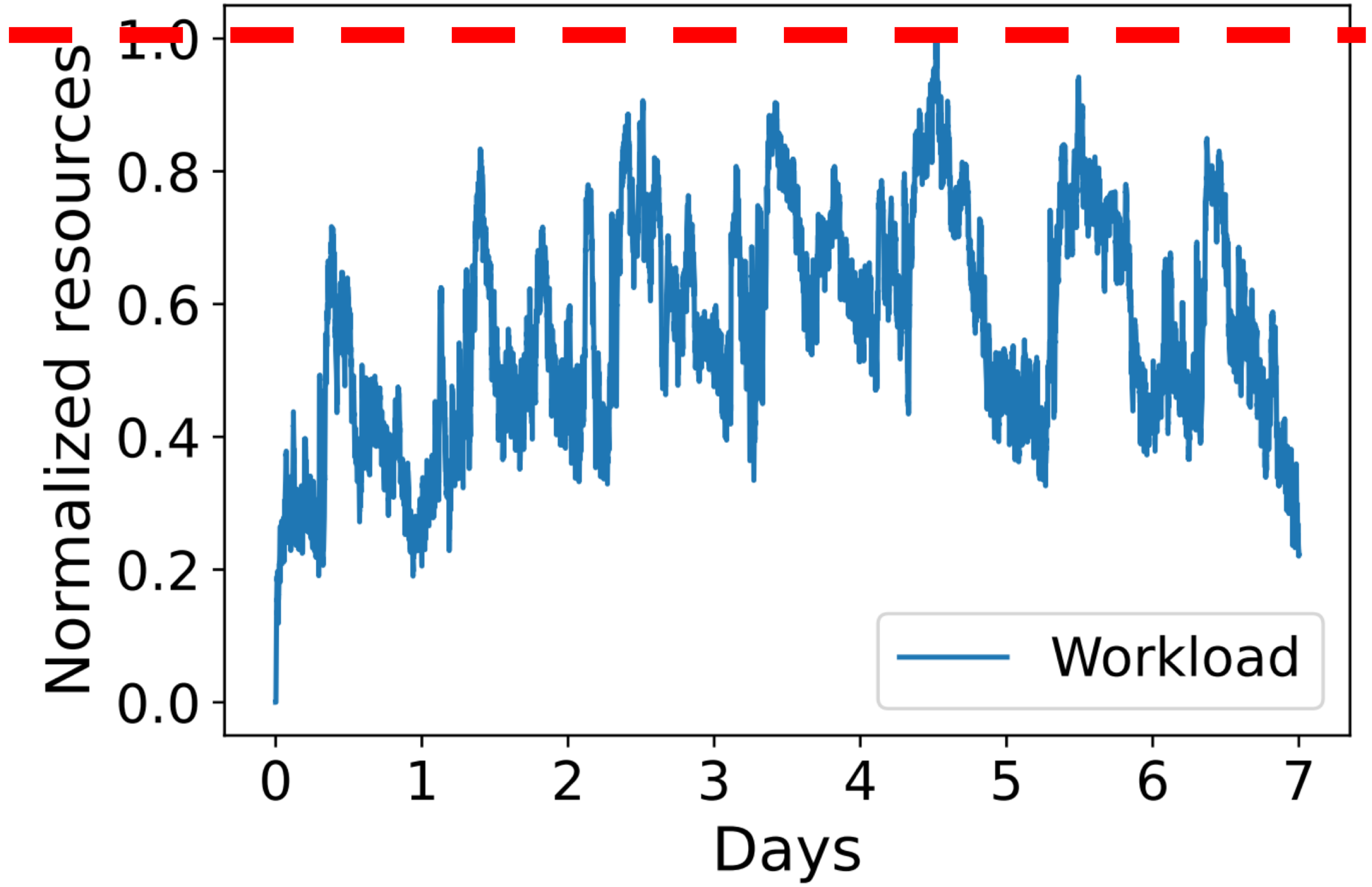
Cosmos workload capacity planning

Capacity planning Cosmos workload peak



Cosmos workload capacity planning

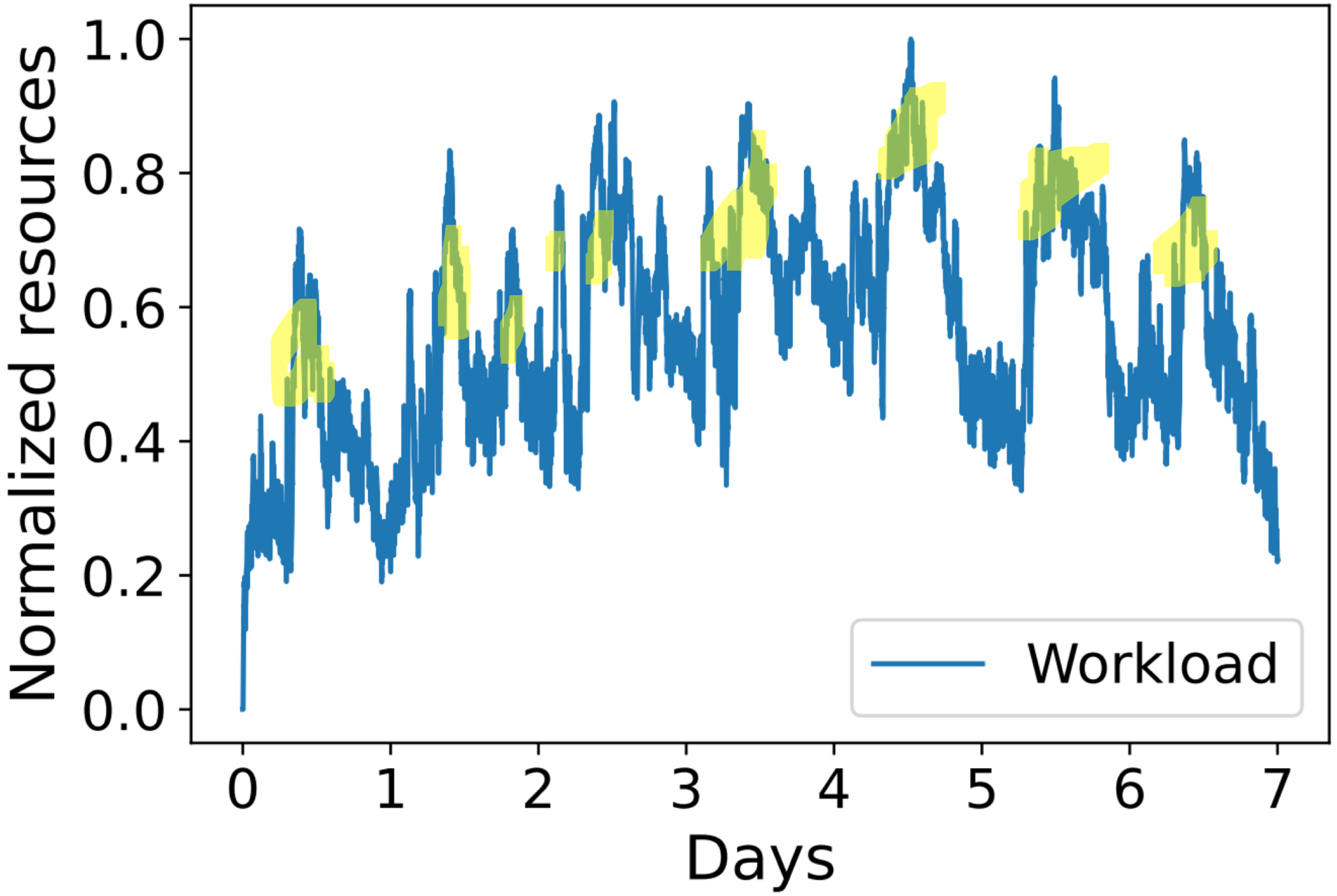
Capacity planning Cosmos workload peak



If only reserved,
need this much cap
(traditional approach)

Cosmos workload + load-shifting

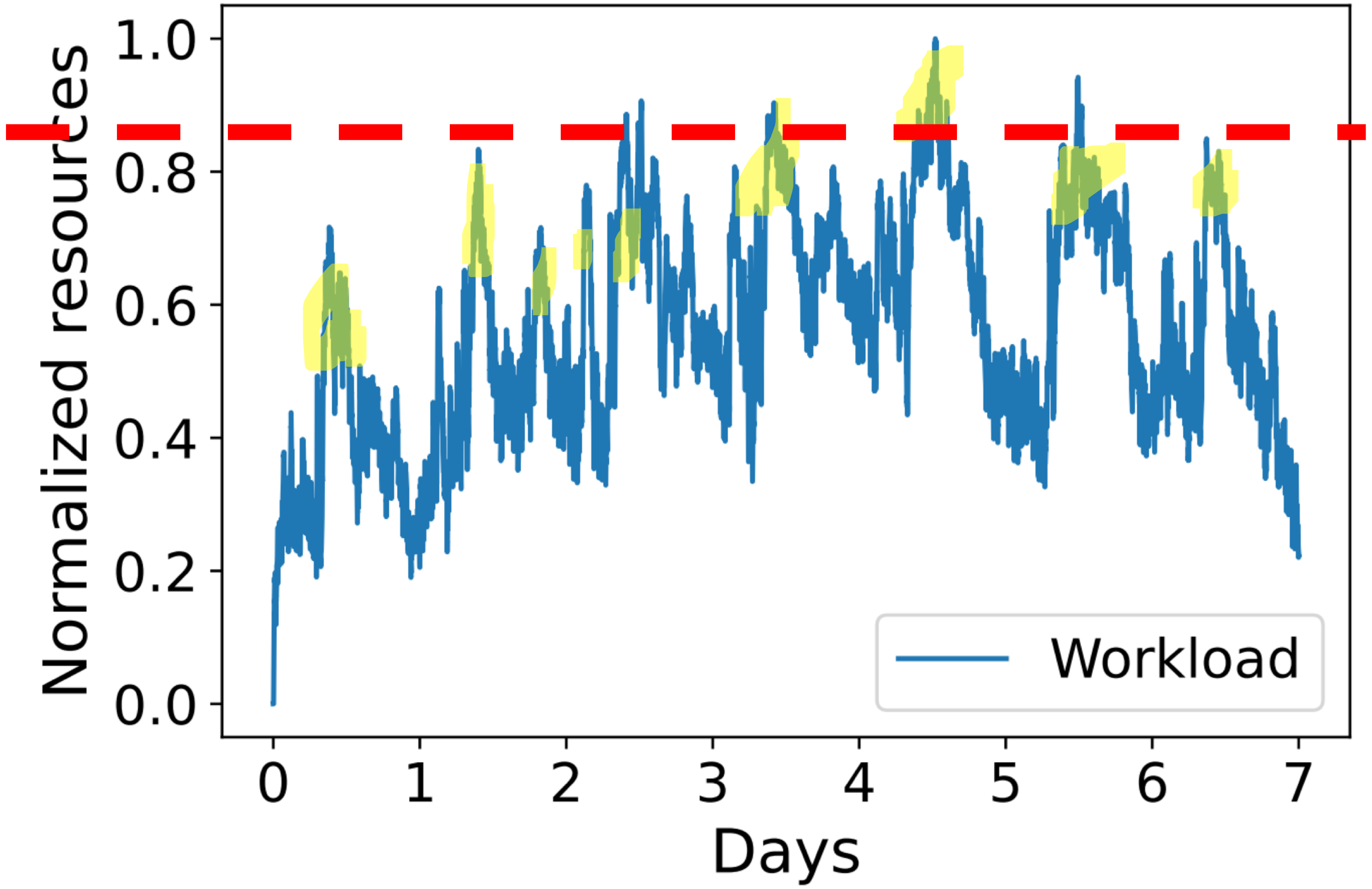
Capacity planning Cosmos workload peak



Scenario:
yellow resource-time can be *load-shifted off-peak*

Cosmos workload + load-shifting

Capacity planning Cosmos workload peak



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Cosmos workload + exploit transient

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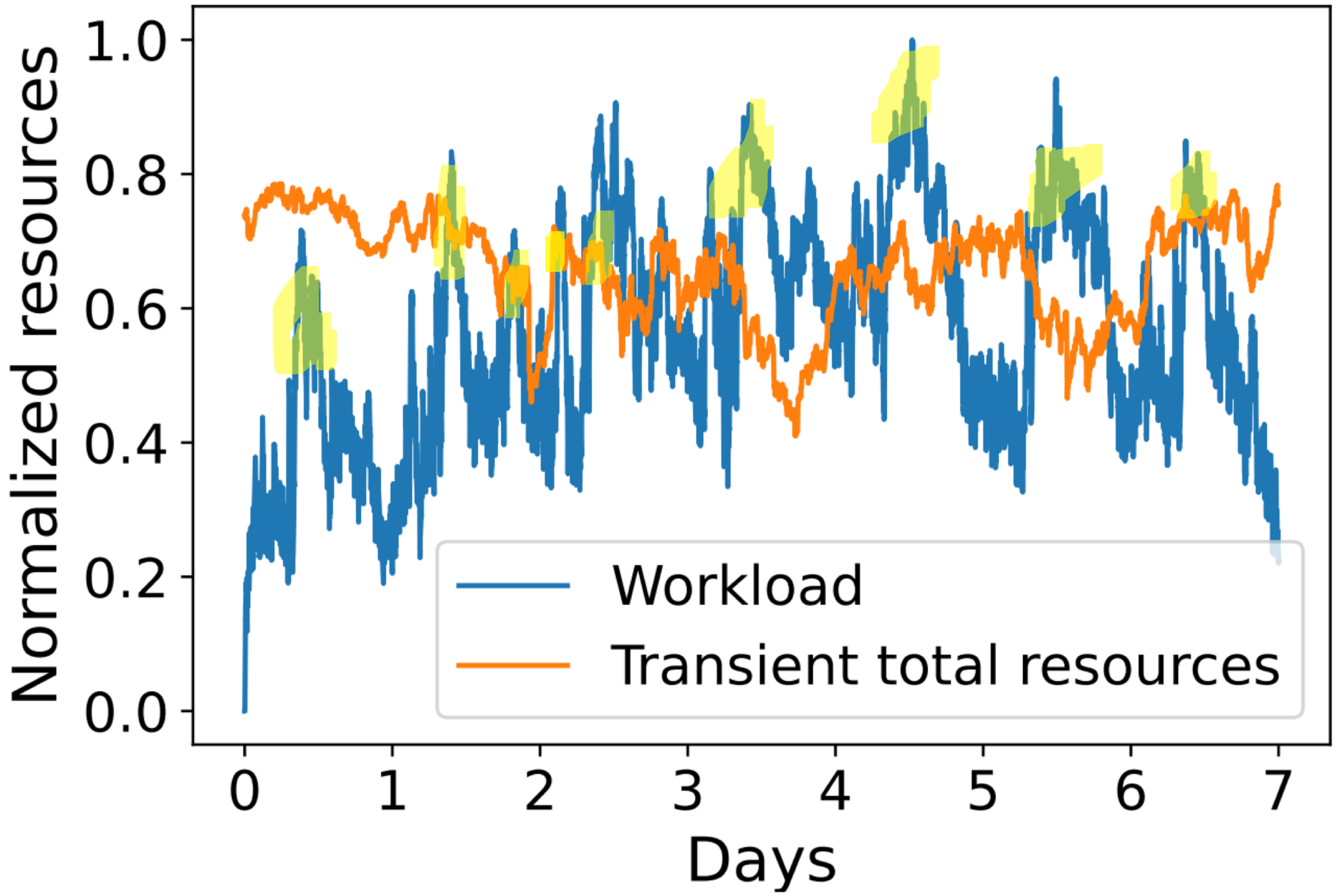
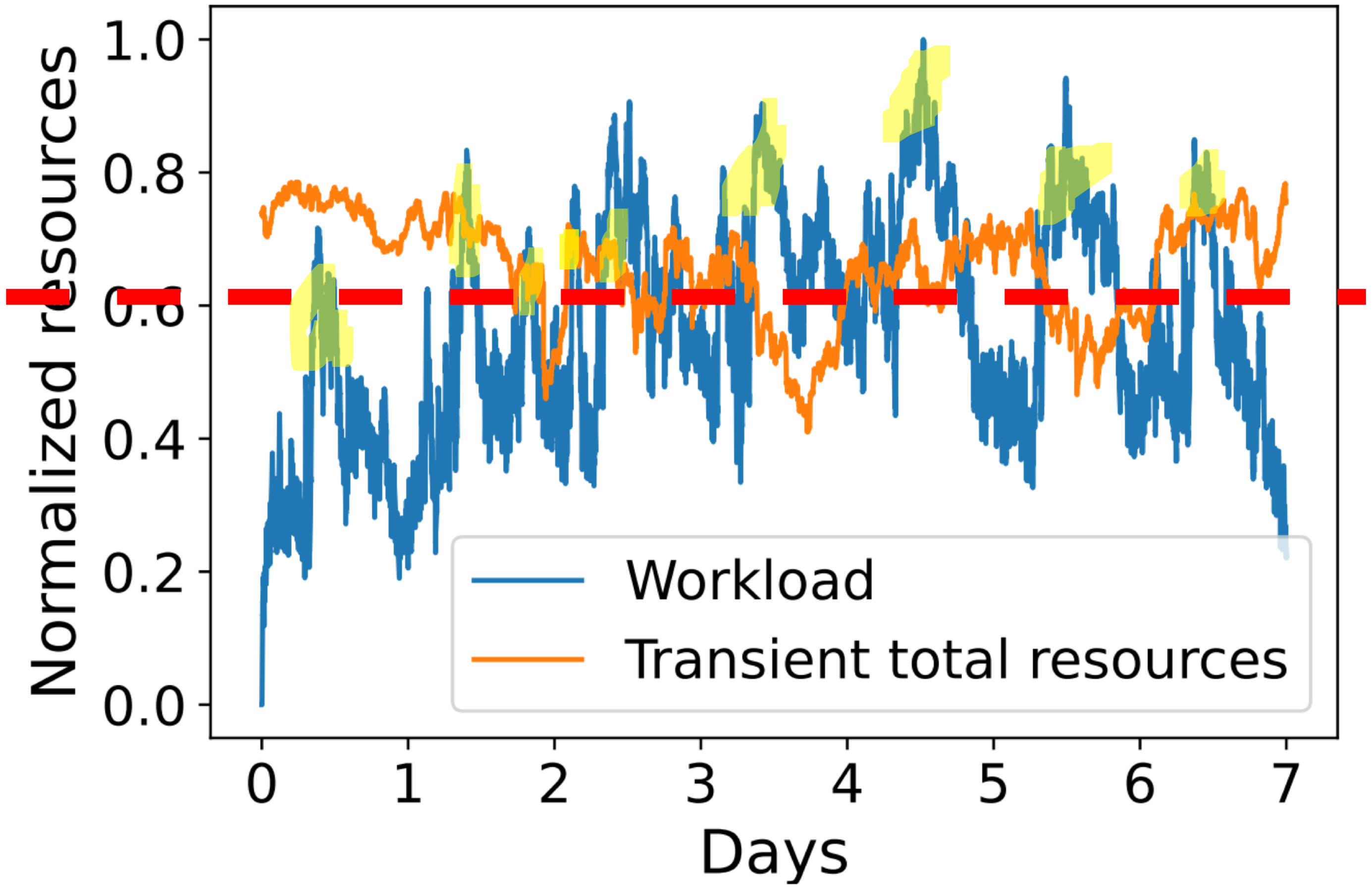


Scenario:
Low-cost transient resources available

Cosmos workload + exploit transient

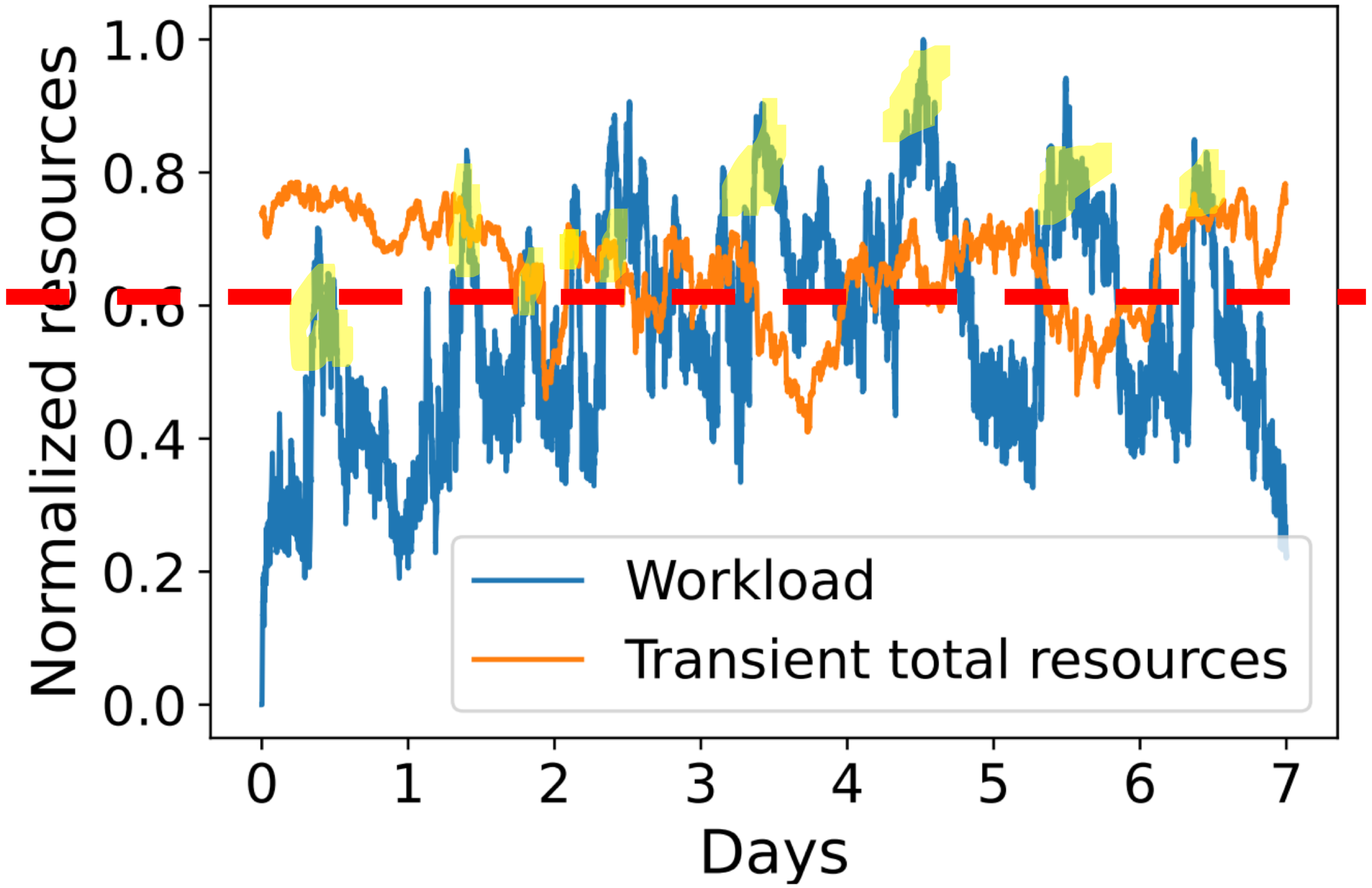
Capacity planning Cosmos workload peak



Scenario:
Low-cost transient resources available

Talon: Reducing reserved lock-in

Capacity planning Cosmos workload peak



Talon:

(1) Reduce reserved resource cap + cost w/ load-shifting and transient resources

(2) Do so without more deadline violations

Two ways to reduce reserved peak

1. Inter-job dependency-based load-shifting

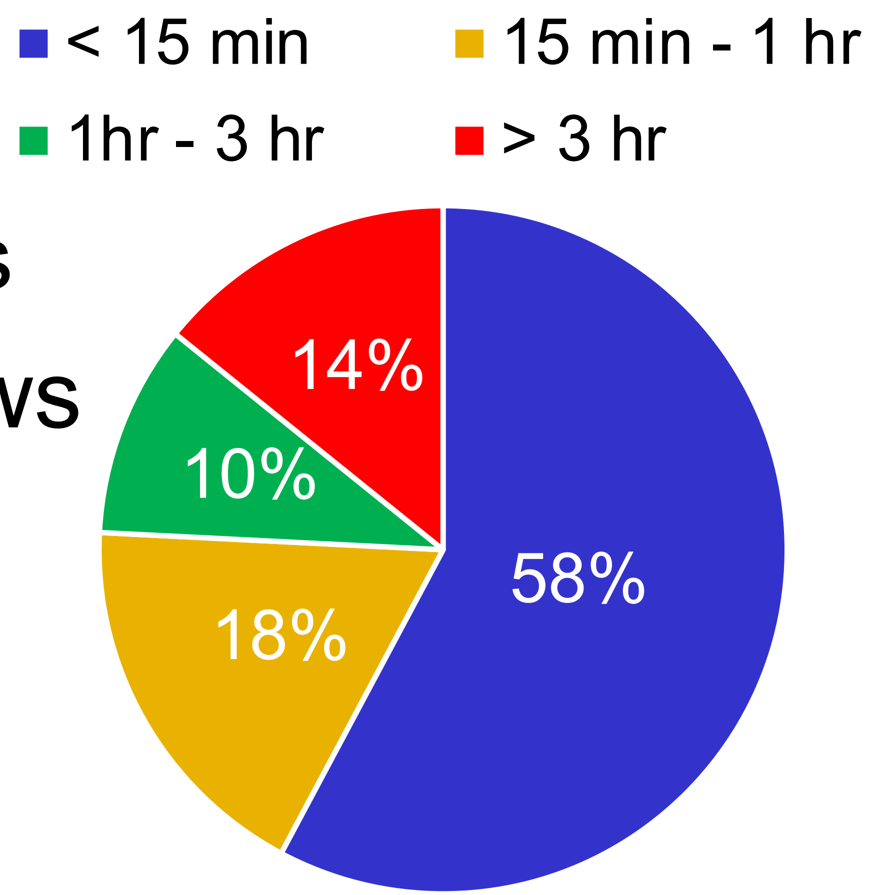
2. Use transient resources

Two modes of load-shifting

1. Delay: Run a job later, try not to violate job DL
   - Output + run time preds both need to be accurate
   - Little benefit (10% resource-time > 1 hr) + risk
   - Talon does not delay jobs
2. Advance: Run job earlier
   - Traditionally difficult, Talon uses inter-job deps

Advancing jobs: Opportunity analysis

- Job eligible to be advanced if:
  - All inputs ready and available
  - *Recurring* + *predictable* based on done jobs
- *Predict* recurring job arrival if dep on + follows completed upstream job w/ high prob
  - e.g., Job B dep on Job A > 90%
- Work with other WF Mgrs for advanceability



~24% resource-time advanceable > 1 hour

Two ways to reduce reserved peak

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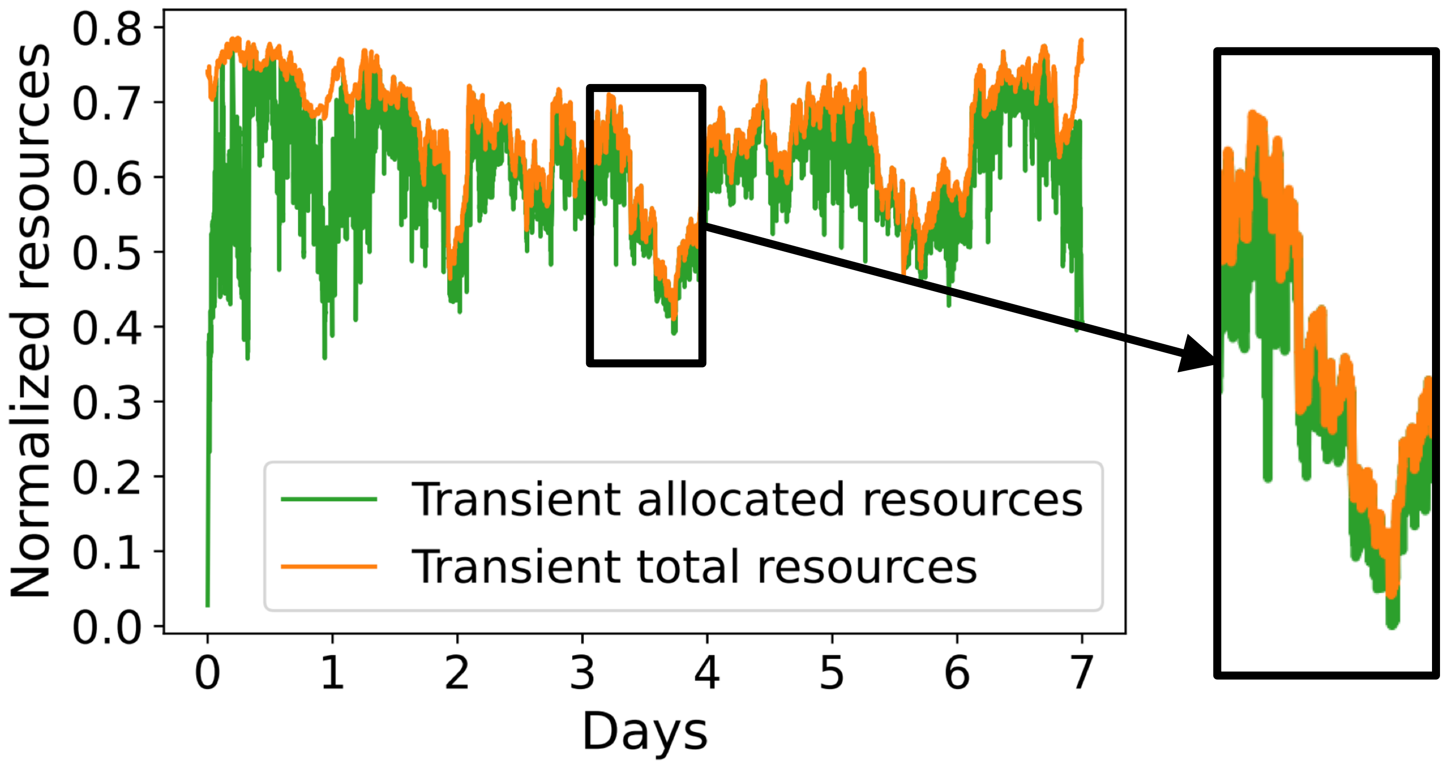
Transient resource risks

- Want to: Use transient resources to reduce reserved
- Risks: Intermittent availability, (bulk) preemption
  - Task replication can help w/ preemptions and DL violations, *but*
  - Aggressive usage → retries → queueing & more DL violations



"Storm" of retries

Scheduling policy: Admission + placement

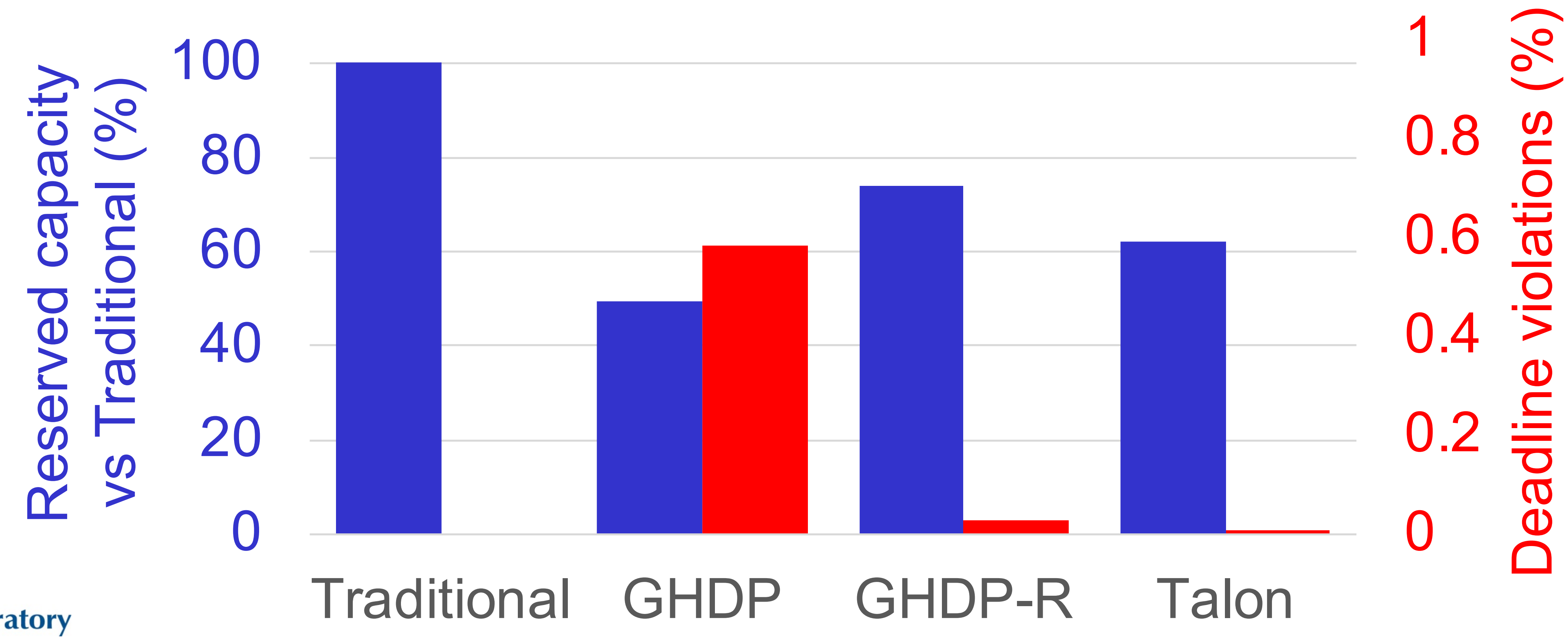
- Jobs eligible to start arrive at scheduling policy
- Policy admit + place jobs on reserved/transient:
  - Based on run time, time load-shifted, resources, etc
  - ex 1: Queue adv'd if low resource avail to reduce reserved
  - ex 2: Urgent jobs run reliably (reserved or transient + reps)
- Key to min DL violations: handling (bulk) preemptions:
  - Do not use transient too aggressively
  - Adv'd jobs w/ long slack can run transient w/o replicas

Experimental setup

- Simulation experiments on Cosmos traces
- Transient resources: Scaled Harvest (Spot) VM traces
- Jobs wait for inputs to start
  - Different from in Wing, where jobs may fail if missing input
- Deadline: Time of first non-job output usage
- Compared approaches:
  - Traditional: Peak-provisioned, reserved only
  - GHDP: GreenHadoop, a green-energy scheduler
  - GHDP-R: Replicas on transient to reduce violations

Experimental results

- GHDP (no rep) experience DL violations due to retries
- Talon 38% reduction vs Traditional
- Talon achieves lowest num of deadline violations



Talon takeaways

- Inter-job dependencies critical to exploit load-shifting
  - 24% job resource-time can be advanced by > 1 hr
- Talon can effectively reduce reserved committed capacity using combination of load-shifting + transient resources
  - Up to 38% reserved capacity reduction vs traditional
  - Lowest # of deadline violations under diff scenarios

Talk outline

- Shared cluster environments
- 2 case studies: specializing application frameworks
- 2 case studies: from perspective of cluster operators
- Conclusion

Thesis statement

Value-realized in shared data environments can be improved both by value- and dependency-aware resource management systems from cluster operators and by cost- and heterogeneity-aware applications from users.

Thesis contributions: App-specific resource acquisition

1. Elastic web services
   - Spot-dancing for elastic services with latency SLOs
   - Tributary [USENIX ATC 2018]
2. General containerized batch task scheduling
   - Cost-aware container scheduling in the public cloud
   - Stratus [ACM SoCC 2018]
     – Best student paper award

Thesis contributions: Cluster operator resource mgmt

1. Scheduling to increase attained utility in cluster
   - Unearthing inter-job dependencies for better scheduling
   - Wing [USENIX OSDI 2020]
2. Load-shifting to reduce cluster operation costs
   - Reducing costs with dependency-informed load-shifting
   - Talon [Submission-prep]