UCF | AREA 67

UNIVERSITY OF CENTRAL FLORIDA

Sandia National Laboratories

Workload-Adaptive Scheduling for Efficient Use of Parallel File Systems in HPC Clusters

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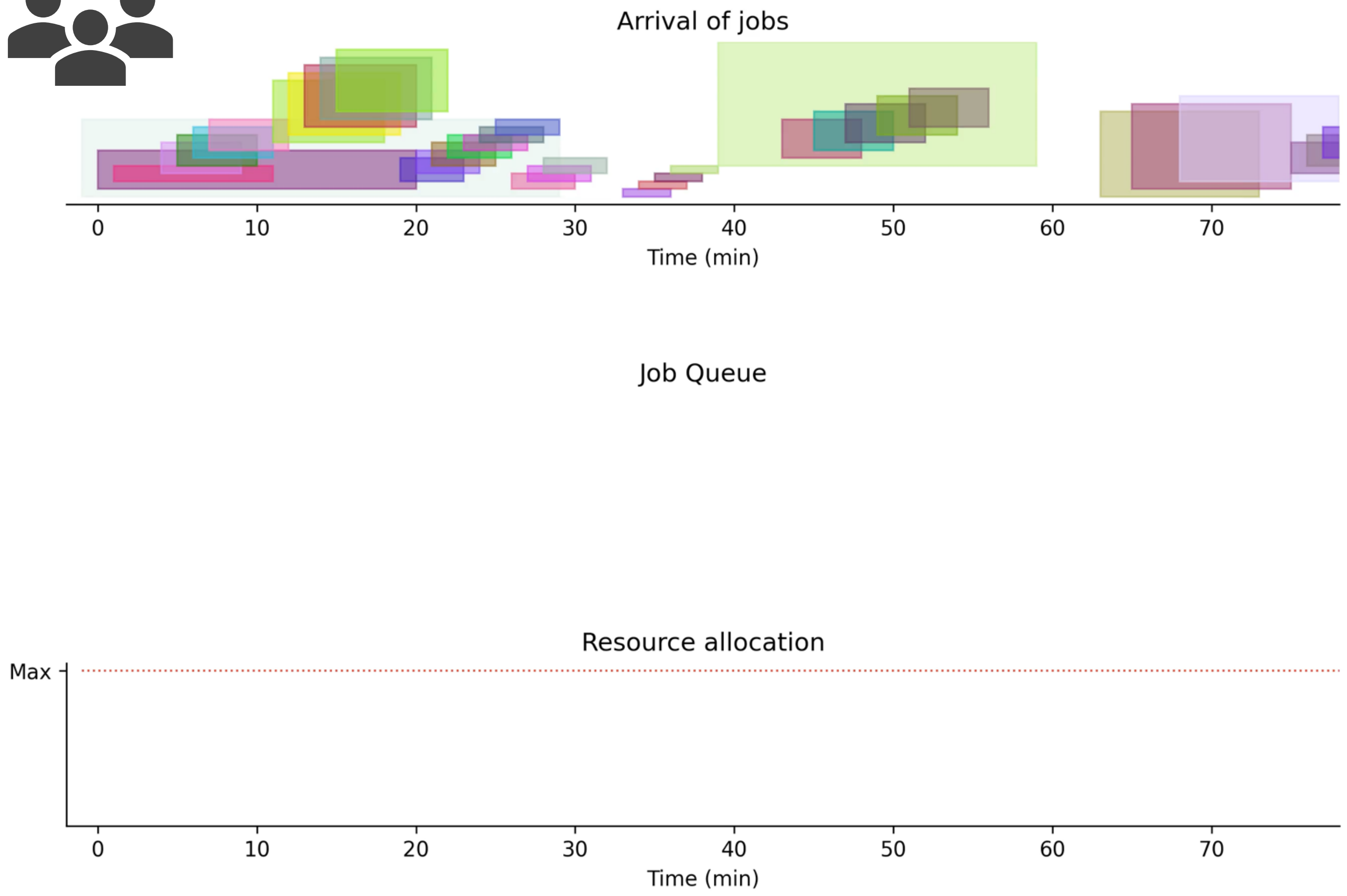
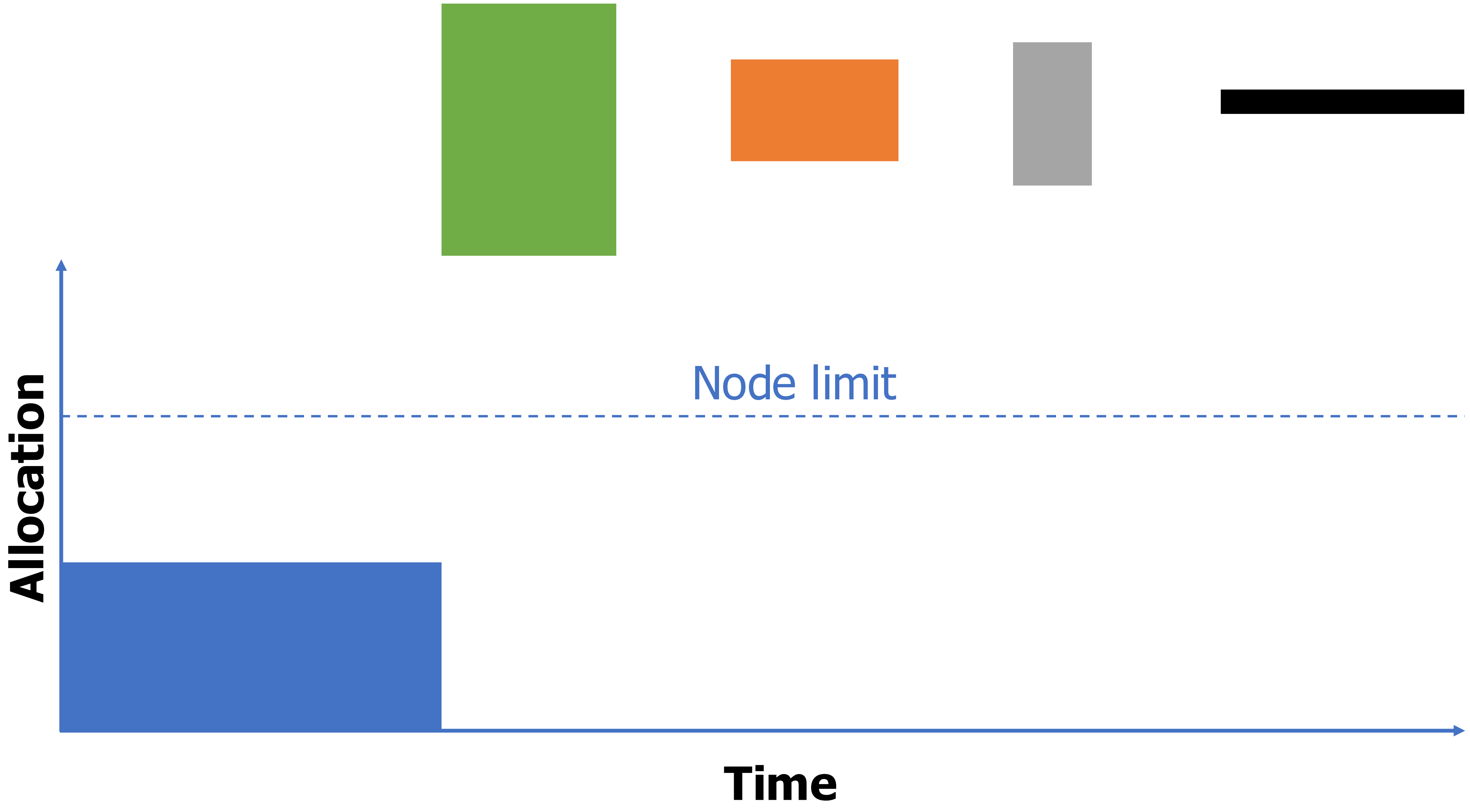
Job scheduling on HPC cluster



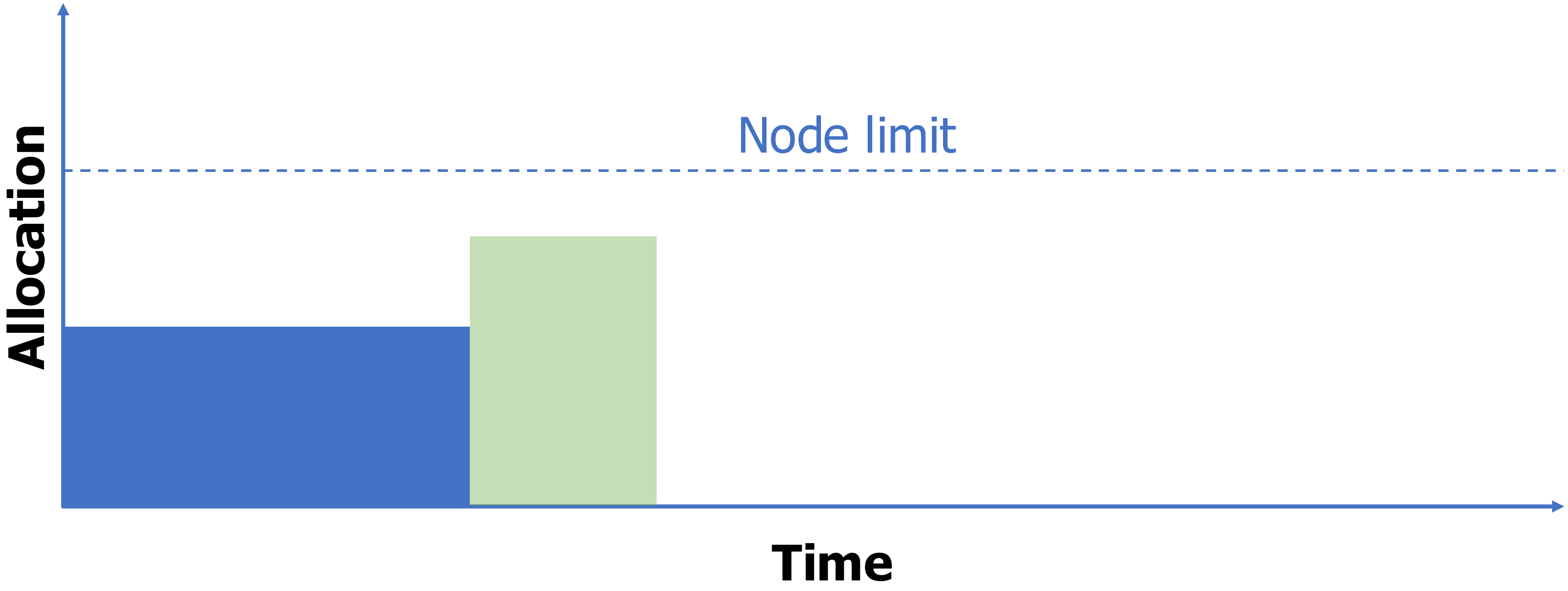
- Users submit jobs and specify jobs' resource requirements
  - Essential parameters:
    - Number of nodes
    - Time limit
- Scheduling algorithms determine the order of starting jobs during shortage of resources
- NP-hard problem

Scheduling with backfilling



Scheduling with backfilling

- If a job cannot run,
  reserve resources
  to prevent any further delays



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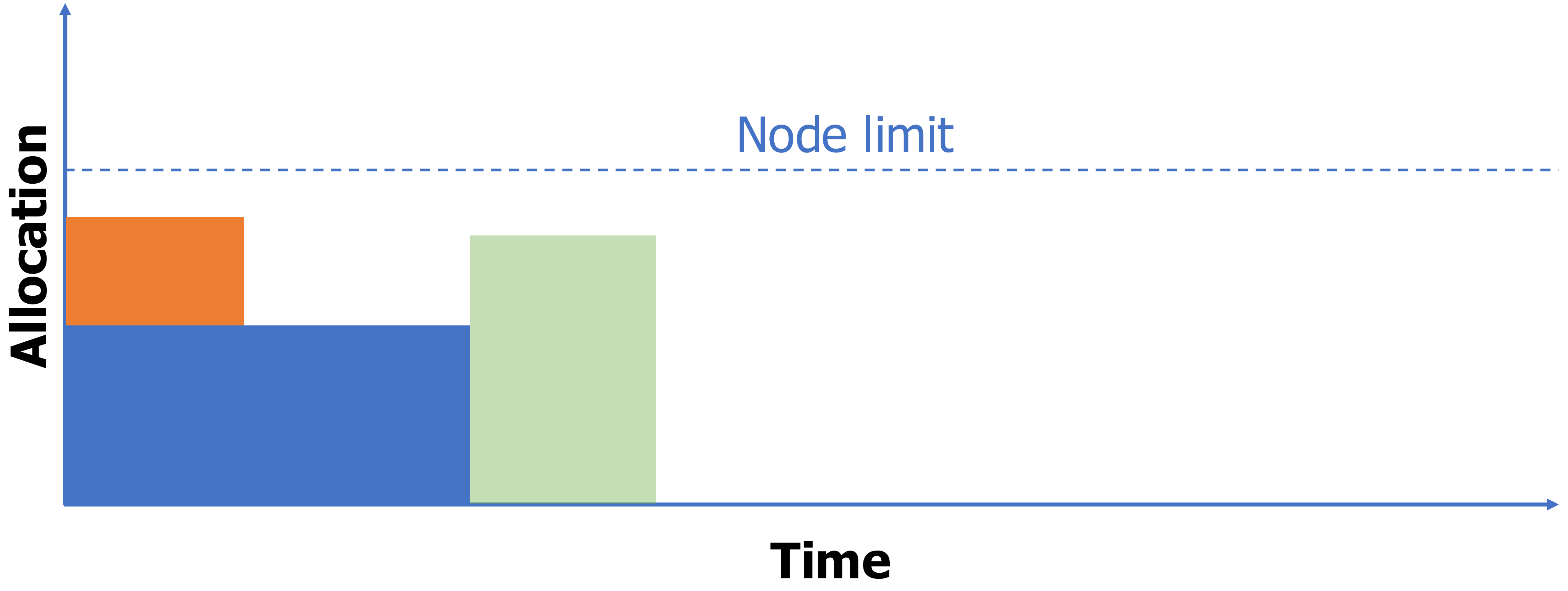

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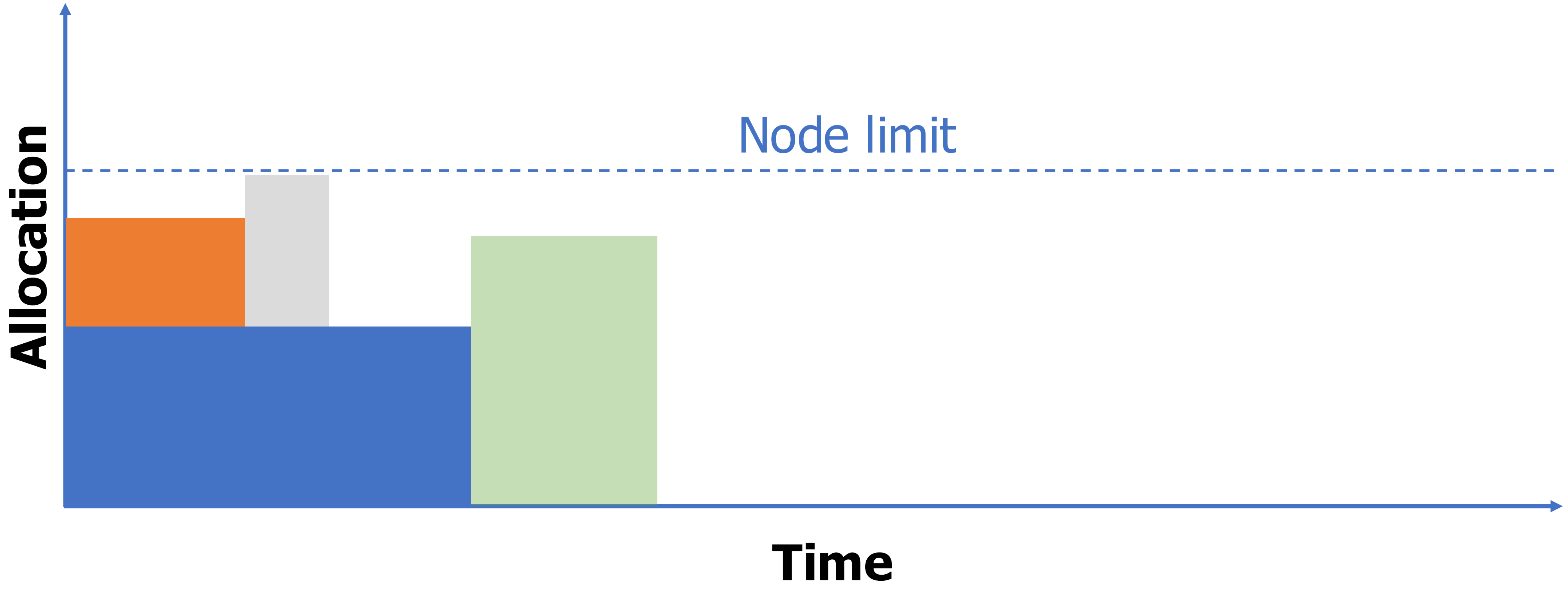

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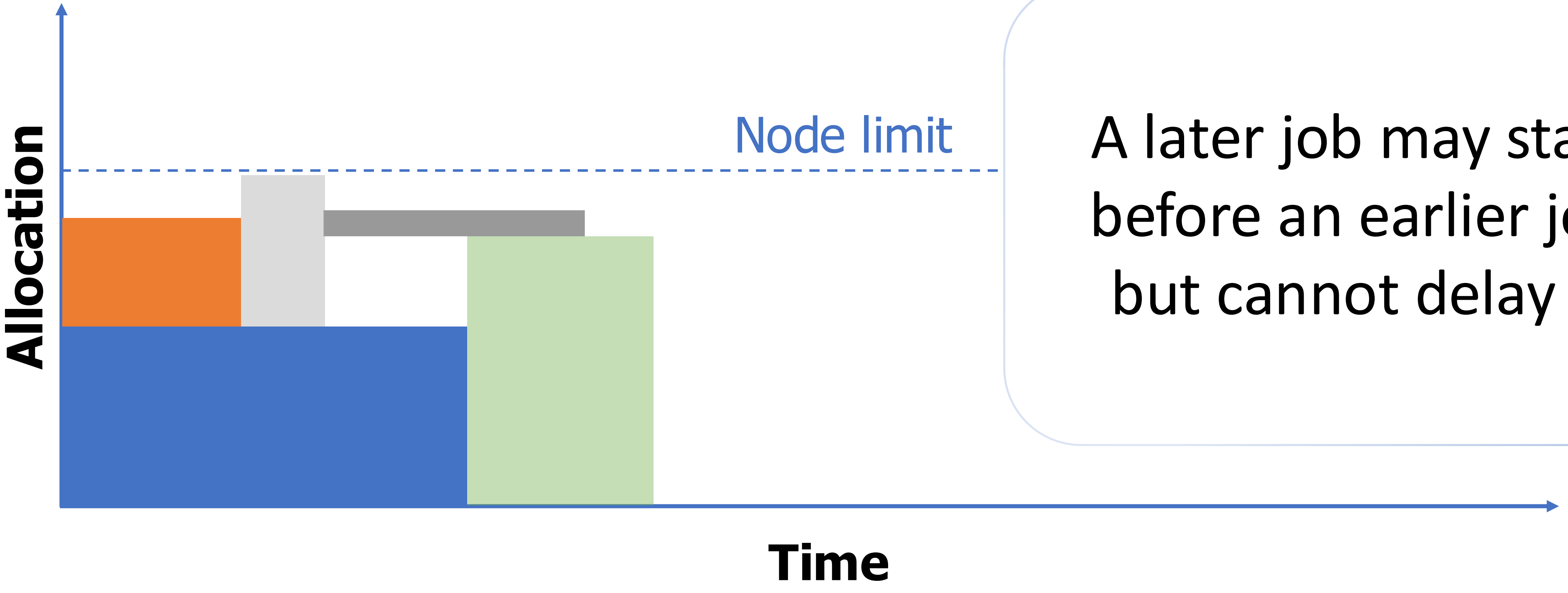
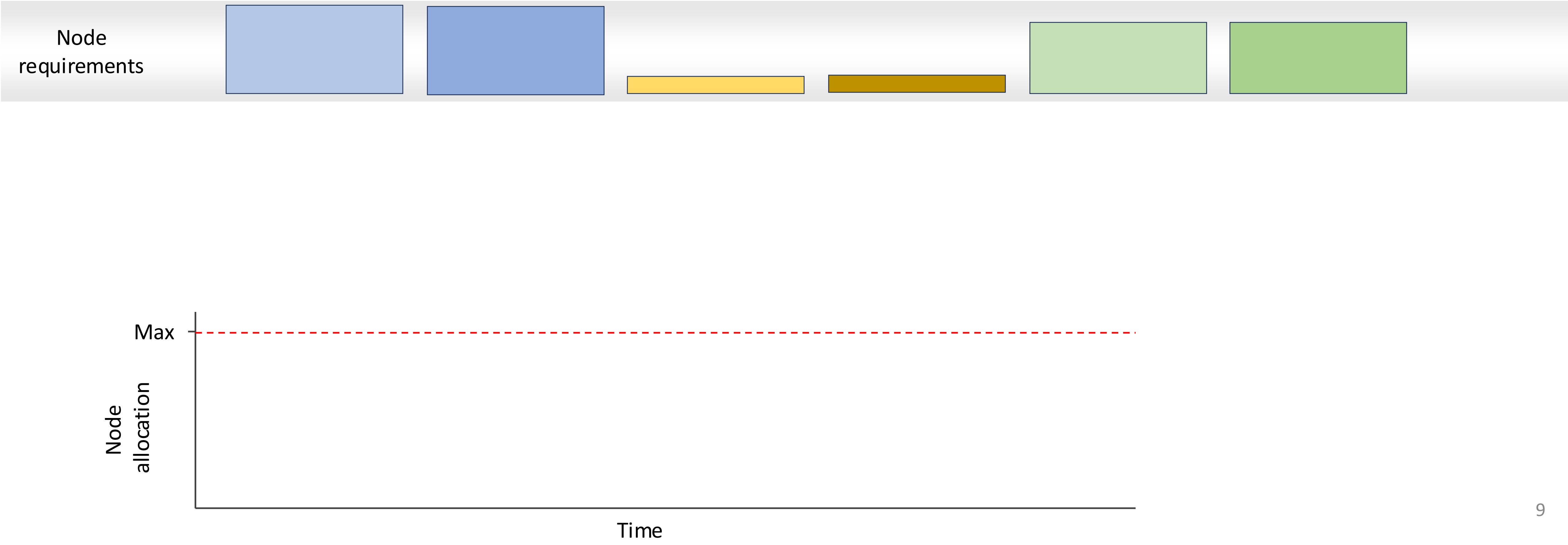


A later job may start before an earlier job but cannot delay it

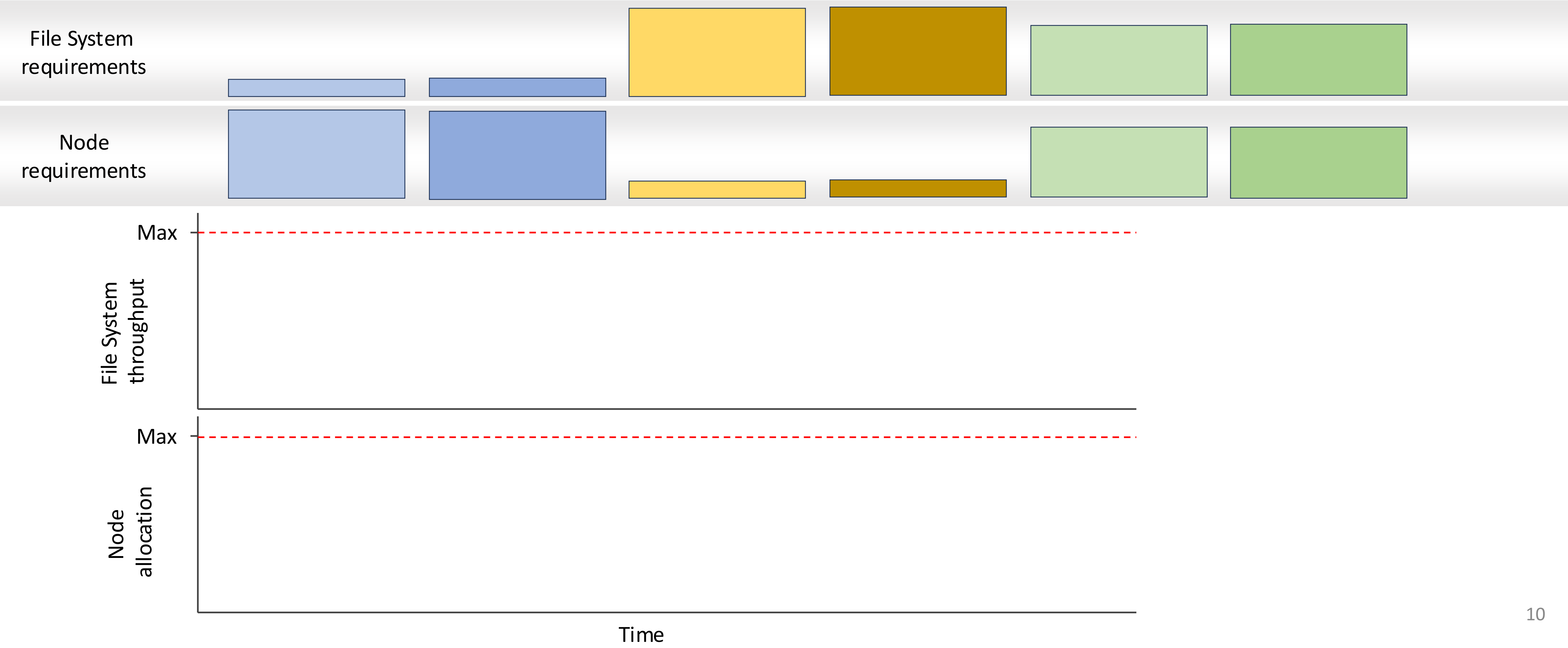
Modern HPC systems require multiple-resource scheduling

- Modern system are complicated
  - Many resources (burst buffers, GPU, etc.)
  - I/O bottlenecks (network, parallel file system)
- Modern schedulers should –
  - – schedule jobs
    - aiming at improving efficiency
    - accounting for user policy considerations
  - – handle various resource constraints
  - – reduce user's burden to provide resource requirements
  - – anticipate that jobs' runtime and resource usage may depend on how the jobs are scheduled

Single-resource scheduling



Multi-resource scheduling



“Common” I/O-aware scheduling

- Key features of “common” I/O-aware scheduling[1]
  - The scheduler estimates the file system throughput of the jobs
  - The scheduler doesn’t let the total estimated throughput to exceed the file system bandwidth
- Our implementation can be configured to perform “common” I/O-aware scheduling and workload-adaptive scheduling

[1] M. R. Wyatt, S. Herbein, T. Gamblin, and M. Taufer, “AI4IO: A suite of AI-based tools for IO-aware scheduling,” *Int. J. High Perform. Comput. Appl.* 2022, doi: 10.1177/10943420221079765.

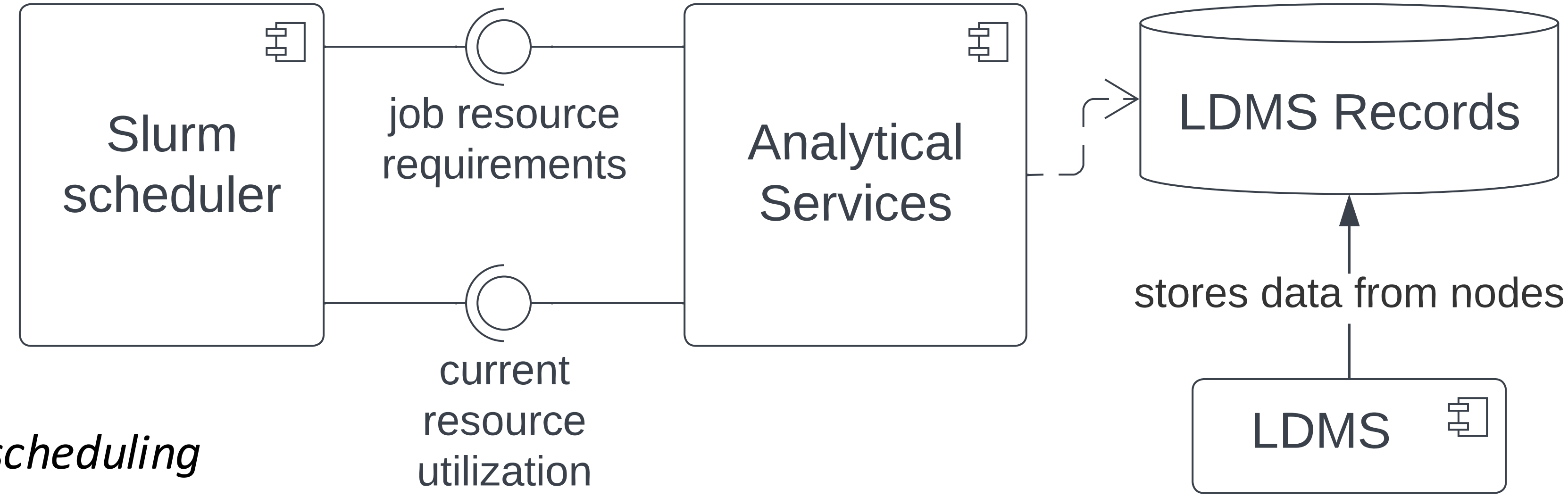
Outline

Overview of our scheduling system

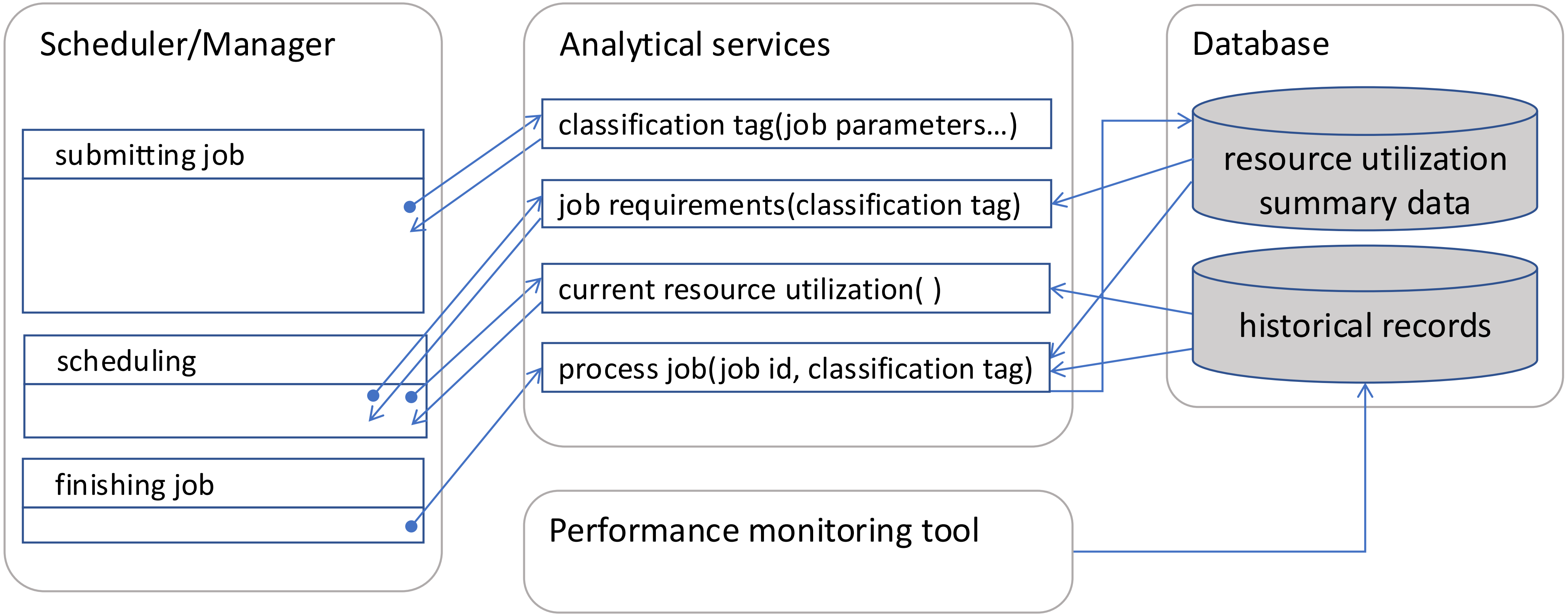
Shortcomings of "common" I/O-aware scheduling

Workload-adaptive scheduling

Overview of our system

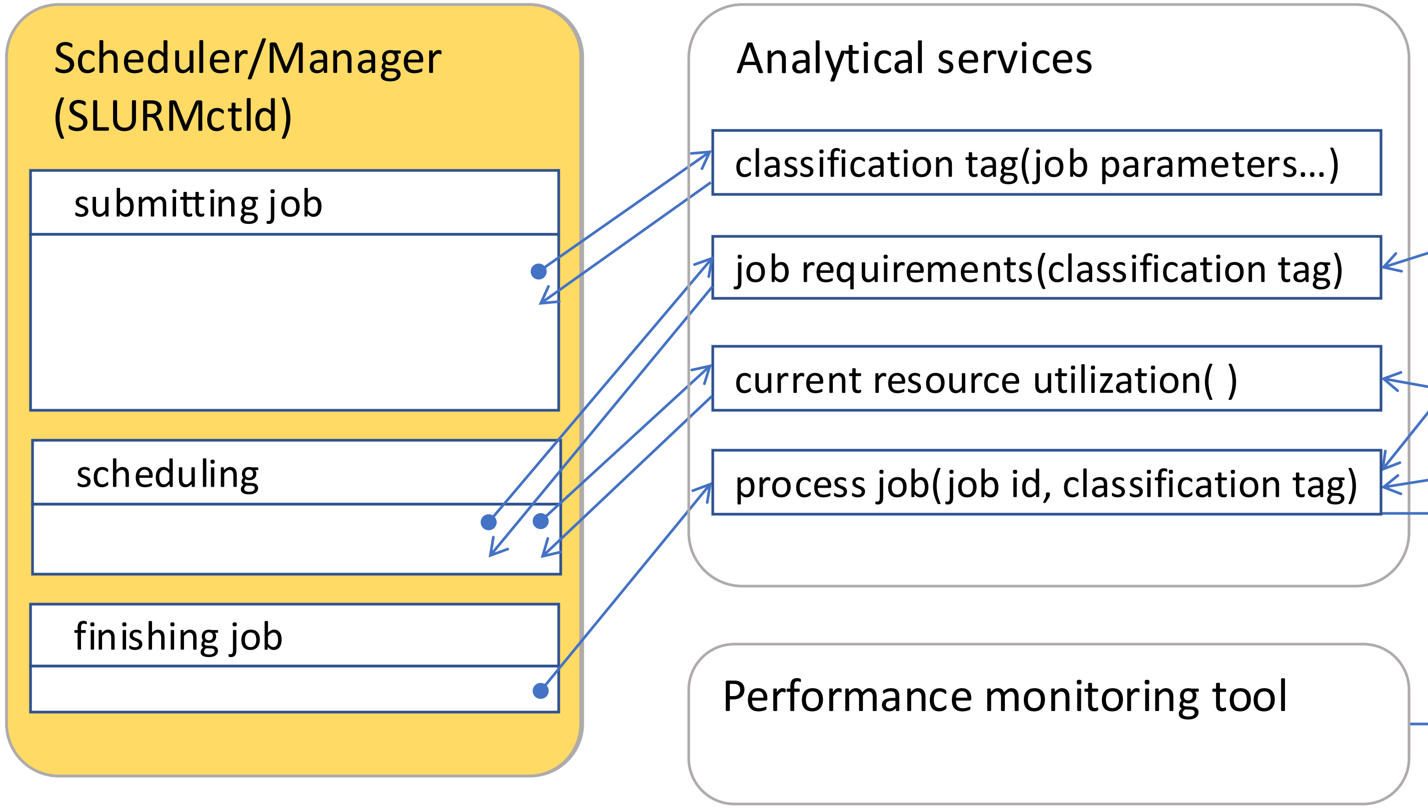


- Slurm – *scheduling*
  - https://slurm.schedmd.com/
  - https://github.com/algo74/slurm/tree/workload-adaptive-paper-2024
- Analytical services – *estimating resource requirements*
  - https://github.com/algo74/py-sim-serv/tree/workload-adaptive-paper-2024
- Lightweight Distributed Metric Service (**LDMS**) – *measuring resource usage*
  - https://github.com/ovis-hpc/ldms


Scheduler/Manager
submitting job
scheduling
finishing job
Analytical services
classification tag(job parameters...)
job requirements(classification tag)
current resource utilization( )
process job(job id, classification tag)
Database
resource utilization summary data
historical records
Performance monitoring tool

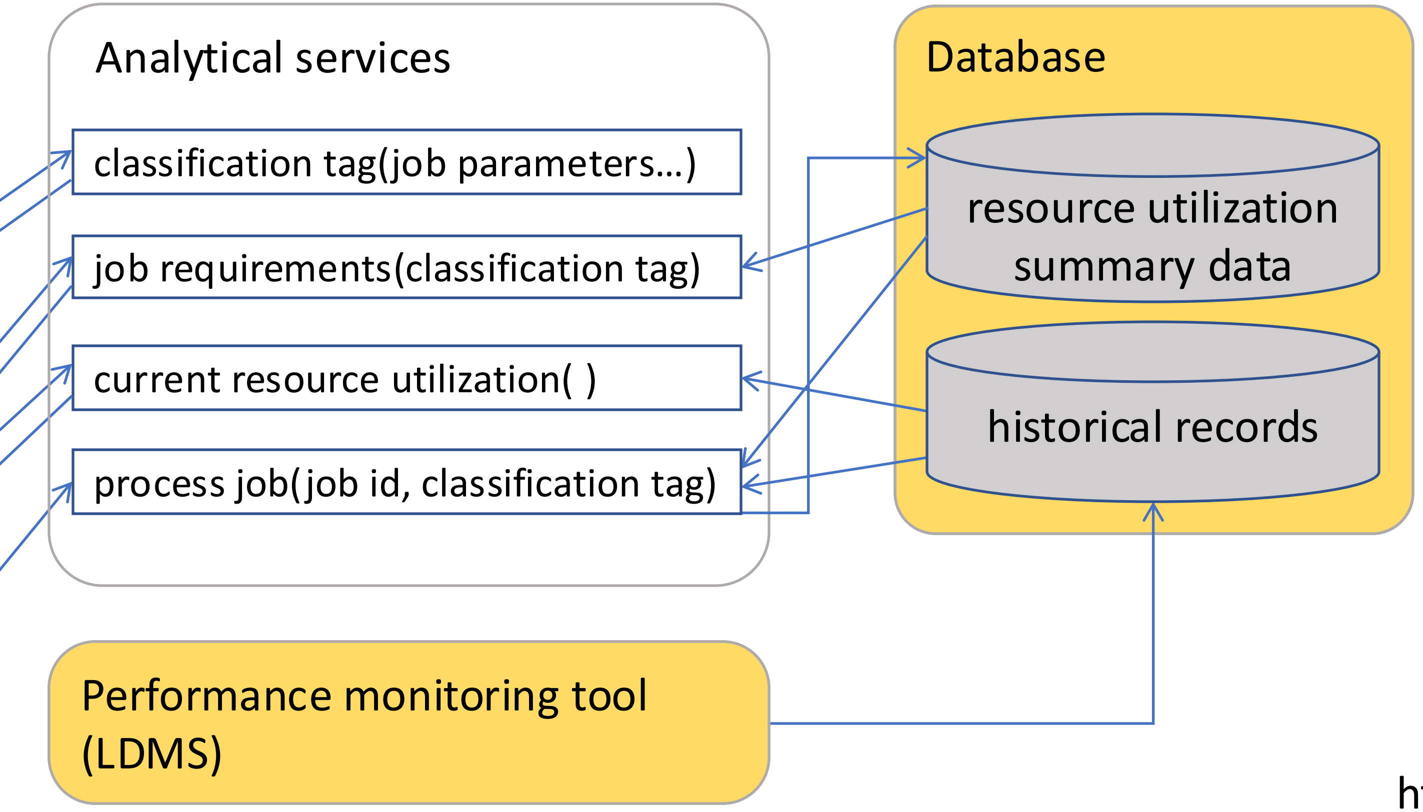
Scheduler

- Request resource requirements for jobs
- Request real-time utilization of the resources
- Take into account the obtained values during scheduling
- Set job ID on the nodes
- Send a signal when a job is completed



https://github.com/algo74/slurm/tree/workload-adaptive-paper-2024

Measuring resource usage

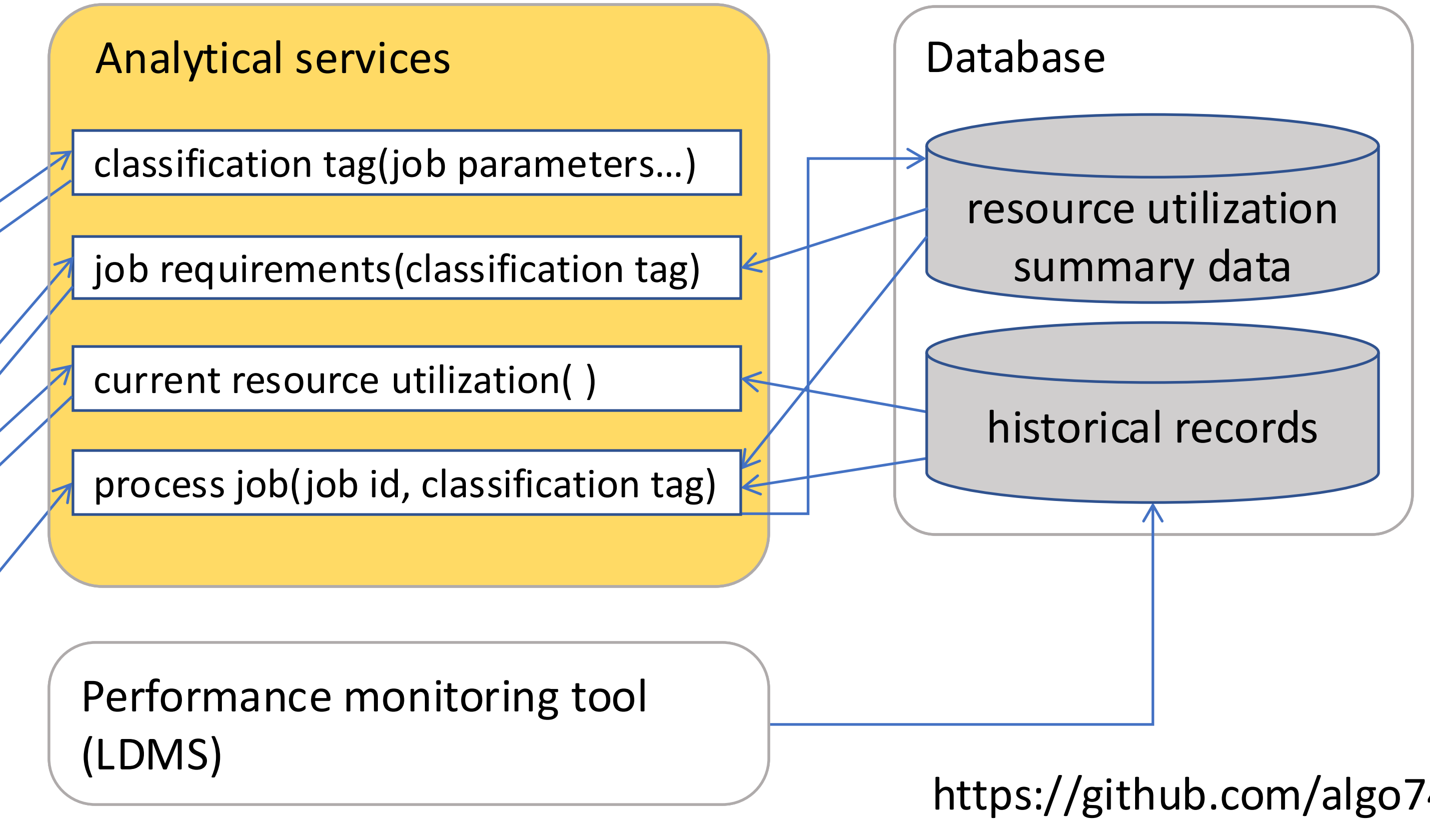


- Lightweight Distributed Metric Service (**LDMS**)
  - No modification
  - jobinfo plugin associates records with jobs

https://github.com/ovis-hpc/ldms

Analytical services

- Prediction of jobs’ resource requirements
  - *classification tag(…)*
  - *job requirements(…)*
  - *process job(…)*
- Real-time utilization of resources
  - *current resource utilization(…)*



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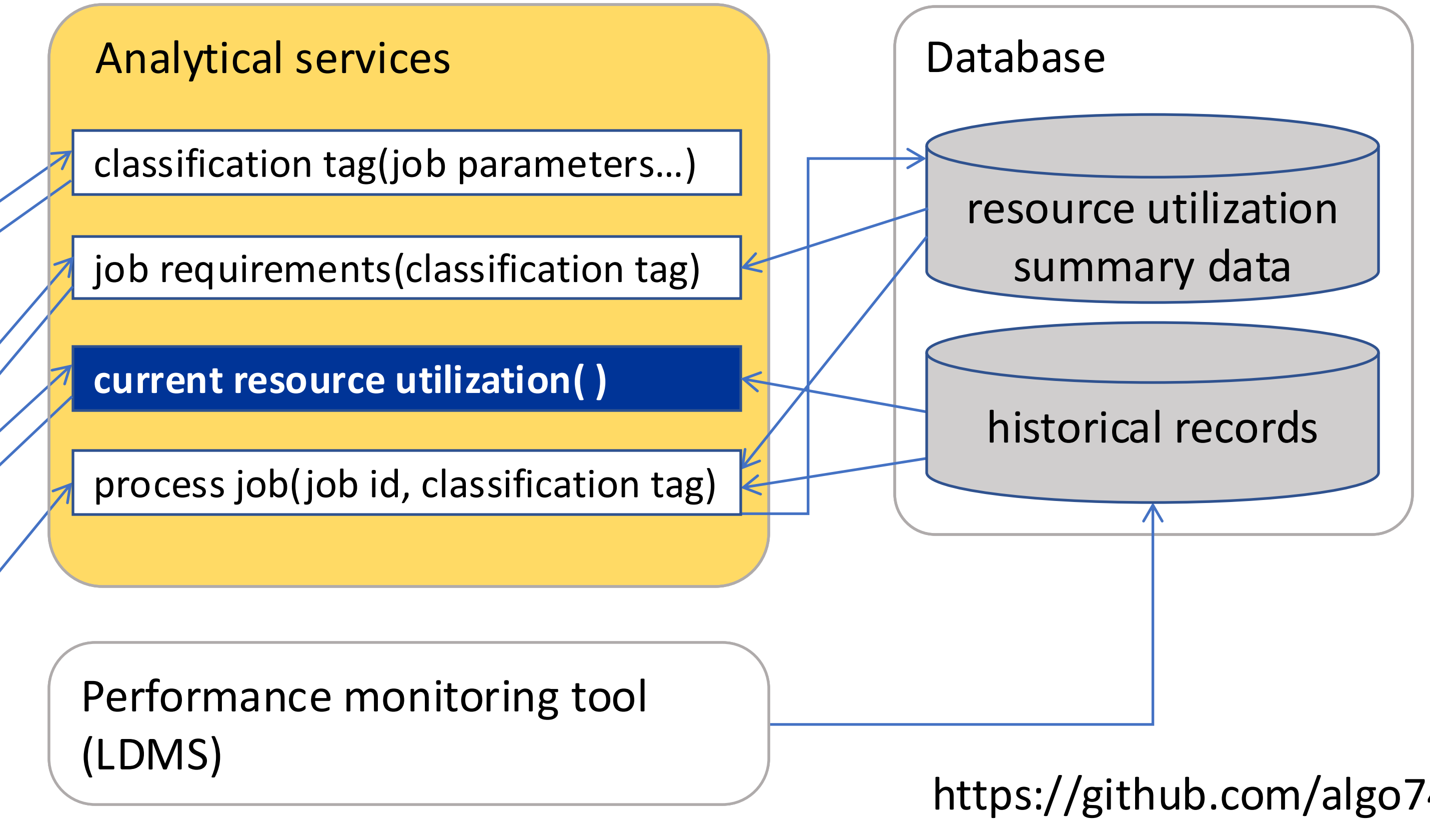
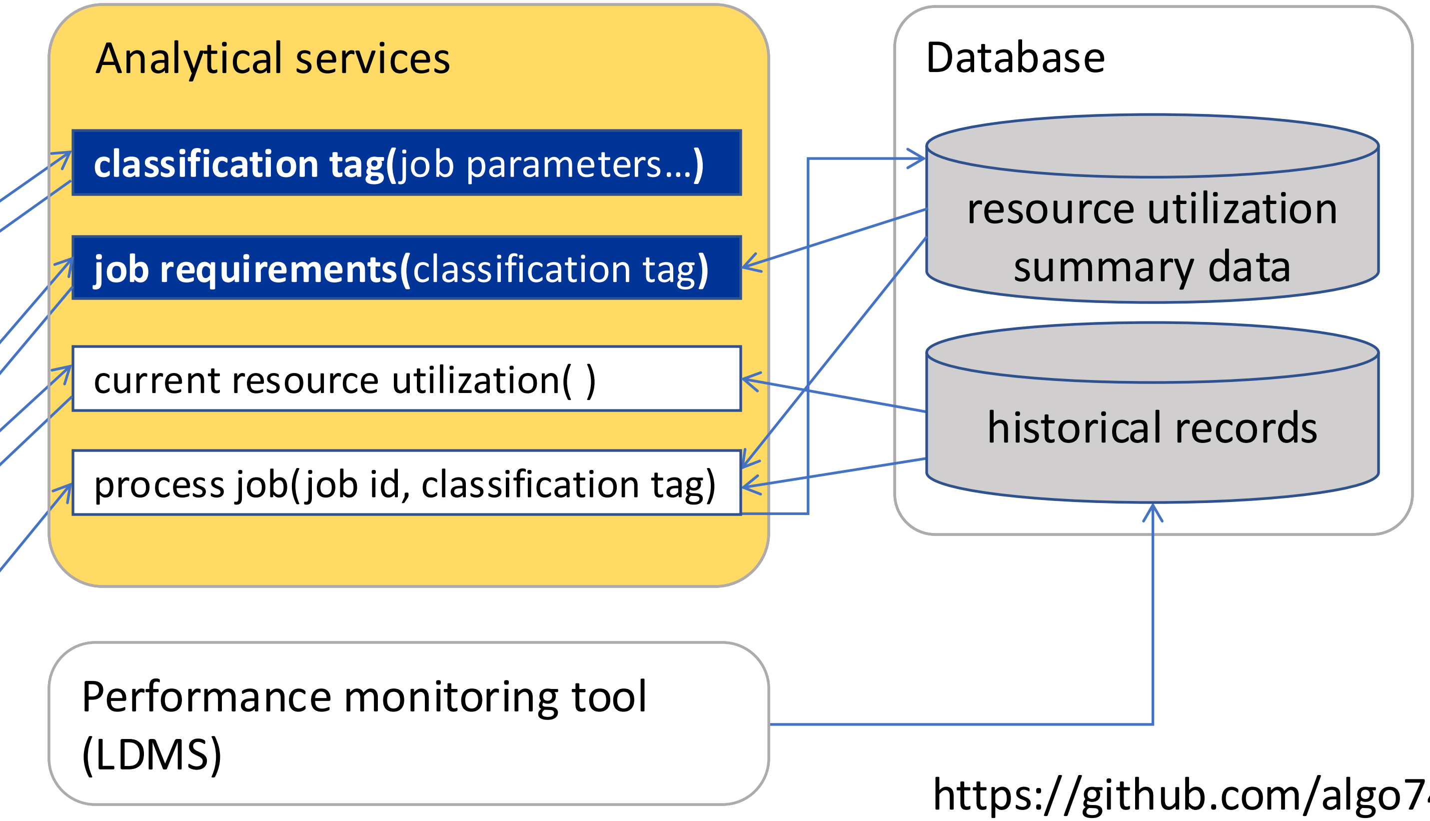
Real-time utilization of resources



- Periodically retrieve recent LDMS records
- Calculate whole-system utilization of the resources
- Fulfill requests with the latest value

https://github.com/algo74/py-sim-serv/tree/workload-adaptive-paper-2024

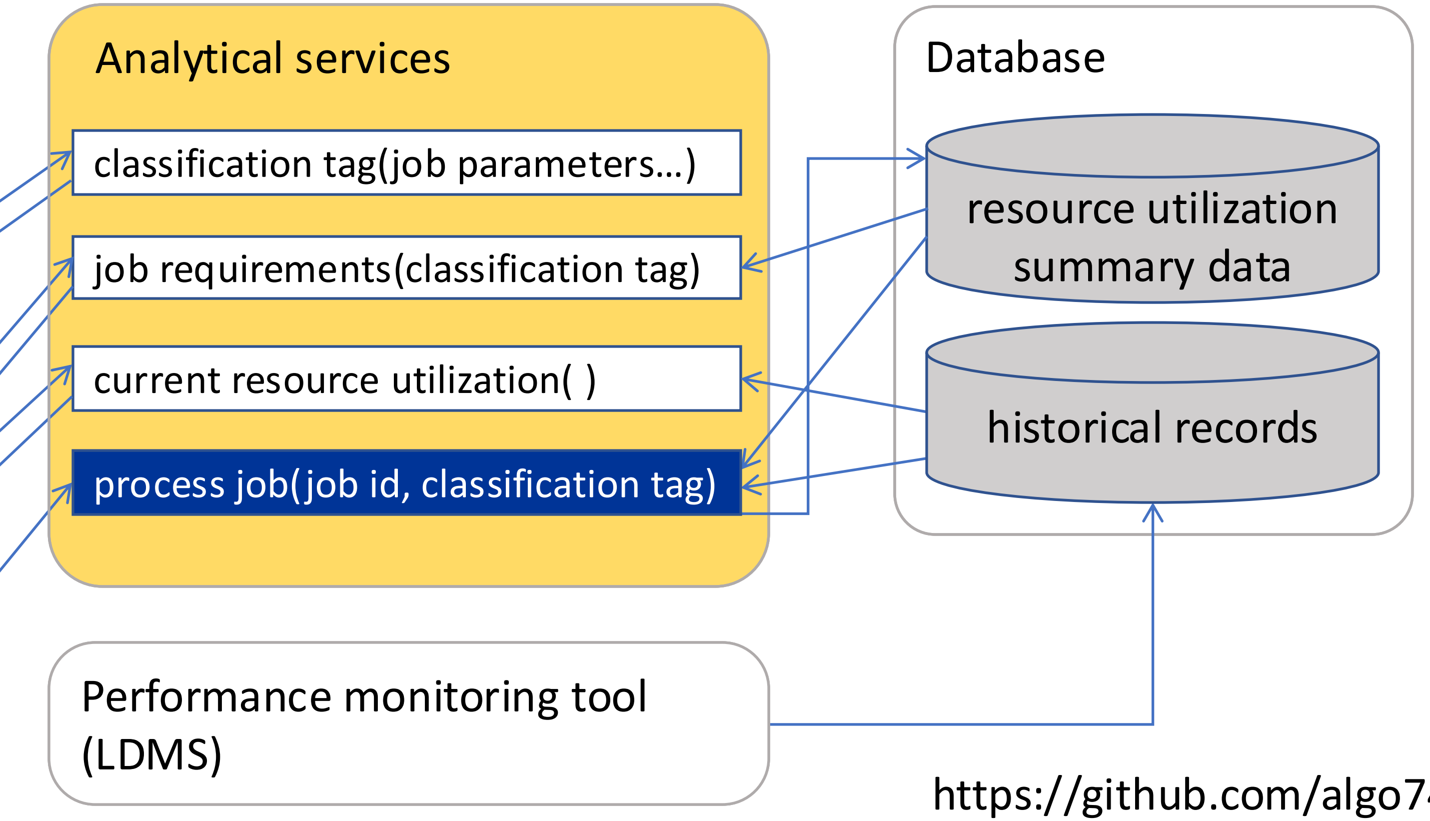
Predicting jobs' resource requirements



- **Step 1:** Classify the job into a group based on the job's parameters, *e.g.*
  - User ID
  - Job type
  - Script name
  - User-specified timelimit
  - Requested number of nodes
- **Step 2:** Retrieve the most recent estimate for the group
  - *We maintain estimates of the groups in a database*

https://github.com/algo74/py-sim-serv/tree/workload-adaptive-paper-2024

Processing finished jobs



- Retrieve LDMS records for the job
- Calculate the average usage and the variance for the job
- Recalculate and update the estimates for the group
  - Exponentially weighted moving average

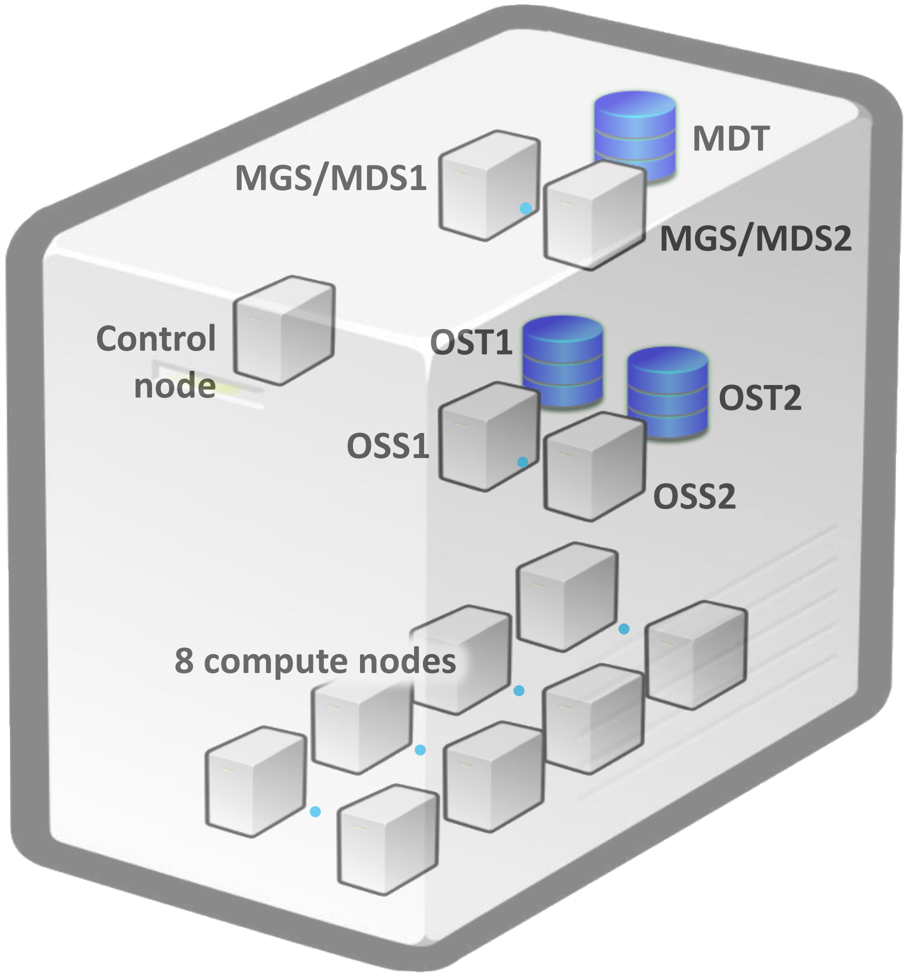
https://github.com/algo74/py-sim-serv/tree/workload-adaptive-paper-2024

Shortcomings of "common" I/O-aware scheduling

- Using "bandwidth" as the throughput limit not necessarily leads to the best performance
- Susceptibility to errors in estimating resource requirements
- May increase idling of in-demand resources

Cluster of virtual machines

- Host
  - Intel Xeon E5-2697 v2 (12 cores, 2.70 GHz)
  - 64 GiB RAM
- Lustre
  - 2 MGS/MDS
  - 2 OSS
- Nodes
  - 1 control node
  - 8 compute nodes



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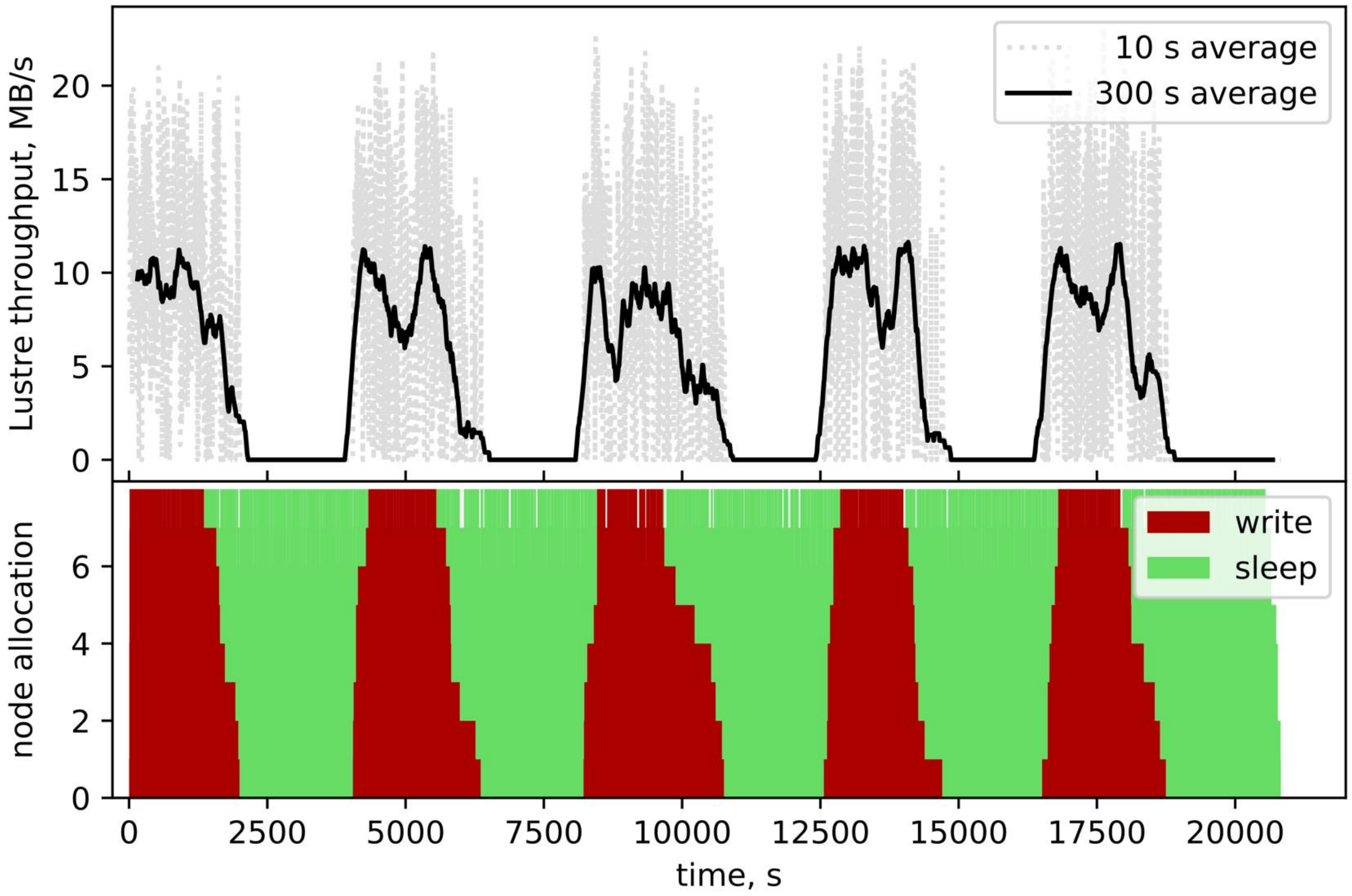
Performance of I/O-aware scheduling:
Job queue 1

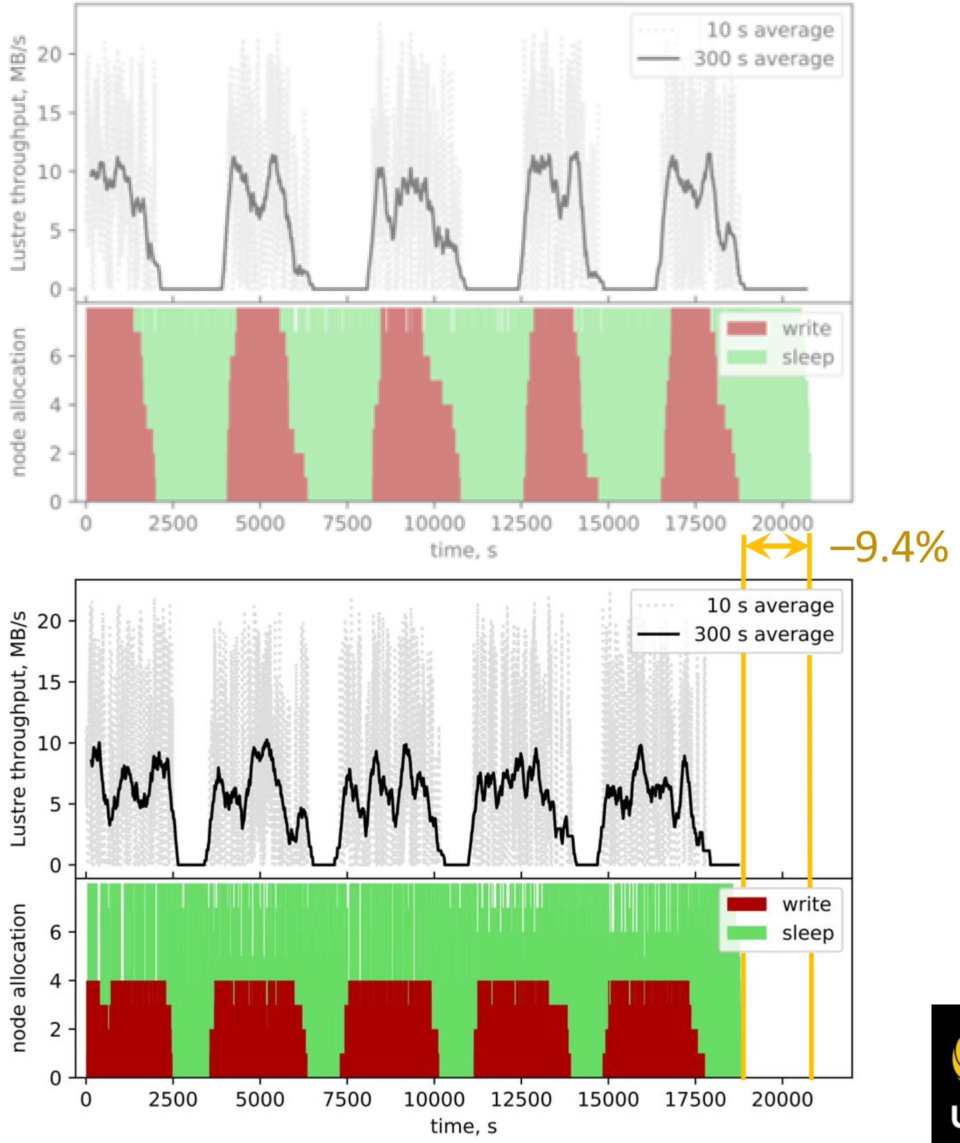
- Periodical pattern:
  5 waves of "write" and "sleep" jobs
- Default Slurm scheduler
  - Start the jobs in order they appear in the queue



Performance of I/O-aware scheduling:
Job queue 1

- Default Slurm scheduler

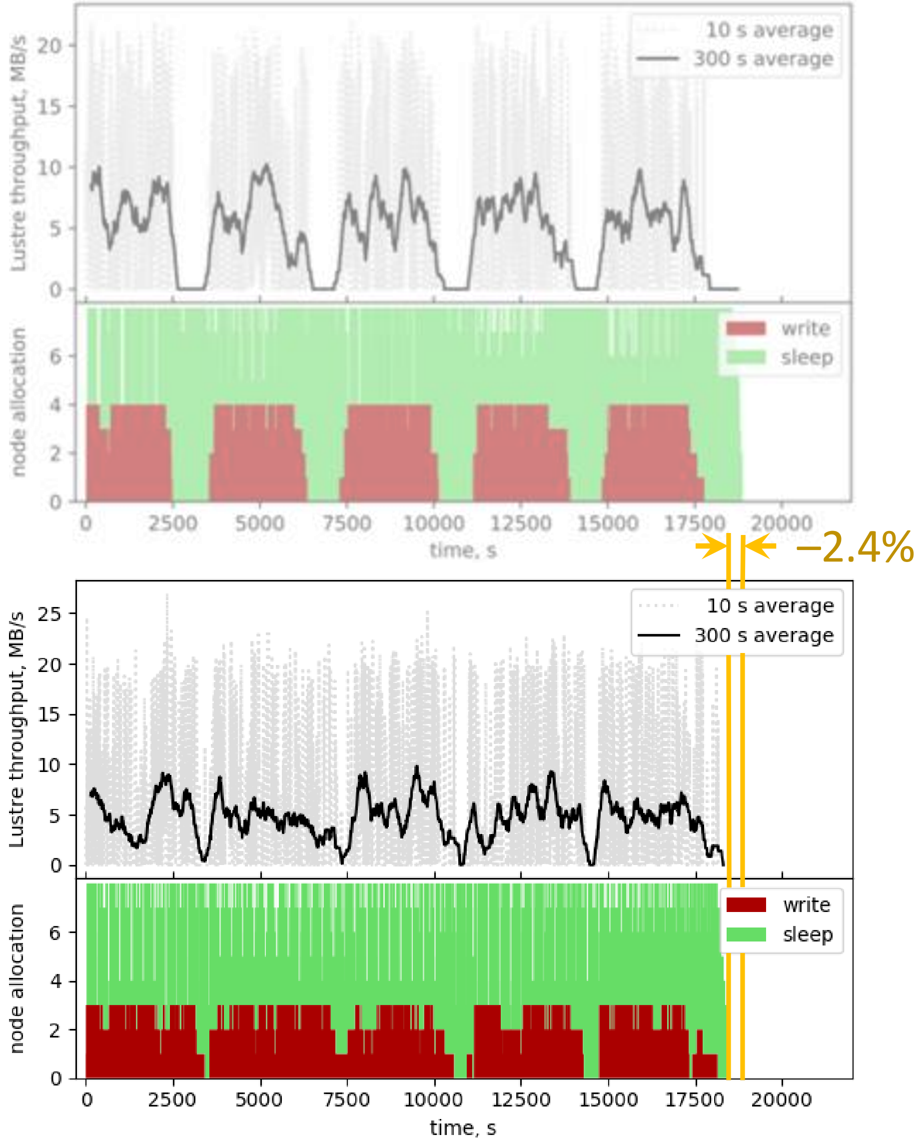
- I/O-aware scheduling
  - 4 "write" jobs simultaneously
  - 9.4% faster



Performance of I/O-aware scheduling:
Job queue 1

- 4 “write” jobs simultaneously

- 3 “write” jobs simultaneously (additional 2.4% speedup)



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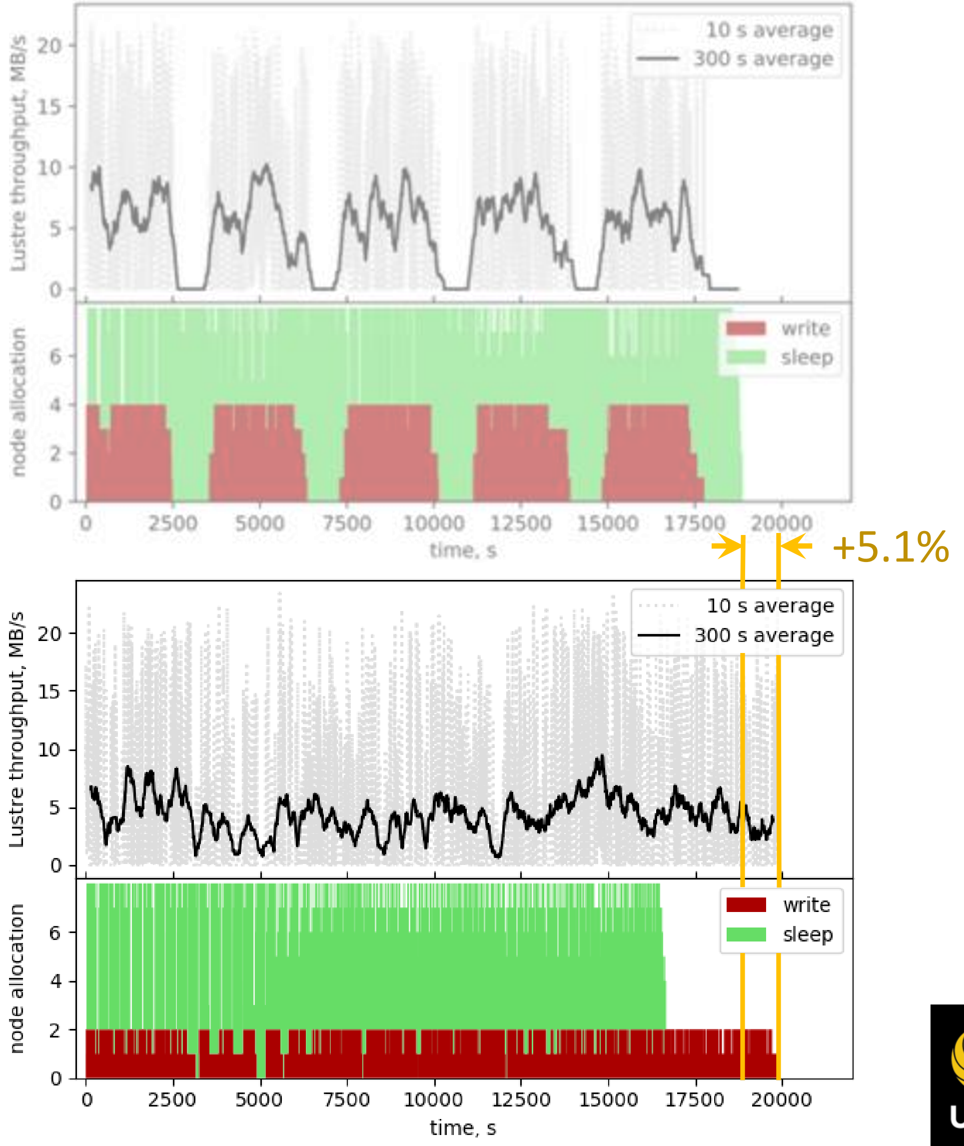
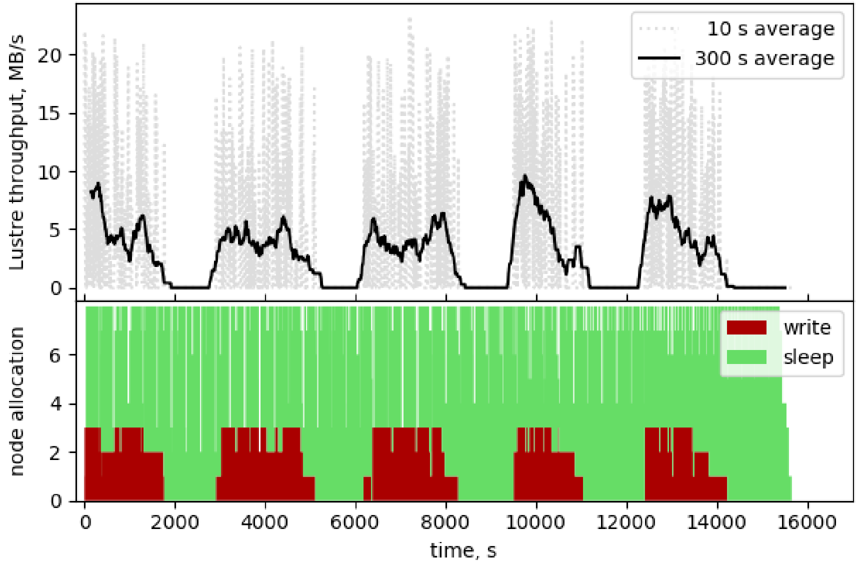
Performance of I/O-aware scheduling:
Job queue 1

- 4 “write” jobs simultaneously
- 2 “write” jobs simultaneously (decrease in performance)

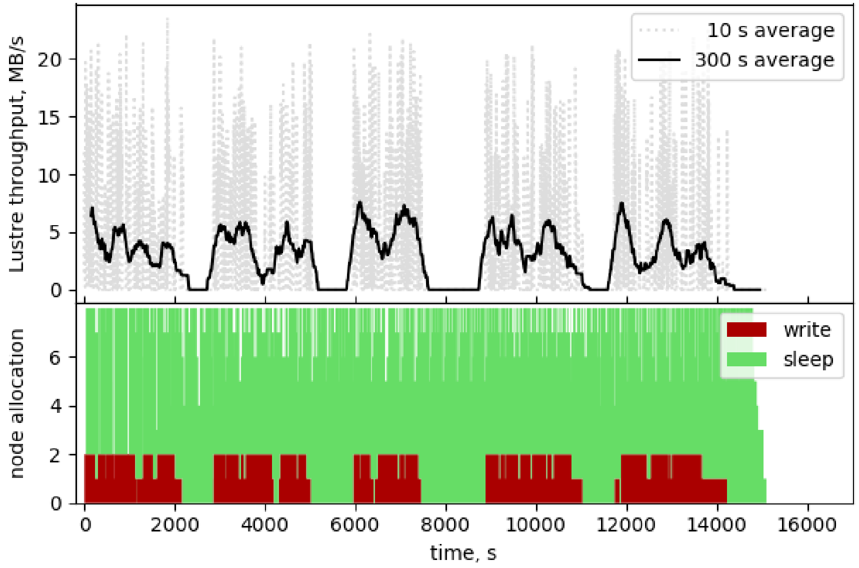


Performance of I/O-aware scheduling:
Job queue 2 (half the ”write” jobs)

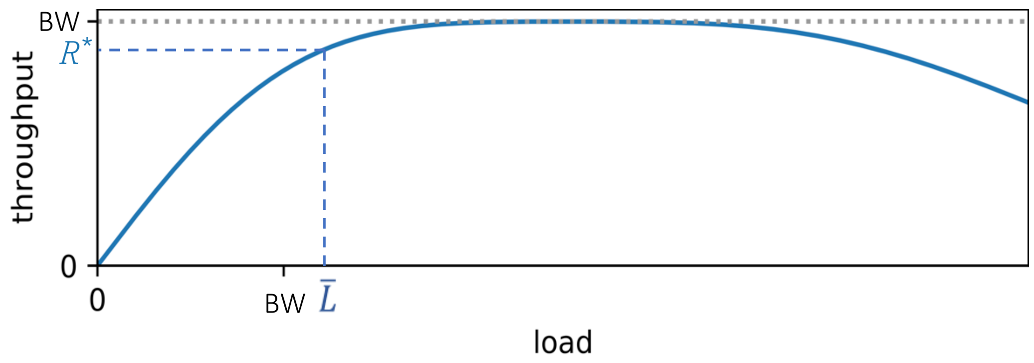
- 3 “write” jobs simultaneously

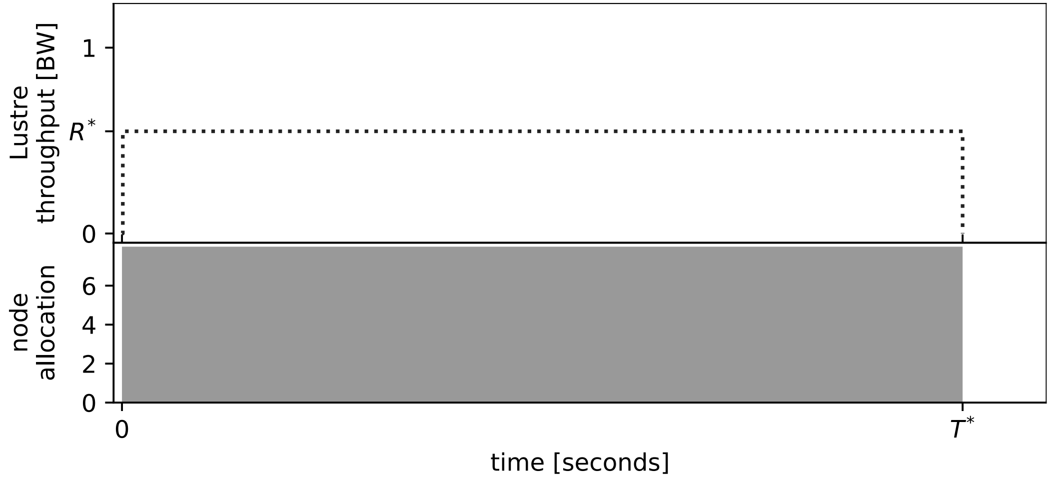


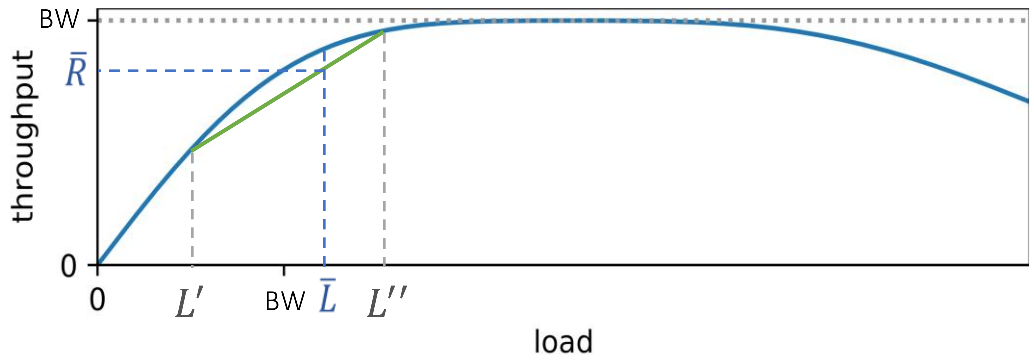
- 2 “write” jobs simultaneously (best performance)

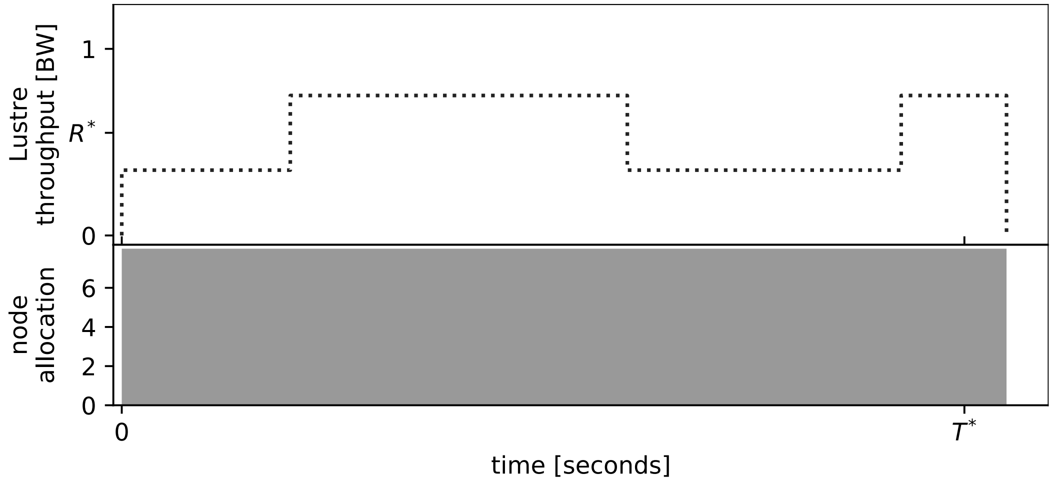


Stable load is optimal

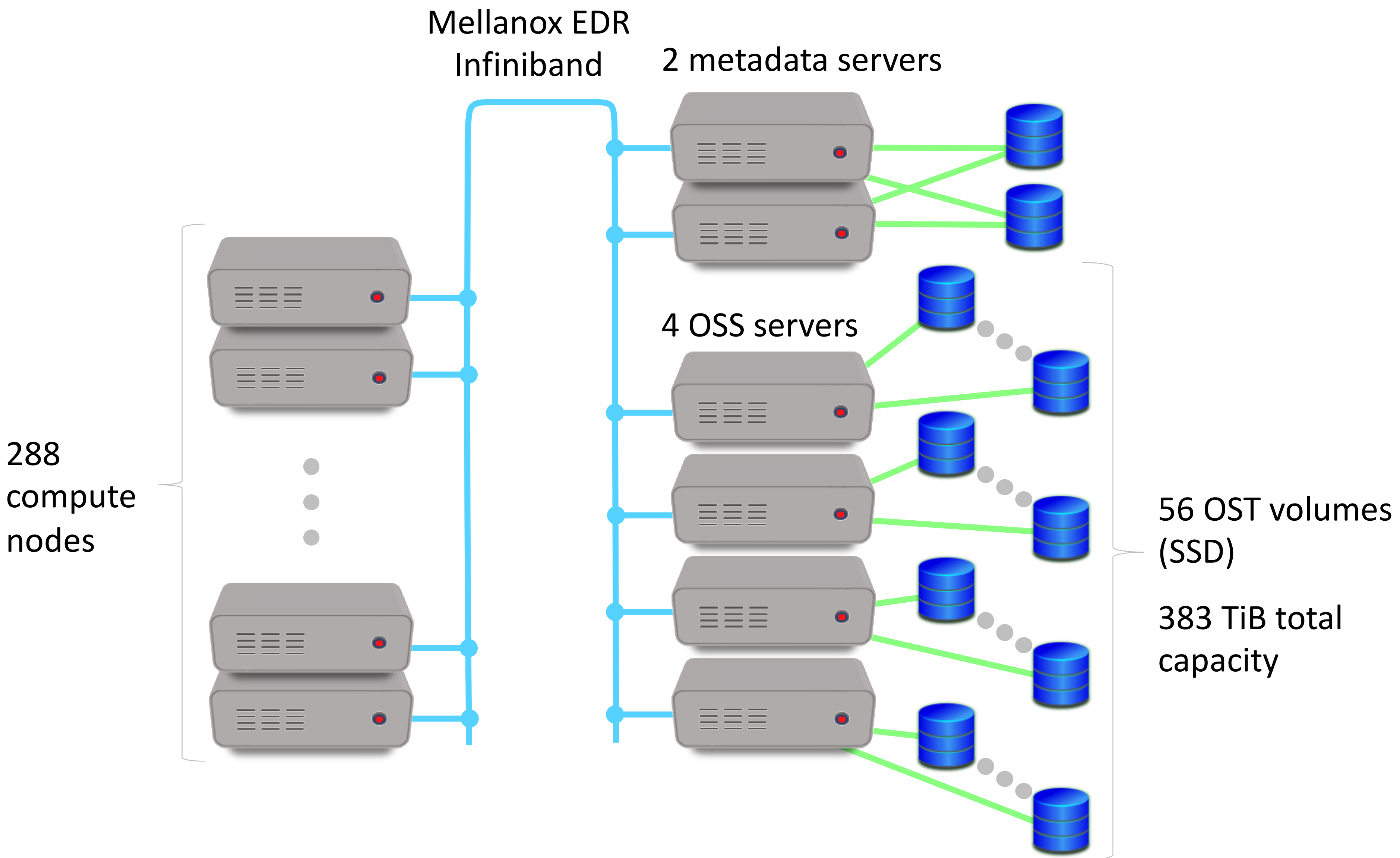








HPC cluster



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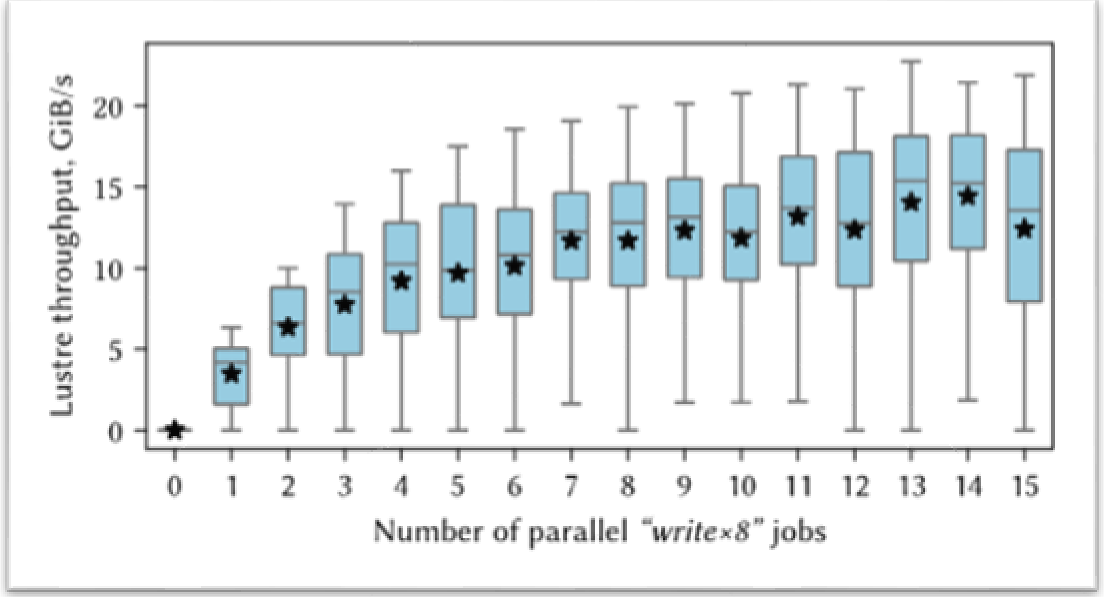
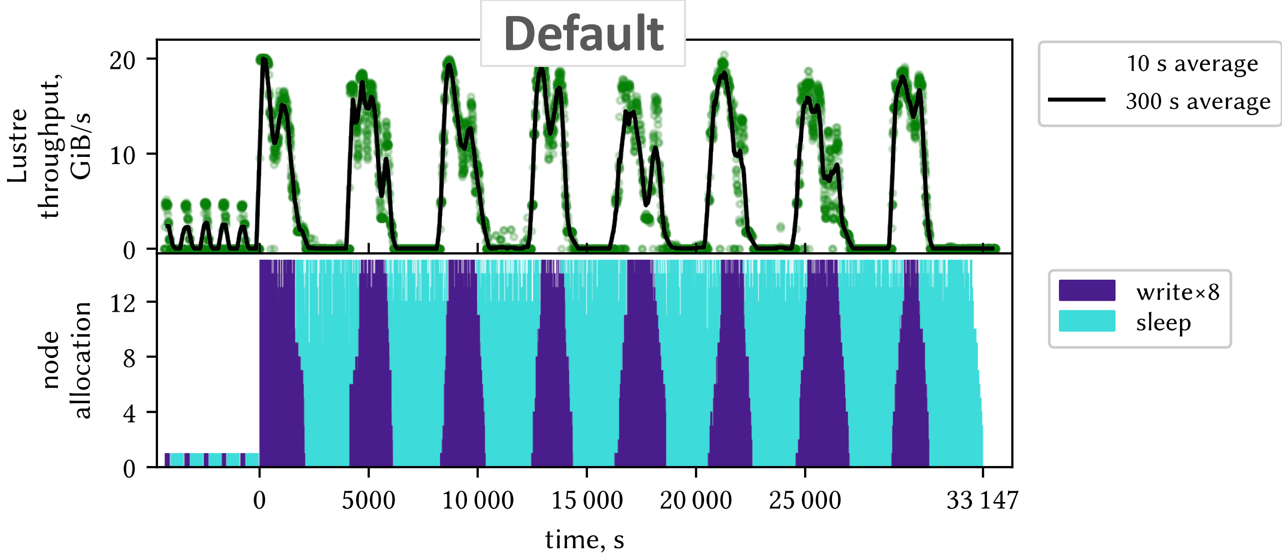
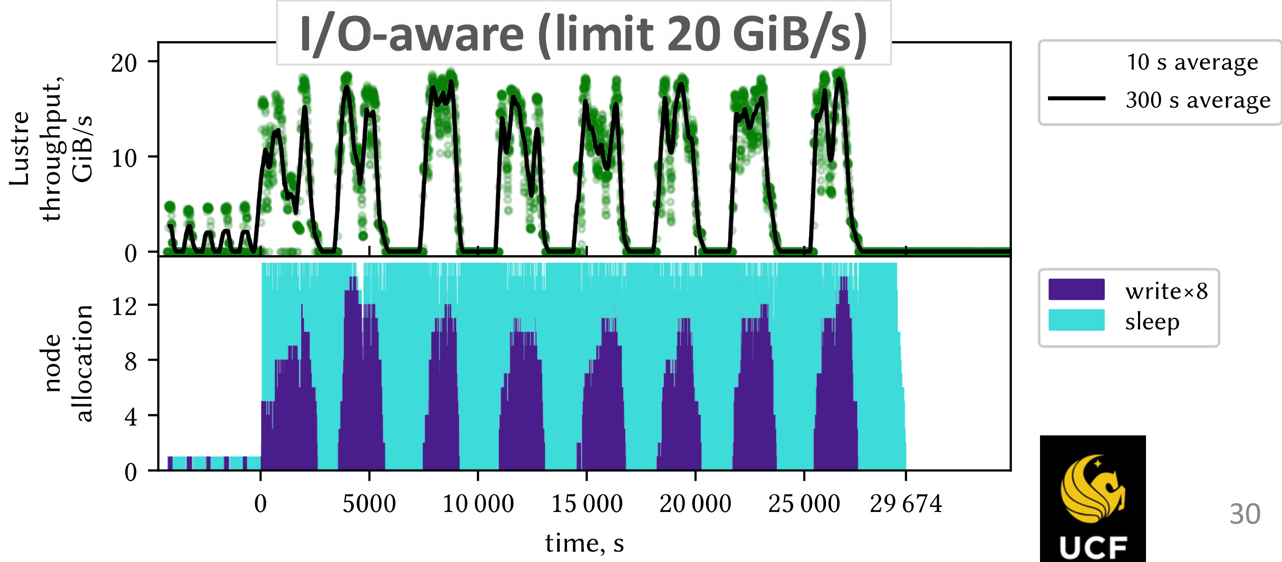
Robustness of I/O-aware scheduling: *"Workload 1"* (HPC cluster)

- Periodical pattern (8×)
  - 30 "write×8" jobs
  - 60 "sleep" jobs
- Bandwidth is 15-20 GiB/s







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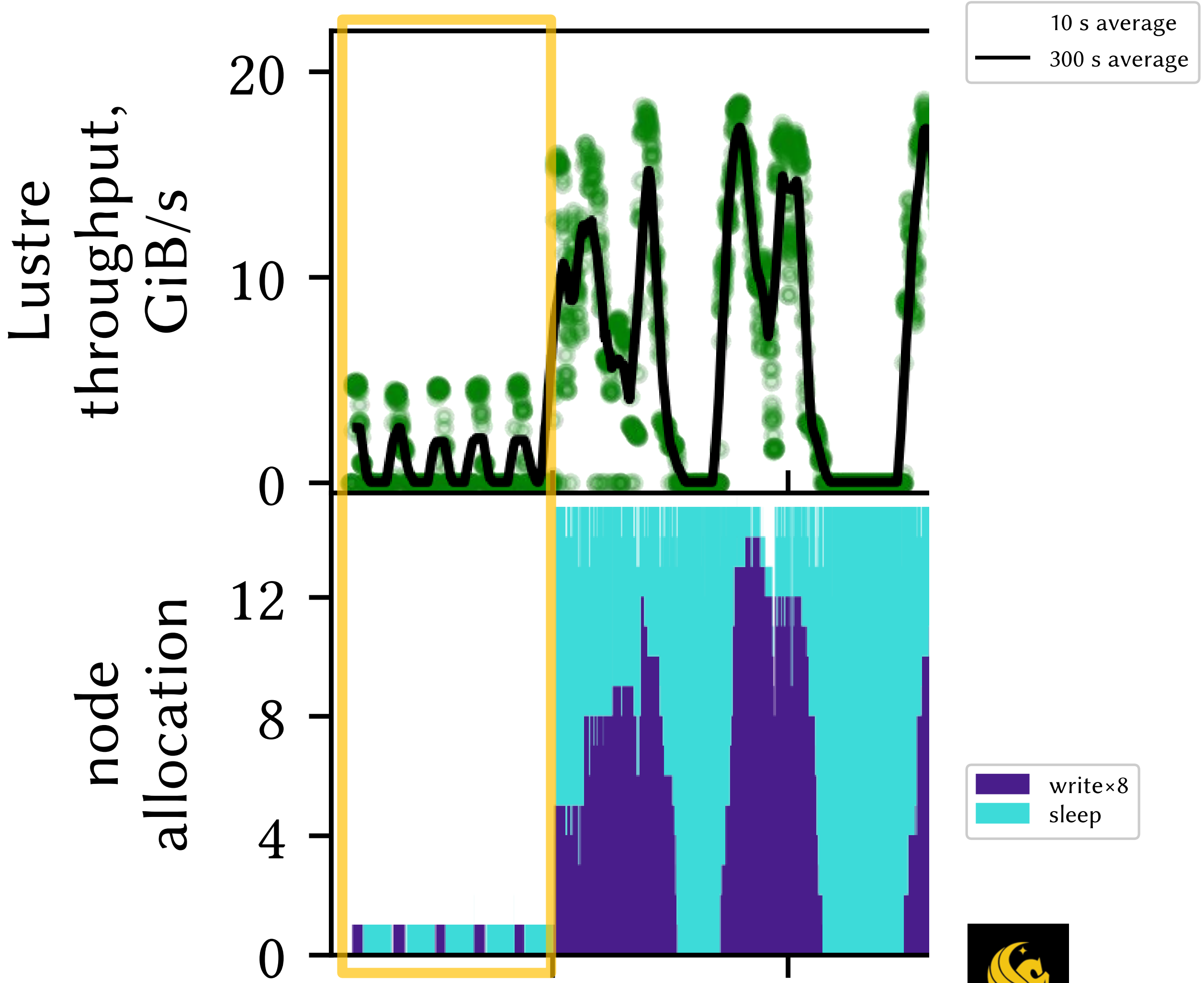
- The estimator is pre-trained by running jobs in isolation



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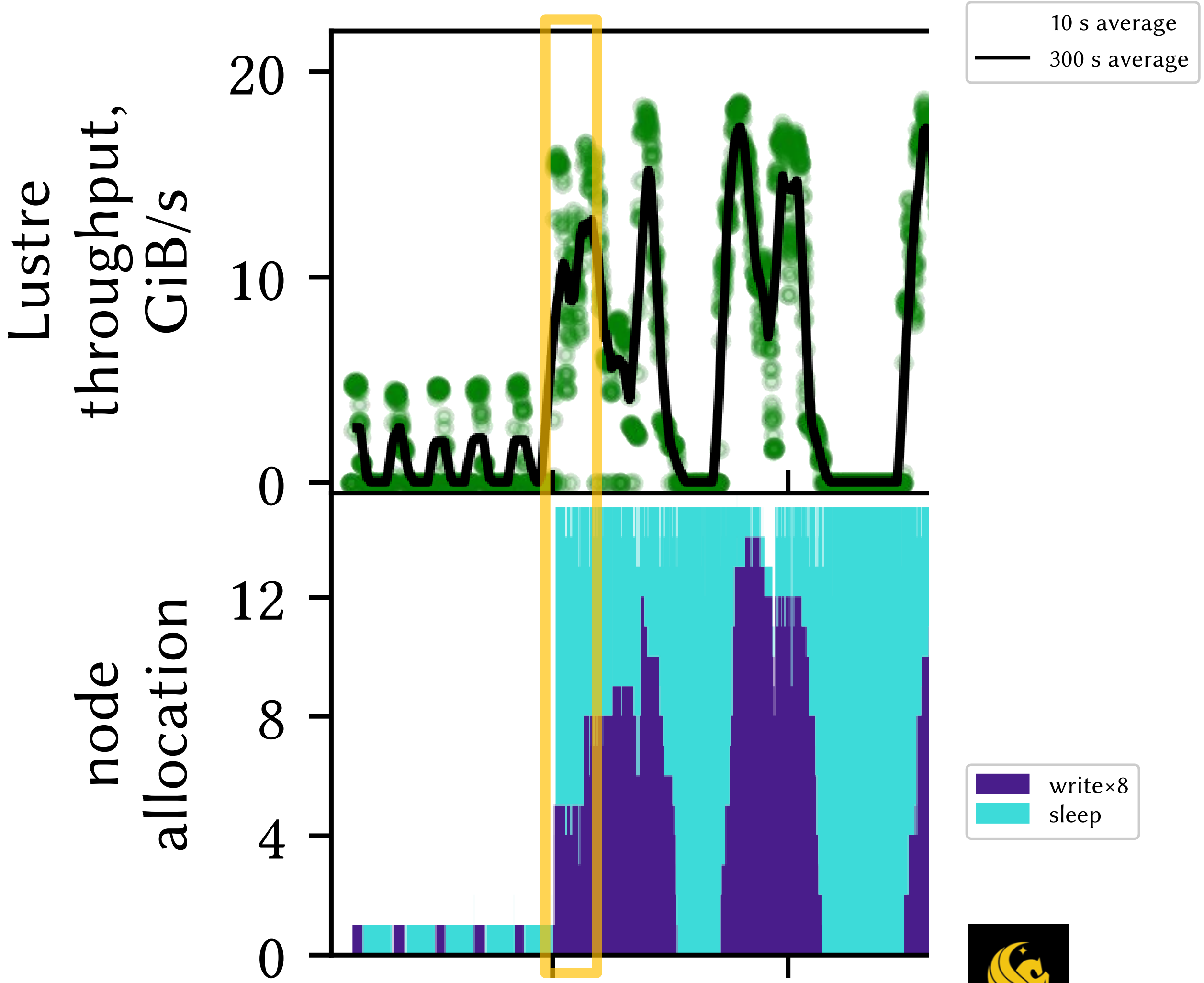

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"Workload 1" (HPC cluster)

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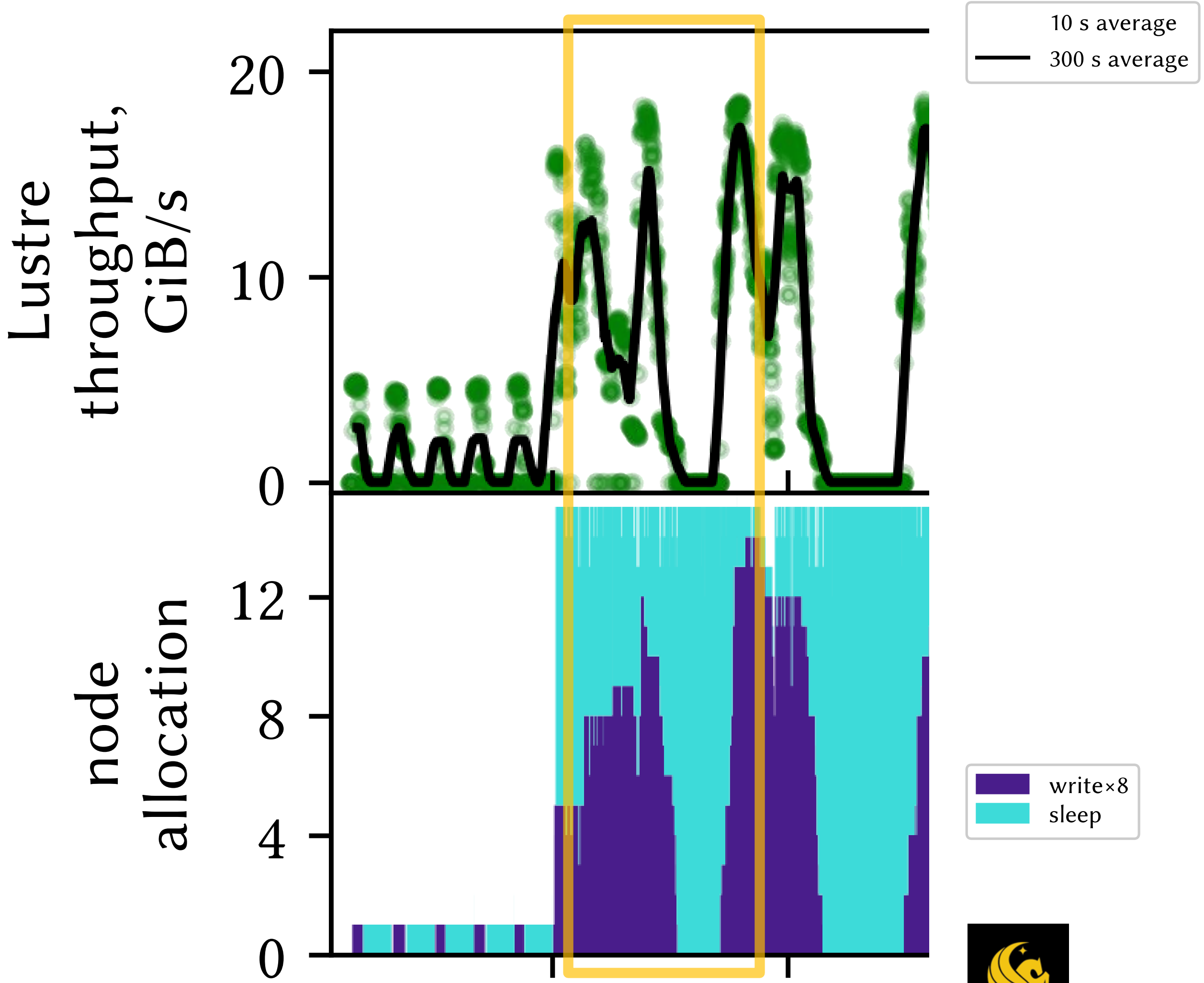
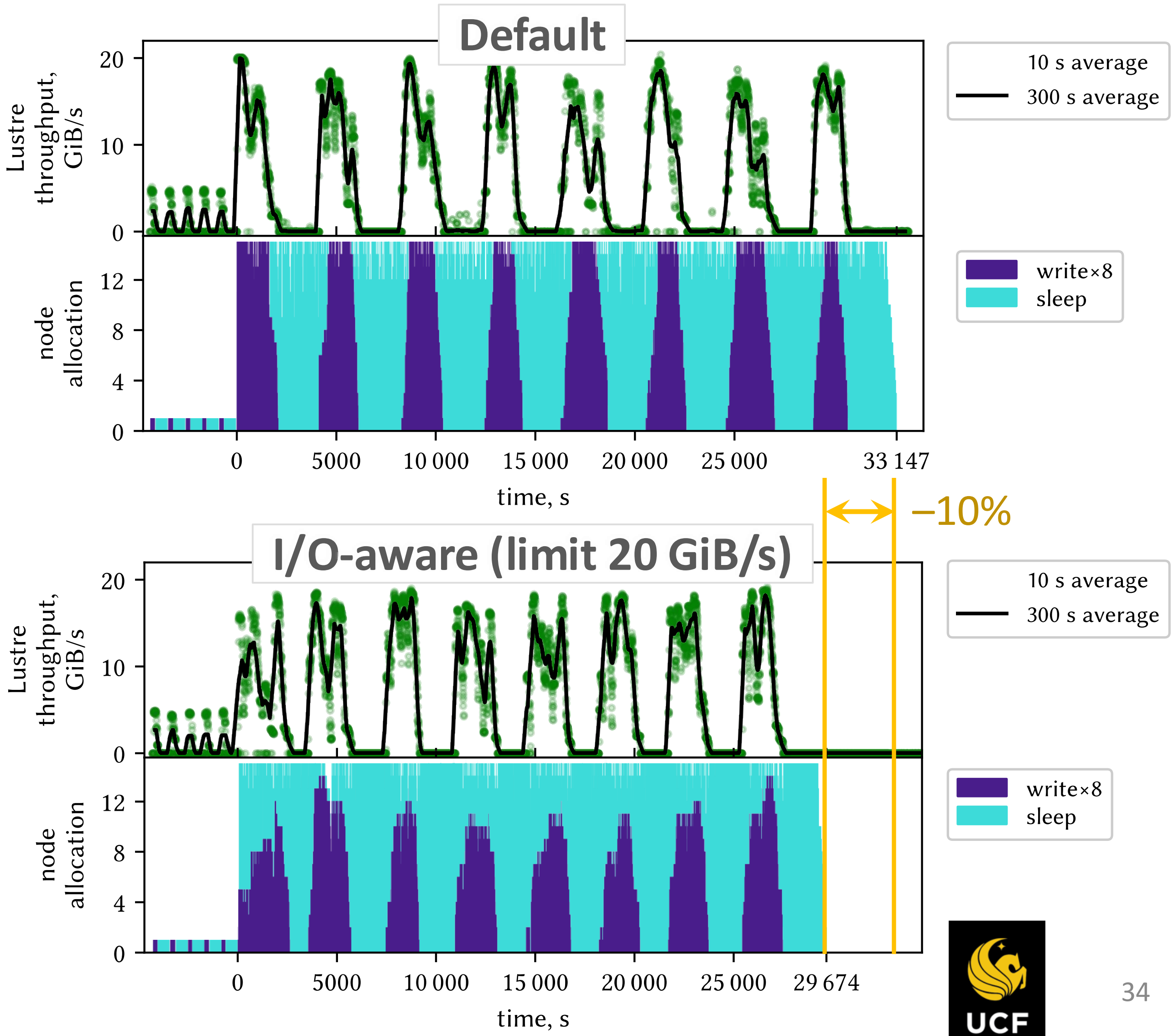
  - 60 "sleep" jobs
- Bandwidth is 15-20 GiB/s
- The estimator is pre-trained by running jobs in isolation
- I/O-aware scheduler initially schedules no more than 5 "write×8" jobs
- Later, I/O-aware scheduler allows as many as 12 "write×8" jobs



Robustness of I/O-aware scheduling:
"Workload 1" (HPC cluster)

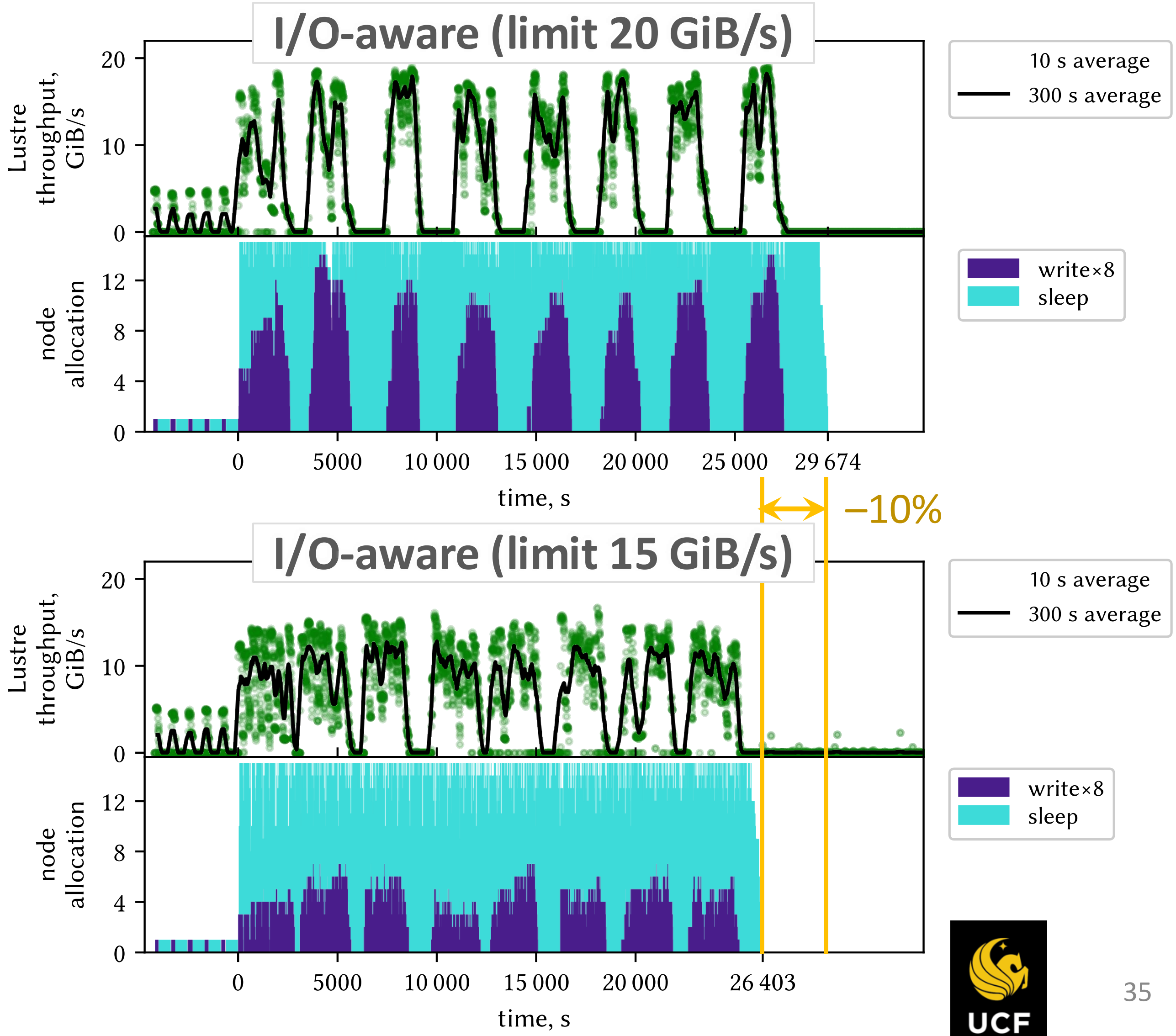
- 10% improvement using I/O-aware scheduler with 20 GiB/s throughput limit



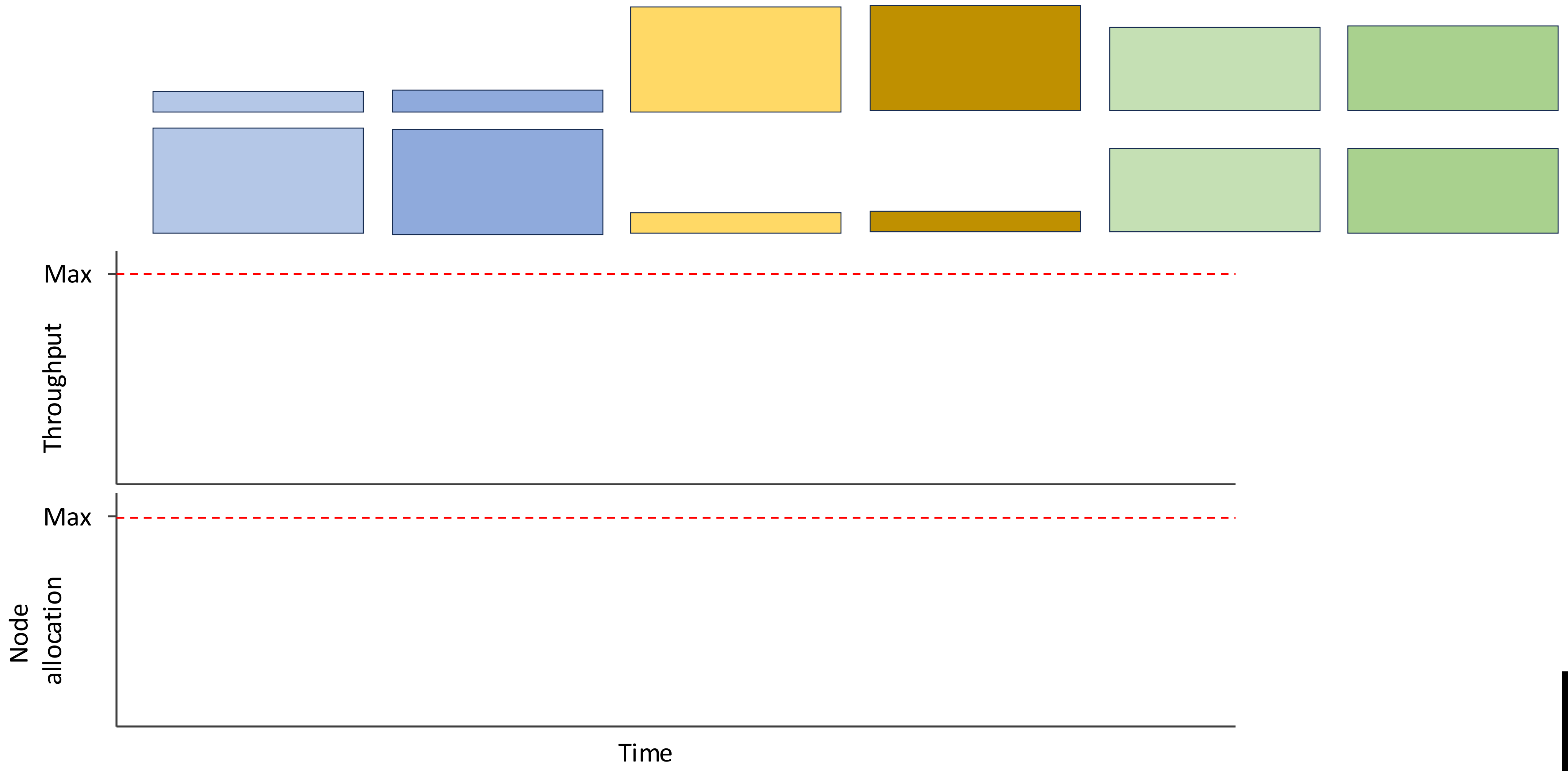
Robustness of I/O-aware scheduling:
"*Workload 1*" (HPC cluster)

- 10% improvement using I/O-aware scheduler with 20 GiB/s throughput limit
- additional 10% improvement using 15 GiB/s throughput limit
  - 20% improvement overall

- **Overscheduling leads to further overscheduling**
- **Systematic error is not corrected**



Multi-resource scheduling: Idling in-demand resources



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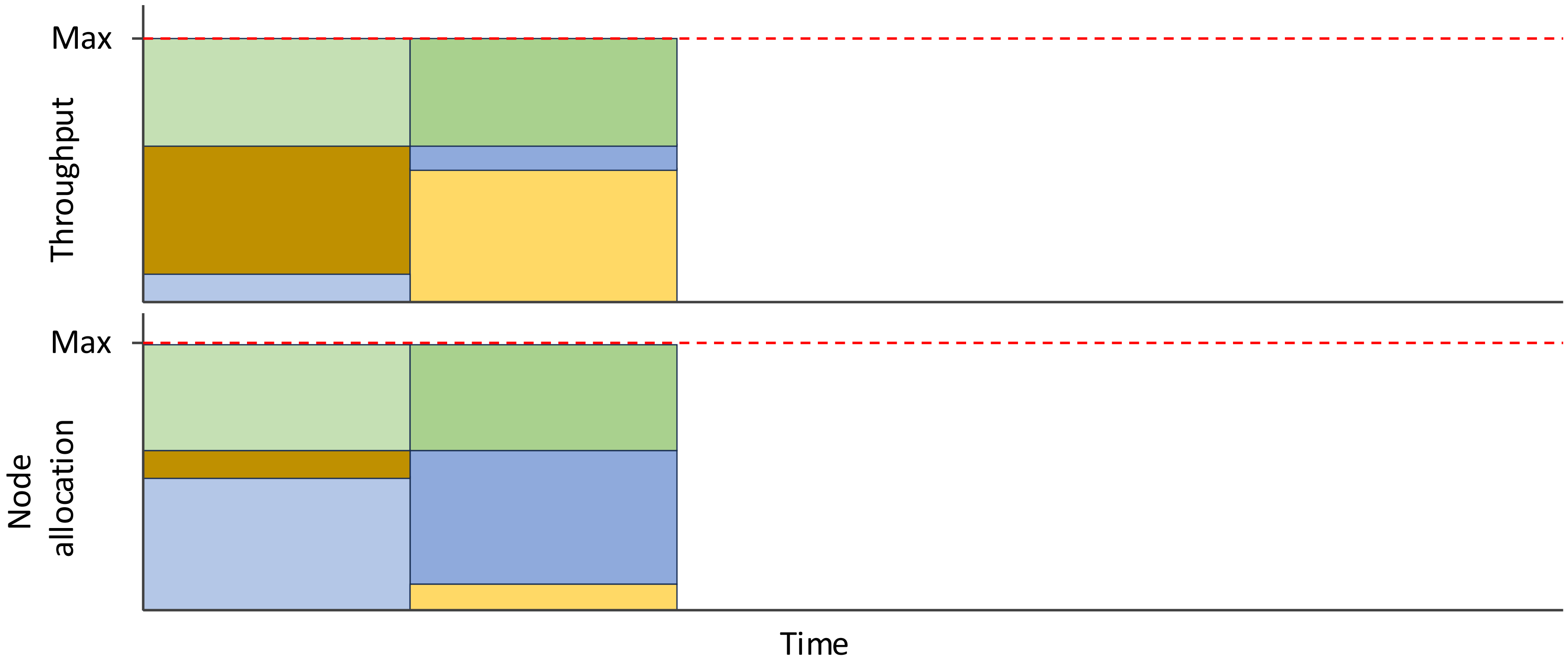

Shortcomings of I/O-aware scheduling

- Better performance can be attained in case rate vs load dependence is concave
- I/O-aware scheduling is not robust when job loads are approximated by job rates
  - Overscheduling leads to further overscheduling
  - Systematic error is not corrected
- I/O-aware scheduling (as other multi-resource scheduling) increase possibly of resources being idle while they are in-demand

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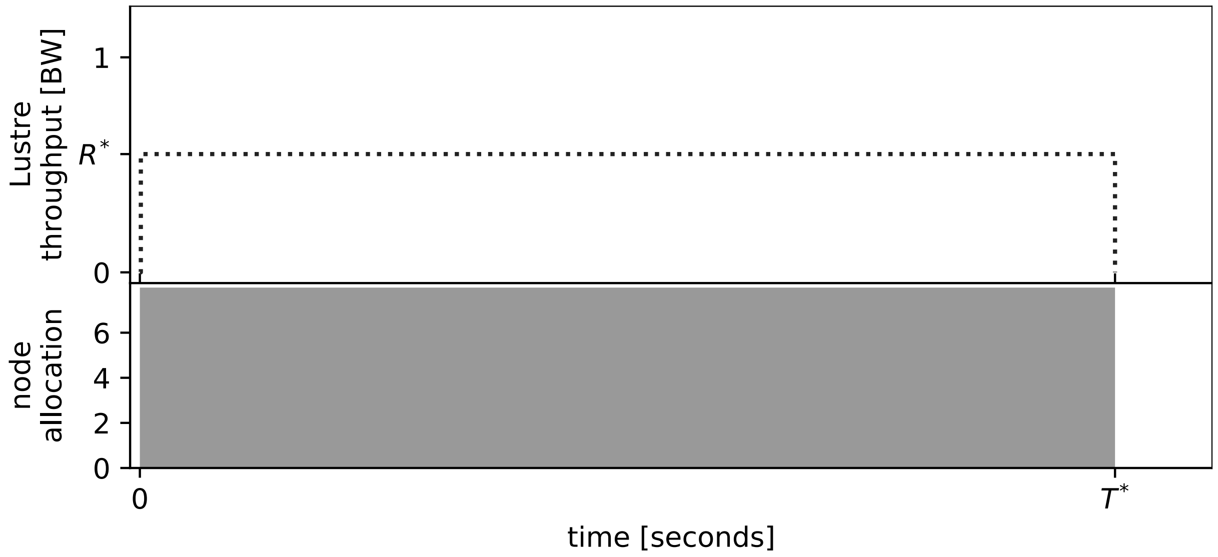
Workload-adaptive scheduling

I/O throughput is a special type of resource

- Cluster-wide, non-exclusive resource
  - The scheduler cannot prevent jobs from using more than allocated
  - Jobs that use the resource can impede each other progress
- Users may not know how their jobs use the resource
  - Measured resource utilization depends on job’s running conditions

Workload-adaptive scheduling: Ideal scenario

- Full utilization of nodes
- Stable I/O throughput



$$Ideal\ makespan = T^* = \frac{Total\ area\ of\ jobs}{Total\ number\ of\ nodes}$$

$$Ideal\ throughput = R^* = \frac{Total\ number\ of\ bytes\ read/written}{Ideal\ makespan}$$

Workload-adaptive scheduling: Practical objective

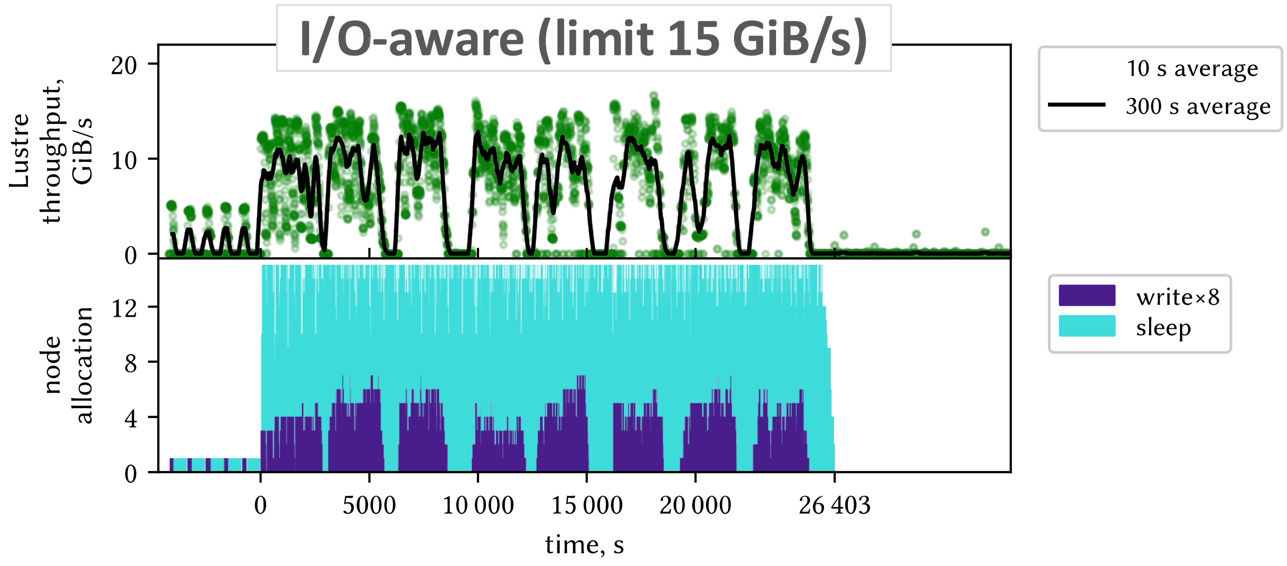
- Target throughput is estimated from pending jobs

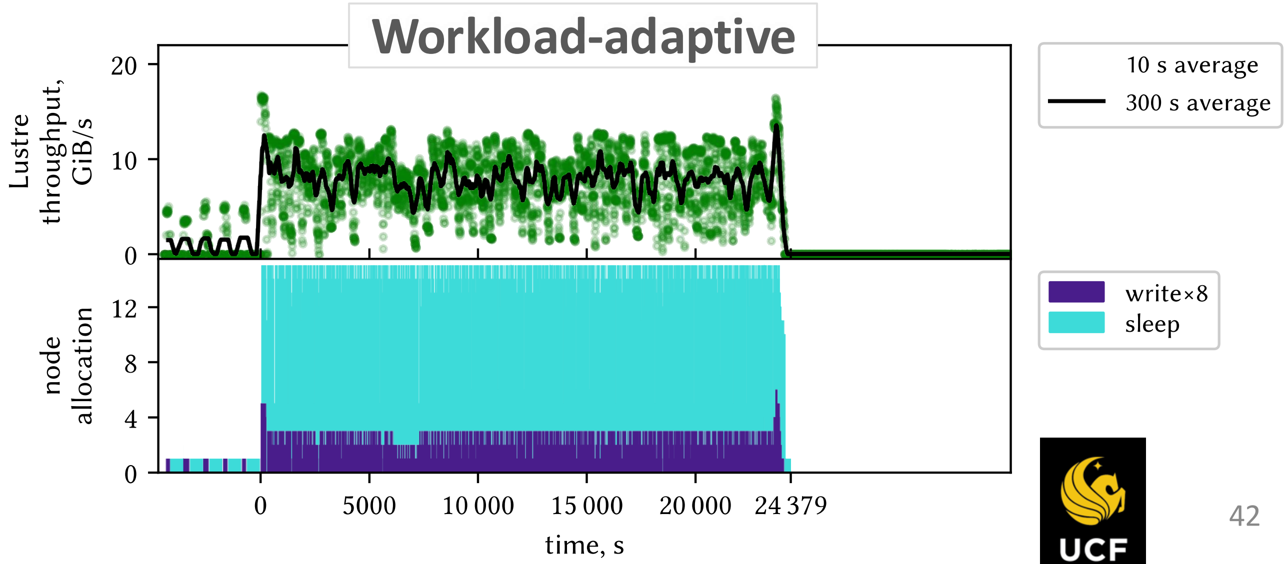
$$Target\ throughput = \frac{Estmated\ number\ of\ bytes\ read/written}{Estimated\ makespan}$$

- Scheduler attempts to maintain the throughput close to $Target\ throughput$ while keeping all nodes occupied
  - "Hard limit" (bandwidth) is still used to prevent overload
- Predictions of job parameters (and correspondingly $Target\ throughput$) are continuously updated

Workload-adaptive scheduling:
"*Workload 1*" (HPC cluster)

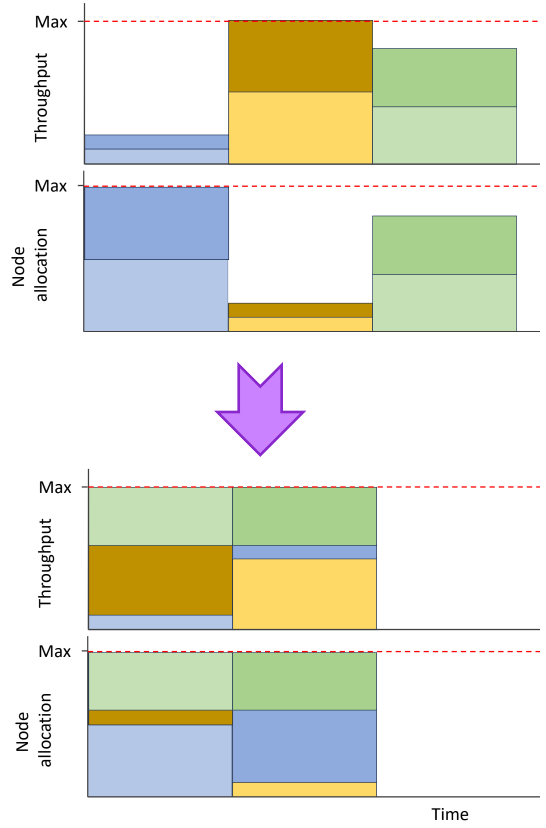
- Workload-adaptive I/O-aware scheduler (bottom) converges to optimal state
  - 5.5% better than "common" I/O-aware scheduler with 15 GiB/s limit
  - 25% better than the default Slurm scheduler





Reducing node idle time

- The algorithm described so far:
  - Jobs using the file system can't be scheduled at time slots for which $Target\ throughput$ has been reached
    - only jobs with "zero load" can still be scheduled
  - The algorithm may cause idle node time and performance degradation if "zero load" jobs are not available
- The algorithm should
  - Keep idle time of the nodes at minimum
  - Keep file system load reasonably close to $Target\ throughput$
- Solution: **Two-group approximation**



Two-group approximation

- Divide jobs into 2 groups according to r^*:

"zero jobs": $\{j: \quad r_j \leq n_j r^*\}$

"regular jobs" : $\{j: \quad r_j > n_j r^*\}$

job's estimated throughput

job's number of nodes

- r^* can be set, for instance, so that

$$\sum_{j \in \text{"zero jobs"}} n_j D_j \geq \sum_{j \in \text{"regular jobs"}} n_j D_j$$

job's estimated runtime

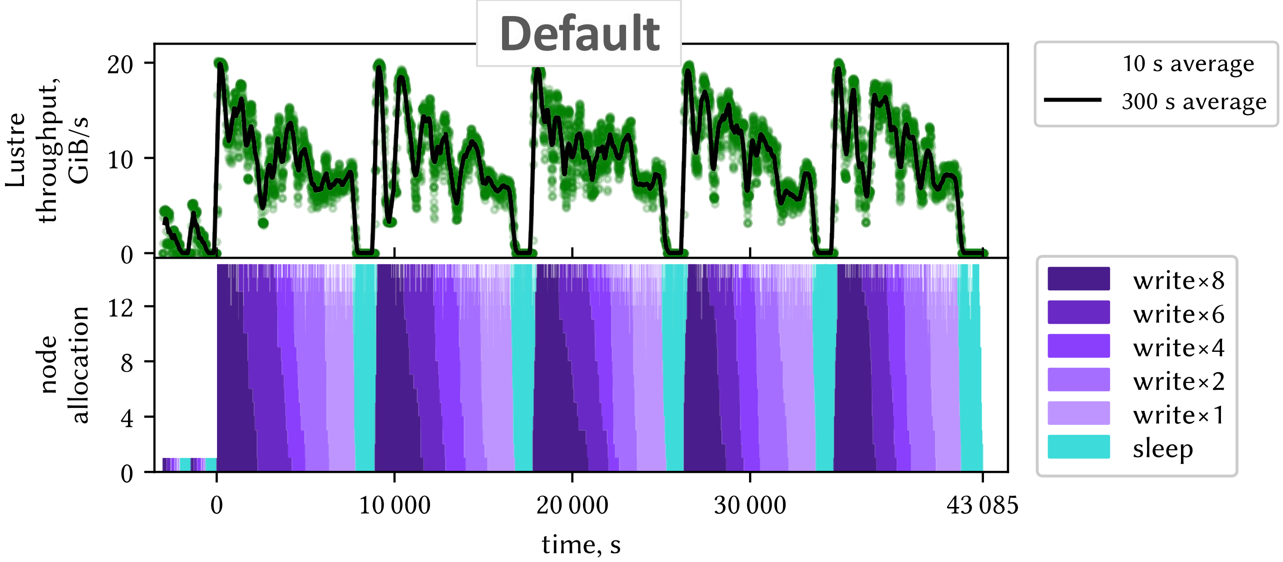
- Find the average load of "zero jobs"

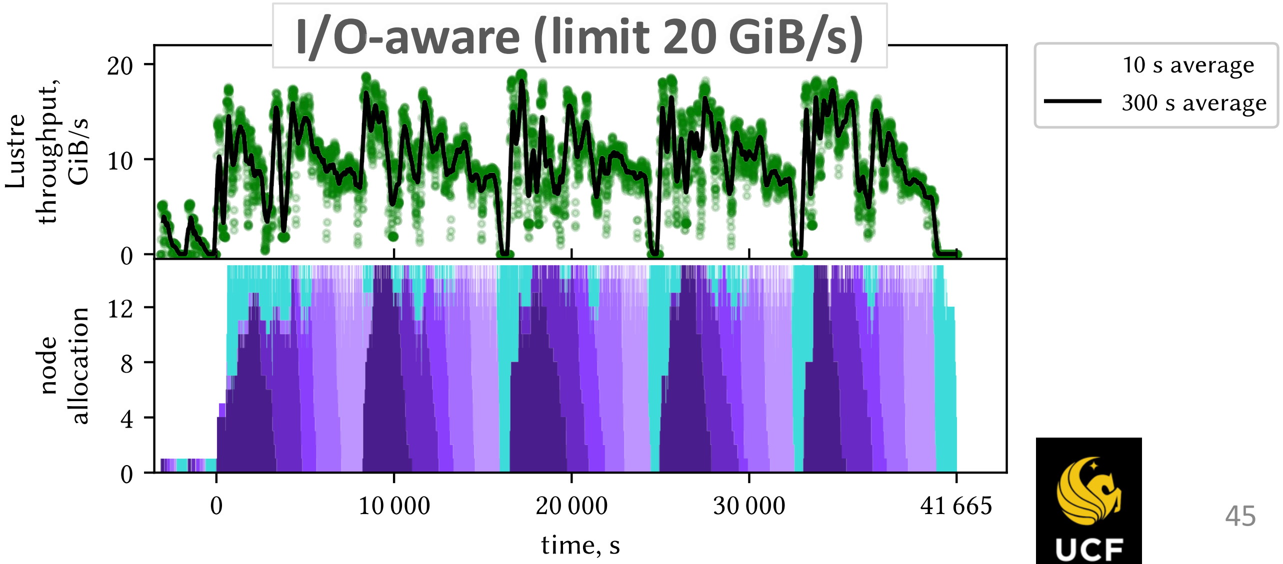
$$\overline{r^*} = \sum_{j \in \text{"zero jobs"}} r_j n_j D_j \Big/ \sum_{j \in \text{"zero jobs"}} n_j D_j$$

- Recalculate target $R^{*\prime} = Target\ throughput - N\overline{r^*}$
- Recalculate jobs' requirements $r_j' = \begin{cases} 0, & j \in \text{"zero jobs"} \\ r_j - n_j\overline{r^*}, & j \in \text{"regular jobs"} \end{cases}$

Two-group approximation:
"Workload 2" (HPC cluster)

- Periodical pattern (5×)
  - 30 "write×8" (8 threads × 10 GiB)
  - 30 "write×6" (6 threads × 10 GiB)
  - 30 "write×4" (4 threads × 10 GiB)
  - 70 "write×2" (2 threads × 10 GiB)
  - 120 "write×1" (1 thread × 10 GiB)
  - 60 "sleep" (10 min)
- 4% improvement using I/O-aware scheduler with 20 GiB/s throughput limit





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Two-group approximation:
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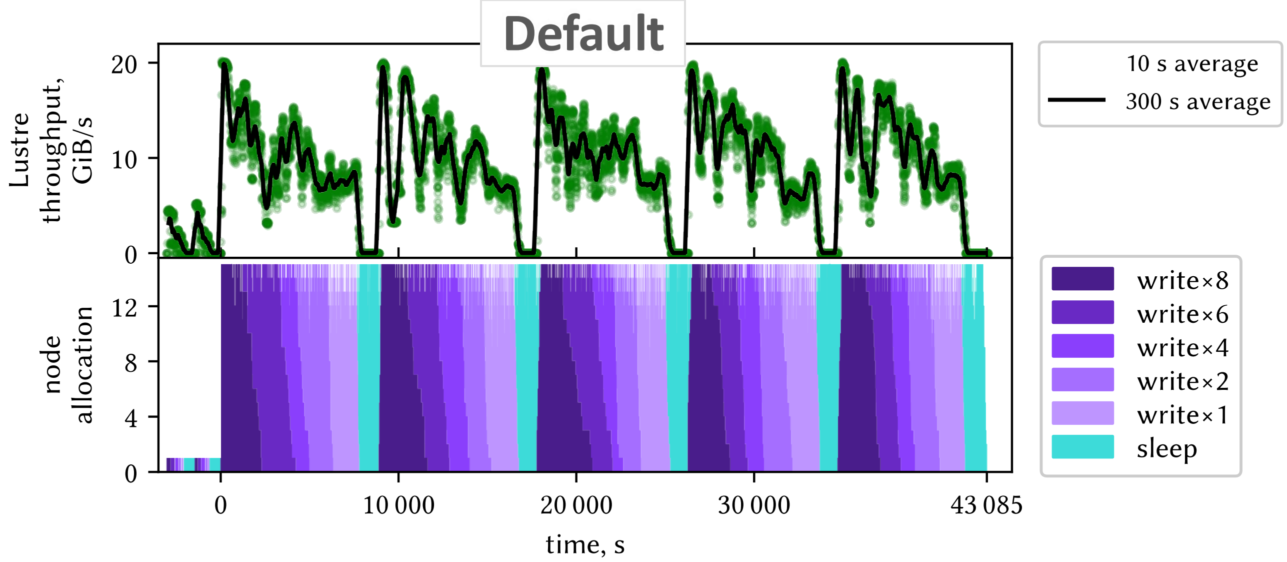
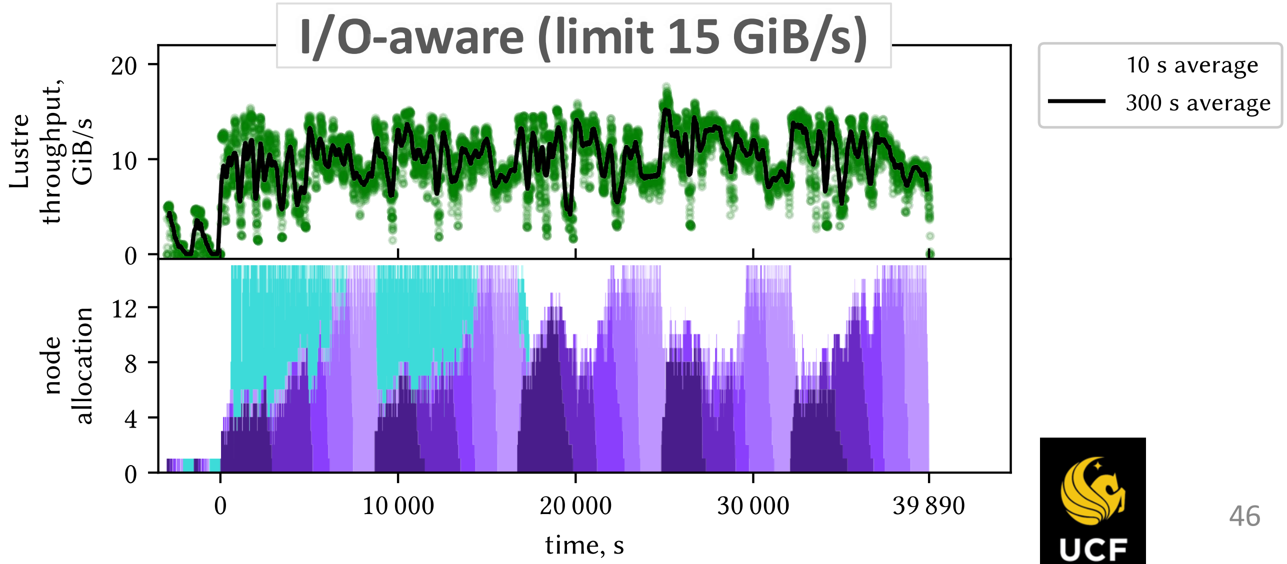
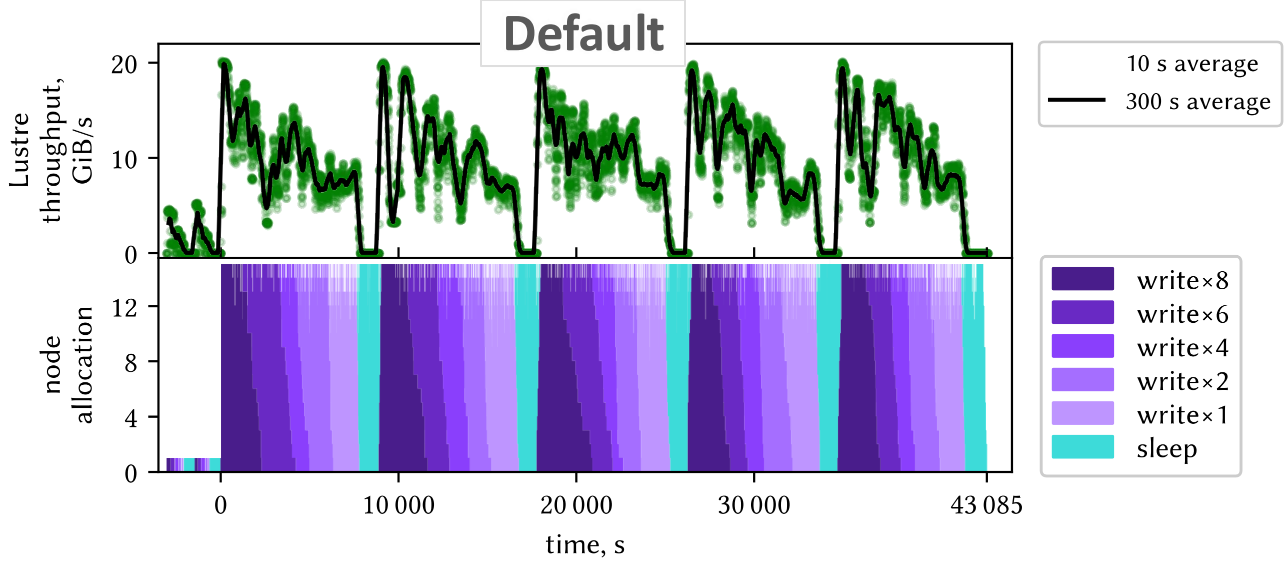
- Periodical pattern (5×)
  - 30 "write×8" (8 threads × 10 GiB)
  - 30 "write×6" (6 threads × 10 GiB)
  - 30 "write×4" (4 threads × 10 GiB)
  - 70 "write×2" (2 threads × 10 GiB)
  - 120 "write×1" (1 thread × 10 GiB)
  - 60 "sleep" (10 min)
- 7% improvement using I/O-aware scheduler with 15 GiB/s throughput limit
  - Idle nodes
  - Could have been worse than the default scheduling

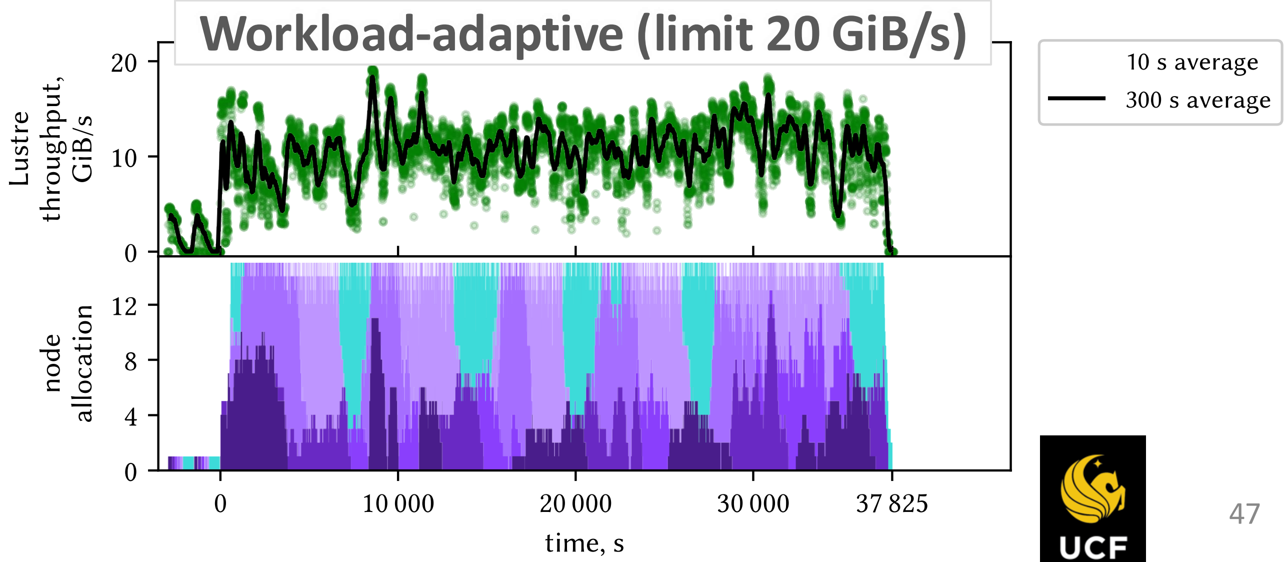




Two-group approximation:
"Workload 2" (HPC cluster)

- Workload-adaptive scheduler with 20 GiB/s limit (bottom) maintains constant throughput without causing idle nodes
  - 5% better than I/O-aware scheduler with 15 GiB/s limit
  - 12% better than the default Slurm scheduler





Conclusions

- We demonstrated a prototype of I/O-aware scheduler based on Slurm and LDMS
  - Predictions of resource requirement based on historical data
  - Ability to manage Lustre throughput
- We proposed Workload-adaptive scheduling approach
  - with "two-group" approximation
- We evaluated the feasibility of the approach
  - on a real HPC cluster
  - on a cluster of virtual machines
  - by simulations

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Acknowledgements

- The works at the University of Central Florida were supported through contracts with Sandia National Laboratories
- Thanks to Benjamin Schwaller, Omar Aaziz, and others at SNL for valuable discussions and help throughout the project
- Thanks to Christina Peterson, Kenneth Lamar and the rest of Prof. Dechev team at UCF

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

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