Managing Pending Events In Sequential and Optimistic Parallel Discrete Event Simulations

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Overview

Introduction - DES

- **Discrete Event Simulation (DES)** is used to simulate a variety of systems that can be decomposed into interacting objects.
- The objects in the simulation are referred to as logical processes (LPs) and model objects in the real world.
- LPs interact by exchanging time stamped events and process events in priority order with event priorities determined by their time stamp.
- Event processing occurs in discrete time steps and indicates a state change in the simulated system.
- Events that have yet to be processed are called "**pending events**".
- Data structures for handling pending events follow a priority queue based implementation.

Introduction - Parallel Simulation

Parallel discrete event simulation (PDES) involves executing a DES on parallel computers.

Benefits:

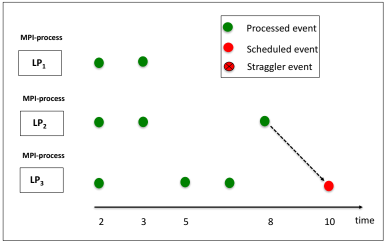
- Increase throughput.
- Increase the scale of problem.

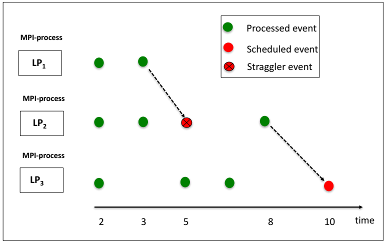
Distributed memory frameworks:

- LPs are subdivided or partitioned to operate on different compute units.
- Event processing on the different compute units must be synchronized – **causality violations**.

Introduction - Time Warp

Synchronization of LPs is needed to prevent causality violations.





Synchronization strategy: optimistic (Time Warp).

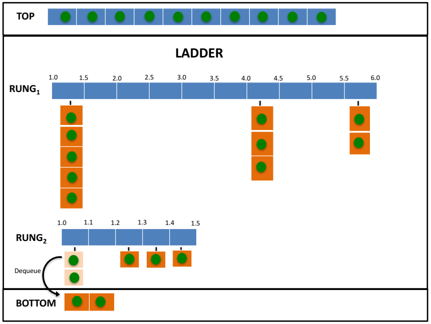
Research Motivation

- The synchronization strategy in PDES can impact the effectiveness of data structure because of the additional processing required during rollback recovery operations.
- Data structures for managing and prioritizing pending events play a critical role in ensuring efficient sequential and parallel simulations.
- A data structure that can effectively handle large number of concurrent events (**i.e. an average of one million events**).

Related Work

- Franceschini et al. compared several priority-queue based pending event data structures to evaluate their performance in the context of sequential DEVS simulations. They found that Ladder Queue outperformed every other priority queue based pending event data structure such as Sorted List, Minimal List, Binary Heap, Splay Tree, and Calendar Queue.
- Dickman et al., compared event list data structures that consisted of Splay Tree, STL Multiset and Ladder Queue. However, the focus of their paper was in developing a framework for handling pending event set data structure in shared memory PDES.
- Gupta et al., extended their implementation of Ladder Queue for shared memory Time Warp based simulation environment, so that it supports lock-free access to events in the shared pending event set.
- Marotta et al., have contributed to the study of pending event set data structures in threaded PDES through the design of the Non-Blocking Priority Queue (NBPQ) data structure.

Ladder Queue (**ladderQ**)



Time Complexity

Enqueue: 1^*

Dequeue: 1^*

Cancel: $e \cdot l$

Legend:

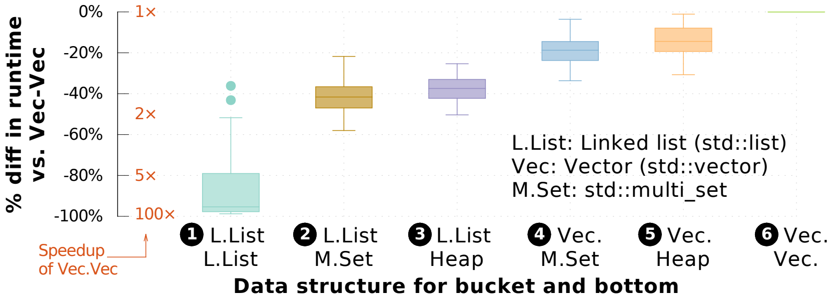
l: #LPs

e: #events / LP

1^*: amortized constant

- Ladder Queue is a priority queue implementation proposed by Tang et al. with amortized O(1) constant time complexity.
- There are two key ideas underlying the Ladder Queue, namely: minimize the number of events to be sorted and delay sorting of events as much as possible.

Ladder Queue (**ladderQ - Fine Tuned**)



- Comparison of execution time using 6 different ladderQ configurations.
- L.List-L.List configuration was slowest and performed 85x slower than the Vec-Vec configuration.

Thesis

- **Research goals**: To develop and assess the effectiveness of novel data structures for managing pending events.

- **Method**: Compare the effectiveness of the data structures using benchmark simulations and a fine-tuned version of the Ladder Queue.

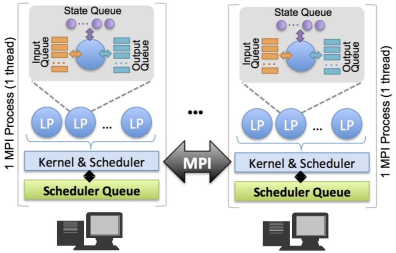
- **Thesis**: multi-tiered data structures, especially the novel, **2tLadderQ** and **3tHeap** pending event structures outperform all other data structures in sequential and optimistic parallel simulations.

- **Contribution:**

1. **3-Tier Heap.**
2. **2-Tier Ladder Queue (extension of Ladder Queue).**
3. **Identification of influential model characteristics for choice of queue.**

Overview

Parallel Simulator Overview



- Assessment of the data structures was conducted on MUSE.
- MUSE performs sequential and optimistically parallel simulations.
- MUSE uses Message Passing Interface (MPI) library for parallel processing.
- The kernel handles LP registration, event processing, state saving, synchronization and garbage collection.

Parallel Simulator Overview

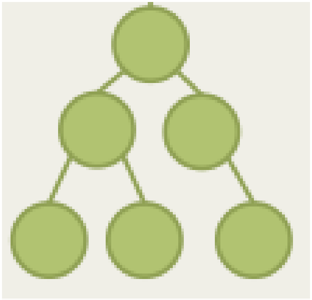
A scheduler queue is required to implement four key operations to manage pending events.

1. **Enqueue one or more future events**.
2. **Peek next event in priority order**.
3. **Dequeue events with the same time stamp for next LP**.
4. **Cancel pending events after a given time**.

Scheduler Queues

- MUSE contains 6 scheduling queues for managing pending events.
- The queues are classified into two categories: single-tier and multi-tier queues.
- Single-tier queues use only a single data structure to implement the 4 key operations.
- Multi-tier queues organizes events into tiers.
- Each tier is implemented using different data structures.

Binary Heap (**heap**)

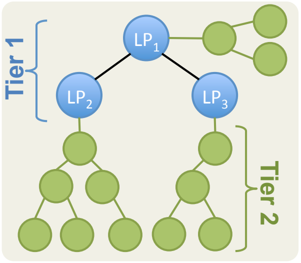


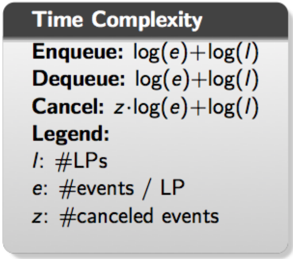
Time Complexity

Enqueue: $\log(e \cdot l)$
Dequeue: $\log(e \cdot l)$
Cancel: $z \cdot \log(e \cdot l)$
Legend:
l: #LPs
e: #events / LP
z: #canceled events

- It is a single-tier data structure that it is implemented as an array object.
- A std::vector is used as the backing container and C++11 algorithms (std::push_heap, st::pop_heap) are used to maintain the heap.
- The heap is prioritized based on time stamp with the lowest time stamp at the root of the heap.

2-tier Heap (**2tHeap**)





Time Complexity

Enqueue: $\log(e) + \log(l)$

Dequeue: $\log(e) + \log(l)$

Cancel: $z \cdot \log(e) + \log(l)$

Legend:

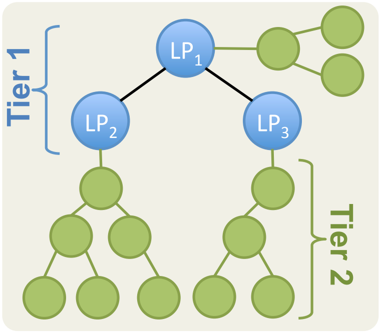
l: #LPs

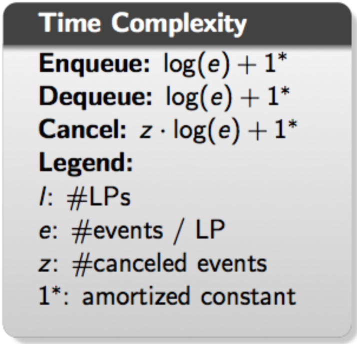
e: #events / LP

z: #canceled events

- 2tHeap was designed to reduced the time complexity of cancel operations by subdividing events into two distinct tiers.
- The first tier has containers for each local LP on an MPI-process.
- Each of the the tier-1 containers has a heap of events to be processed by a given LP.
- A std::vector is used as the backing container for both tiers and standard algorithms are used to maintain the min-heap property for both tiers after each operation.

2-tier Fibonnaci Heap (**fibHeap**)

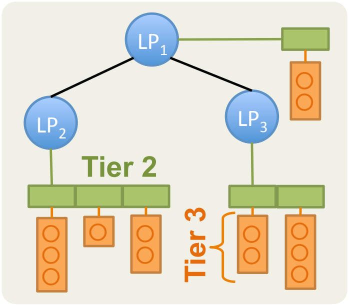



Time Complexity

Enqueue: $\log(e) + 1^*$
Dequeue: $\log(e) + 1^*$
Cancel: $z \cdot \log(e) + 1^*$
Legend:
l: #LPs
e: #events / LP
z: #canceled events
1^*: amortized constant

- The fibHeap is an extension of the 2tHeap data structure. It uses a Fibonnaci heap for scheduling LPs.
- The second tier is a binary heap data structure.

3-tier Heap (**3tHeap**)

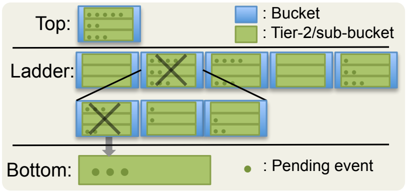


Time Complexity

Enqueue: $\log(\frac{e}{c}) + \log(l)$
Dequeue: $\log(l)$
Cancel: $e + \log(l)$
Legend:
l: #LPs
e: #events / LP
c: #concurrent events
z: #canceled events

- The 3tHeap builds upon 2tHeap by further subdividing the second tier into two tiers.
- The binary heap implementation for the first tier that manages LPs for scheduling has been retained from 2tHeap.
- Assuming each LP has c concurrent events on an average, there are $\frac{e}{c}$ tier-2 entries with each one having c pending events.

2-tier Ladder Queue (**2tLadderQ**)



Time Complexity

Enqueue: 1^*

Dequeue: 1^*

Cancel: $e \cdot l \div {}_{t2}k$

Legend:

l: #LPs

e: #events / LP

1^*: amortized constant

${}_{t2}k$: parameter

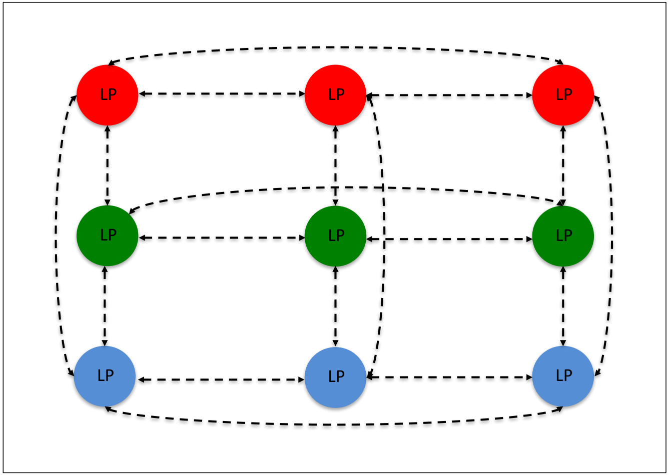
- 2-tier Ladder Queue is the proposed alternative to Ladder Queue because the cost of event cancellation during rollbacks is reduced.
- 2tLadderQ retains the amortized constant time complexity of ladderQ with performance gains during event cancellation.

Table: Comparison of algorithmic time complexities of different data structures

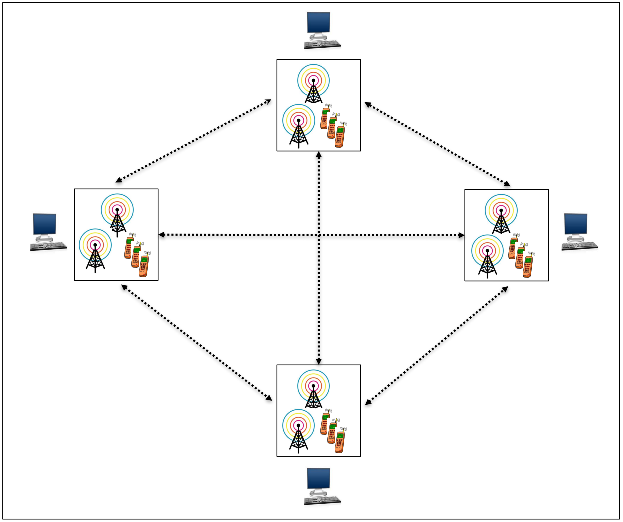
Legend – l: #LPs, e: #events / LP, c: #concurrent events, z: # canceled events, ${}_{\text{t2}}k$: parameter, 1^*: amortized constant

Name	Enqueue	Dequeue	Cancel
heap	$\log(e \cdot l)$	$\log(e \cdot l)$	$z \cdot \log(e \cdot l)$
2tHeap	$\log(e)+ \log(l)$	$\log(e)+ \log(l)$	$z \cdot \log(e)+ \log(l)$
fibHeap	$\log(e) + 1^*$	$\log(e) + 1^*$	$z \cdot \log(e) + 1^*$
3tHeap	$\log(\frac{e}{c}) + \log(l)$	$\log(l)$	$e + \log(l)$
ladderQ	1^*	1^*	$e \cdot l$
2tLadderQ	1^*	1^*	$e \cdot l \div {}_{\text{t2}}k$

Simulation Model - PHOLD



Simulation Model - PCS



Overview

Methodology

- Identify the most influential parameters that impact performance of the scheduler queues using **Generalized Sensitivity Analysis**.
- Run different configurations of the PHOLD benchmark and PCS simulation in sequential and optimistically parallel simulations.
- The data to be collected and assessed consists of the following:
  1. **simulation run time.**
  2. **peak memory usage.**
  3. **# of rollbacks.**
  4. **characteristics of key scheduler queue operations.**
  5. **# of network messages exchanged.**

Overview

GSA sequential results - PCS

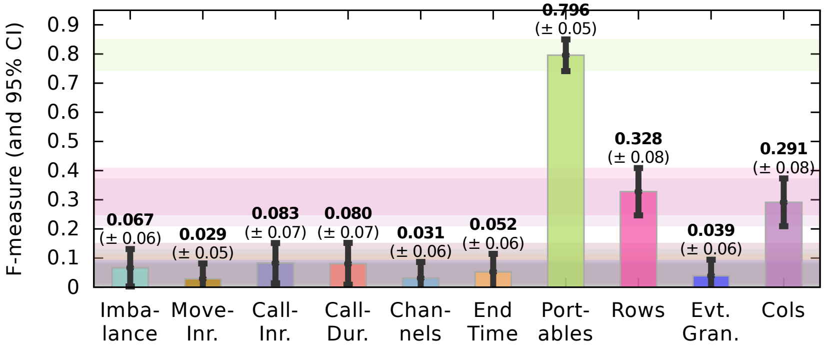


Figure: **GSA data from sequential simulations (1 MPI-process) showing influential PCS parameters (2tLadderQ vs. 3tHeap).**

GSA parallel results - PHOLD

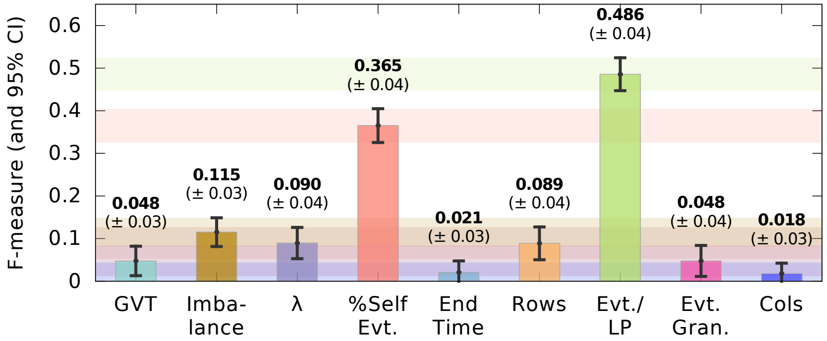


Figure: **GSA data from parallel simulations (4 MPI-processes) showing influential PHOLD parameters (2tLadderQ vs. 3tHeap).**

Summary of GSA results

- **Events per LP** - parameter with most influence using **PHOLD** benchmark in sequential and parallel simulations.
- **lambda** - parameter with marginal influence using **PHOLD** benchmark in sequential simulations.
- **%Self-Events** - parameter has a more pronounced influence in comparison to **lambda** using **PHOLD** benchmark in parallel simulations.
- **Portables per Cell** - parameter with most influence using **PCS** in sequential and parallel simulations.
- **Model size** - marginal influence using **PCS** in sequential simulations.

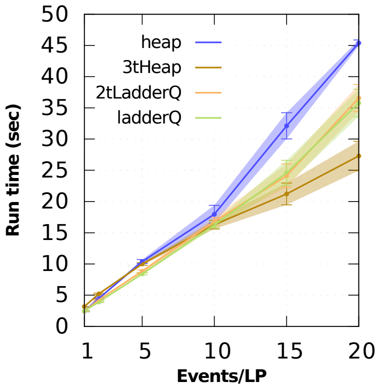
Configuration for further analysis

Table: **Configurations of PHOLD and PCS**

Name	#LPs (Rows x Cols)	Sim. End Time Seq	Sim. End Time Parallel
ph3	1,000 (100 x 10)	5000	20000
ph4	10,000 (100 x 100)	500	5000
ph5	100,000 (1000 x 100)	100	1000
pcs6	100 (10 x 10)	5000	50000
pcs7	1,000 (100 x 10)	1000	4500
pcs8	10,000 (100 x 100)	100	200

Overview

Sequential simulation results



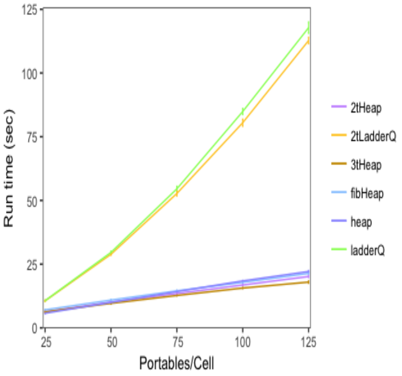


Figure: **Sequential simulation runtimes for ph3 and pcs6 configurations.**

Overview

Parallel simulation assessment - Efficient case for **ladderQ**

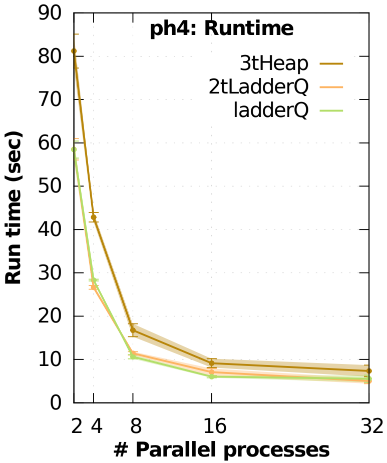


Figure: **Statistics from PH4 configuration of PHOLD parallel simulation with eventsPerLP=2, $\lambda = 1$, %selfEvents=25%**

Parallel simulation assessment - Knee point for **3tHeap** vs. **ladderQ**

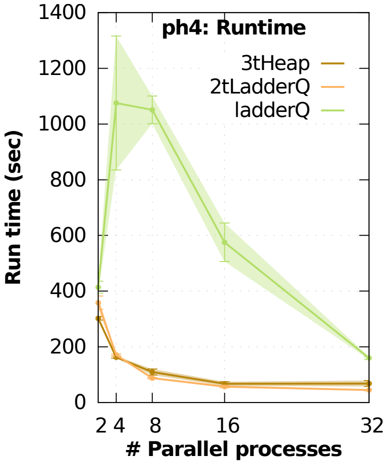


Figure: **Statistics from PH4 configuration of PHOLD parallel simulation with eventsPerLP=10, $\lambda = 10$, %selfEvents=25%**

Parallel simulation assessment - Best case for **3tHeap**

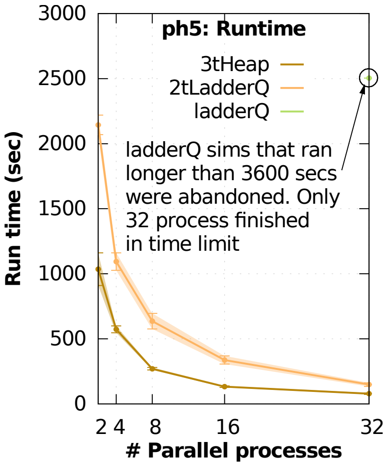


Figure: **Statistics from PH5 configuration with eventsPerLP=20, $\lambda = 10$, %selfEvents=25%**

Parallel simulation assessment - Best case for **3tHeap**

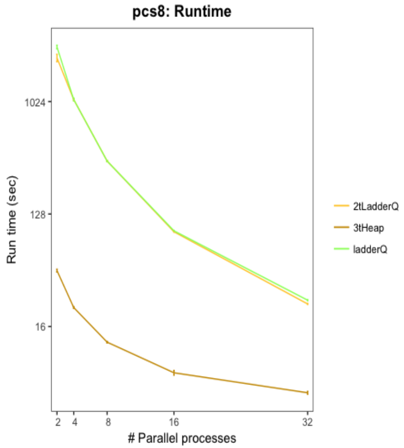


Figure: **Statistics from PCS8 configuration with portables per cell = 75**

Overview

Conclusions

- **2tLadderQ** performs no worse than **ladderQ** in sequential simulations with $_{t2}k=1$.
- Results favor the general use of **2tLadderQ** over the **ladderQ**.
- The advantages of **3tHeap** is realized only when each logical process has 10 or more concurrent events at each time step.
- Recommend the use of General Sensitivity Analysis (GSA) to reduce the parameter space in simulation models with large parameters.

Future Work

- Implement the multi-tier data structures in a different language and compare performance.
- Test data structures on other parallel simulation frameworks.
- Assess the performance of our data structures using a wider range of simulation models.
- Assess the effectiveness of multi-tier data structures in multi-threaded simulations.

References

Dickman et al., (2013) Event Pool Structures for PDES on Many-core Beowulf Clusters. *In Proceedings of the 1st ACM SIGSIM Conference on Principles of Advanced Discrete Simulation* ACM, New York, NY, USA, 103-114.

Franceschini et al., (2015) A Comparative Study of Pending Event Set Implementations for PDEVS Simulation. *In Proceedings of the Symposium on Theory of Modeling and Simulation* Society for Computer Simulation International San Diego, CA, USA, 77-84.

Gupta et al., (2014) Lock-free Pending Event Set Management in Time Warp. *In Proceedings of the 2nd ACM SIGSIM Conference on Principles of Advanced Discrete Simulation* ACM, New York, NY, USA, 15-26.

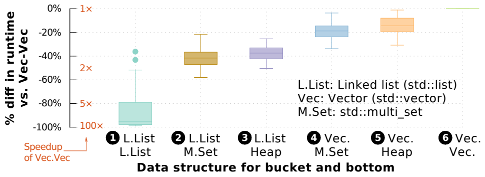
Jafer et al., (2013) Synchronization methods in parallel and distributed discrete-event simulation Simulation Modeling Practice and Theory 30(2013), 54-73.

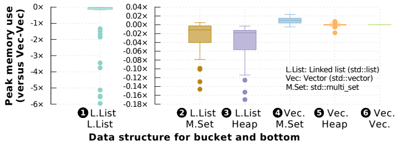
Marotta et al., (2016) A Non-Blocking Priority Queue for the Pending Event Set.In Proceedings of the 9th EAI International Conference on Simulation Tools and Techniques ICST, Brussels, Belgium, 46-55.

Tang et al., (2005) Ladder Queue: An O(1) Priority Queue Structure for Large-scale Discrete Event Simulation.ACM Trans. Model. Comput. Simul. 15, 3(July 2005), 175-204.

The End

Ladder Queue (**ladderQ - Fine Tuned**)





- Comparison of execution time and peak memory using 6 different ladderQ configurations.
- L.List-L.List configuration was slowest and performed 85x slower than the Vec-Vec configuration.
- The increased performance of Vec-Vec comes at about a 6x increase in peak memory footprint when compared to L.List-L.List.

GSA sequential results - PHOLD

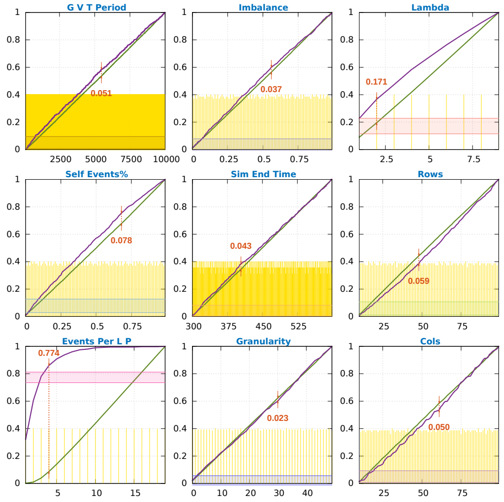


Figure: **Results from GSA comparing 2tLadderQ and 3tHeap using the PHOLD benchmark.**

GSA sequential results - PHOLD

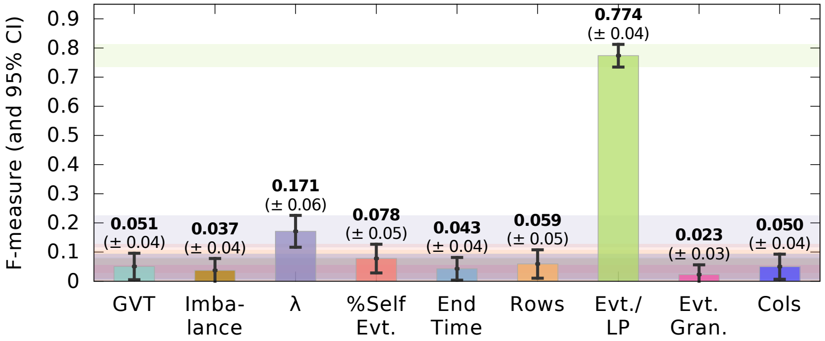


Figure: **GSA data from sequential simulations (1 MPI-process) showing influential PHOLD parameters (2tLadderQ vs. 3tHeap).**

GSA sequential results - PCS

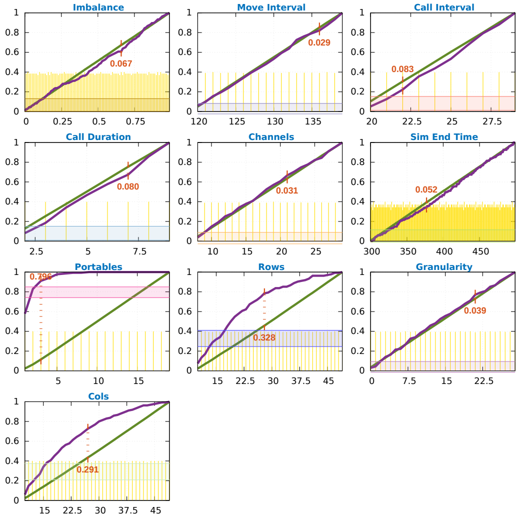


Figure: **Results from GSA comparing 2tLadderQ and 3tHeap for sequential simulation using PCS simulation.**

GSA sequential results - PCS

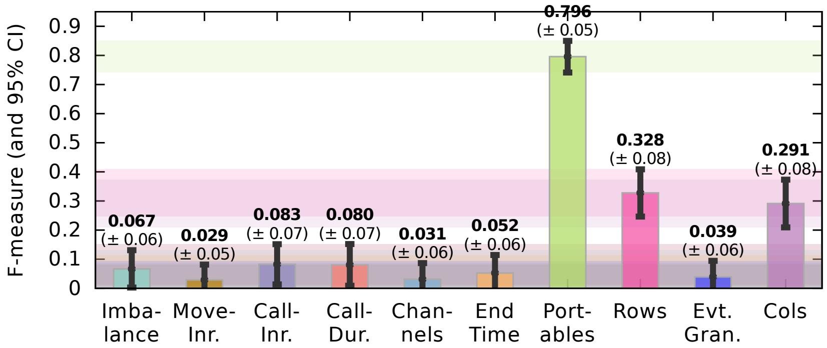


Figure: **GSA data from sequential simulations (1 MPI-process) showing influential PCS parameters (2tLadderQ vs. 3tHeap).**

GSA parallel results - PHOLD

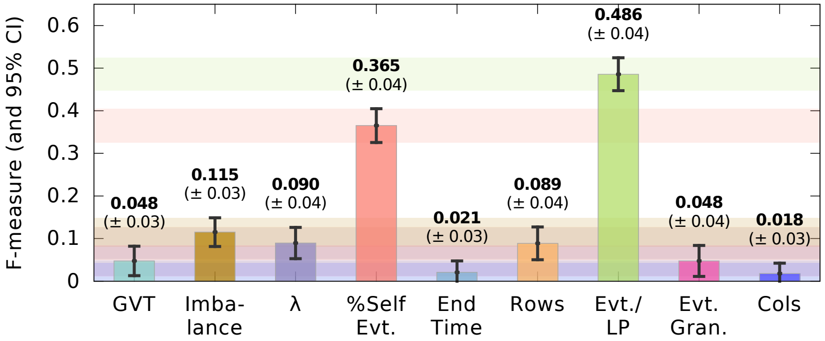


Figure: **GSA data from parallel simulations (4 MPI-processes) showing influential PHOLD parameters (2tLadderQ vs. 3tHeap).**

GSA parallel results - PCS

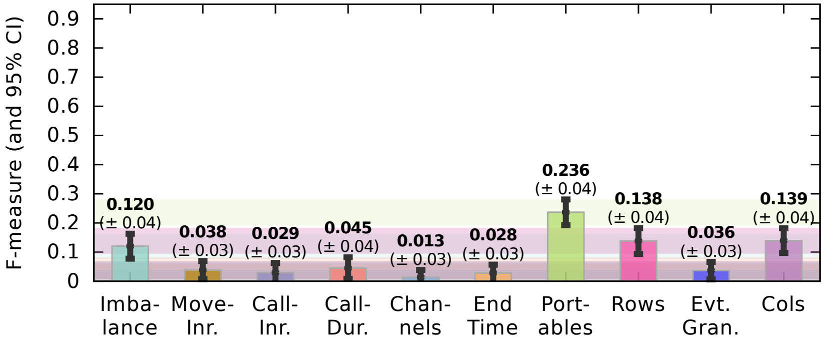
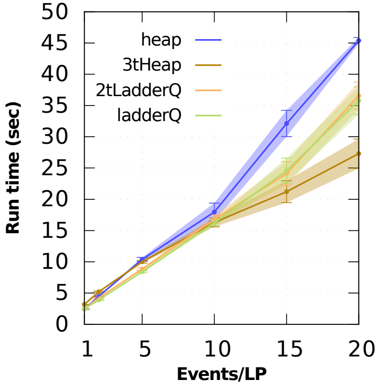


Figure: **GSA data from parallel simulations (4 MPI-processes) showing influential PCS parameters (2tLadderQ vs. 3tHeap).**

Sequential simulation results - PHOLD



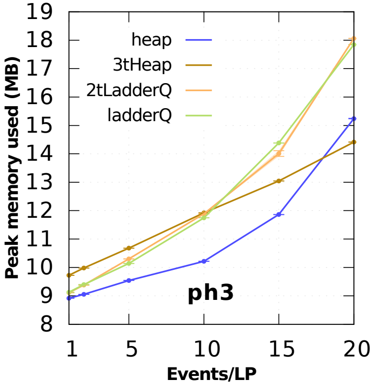
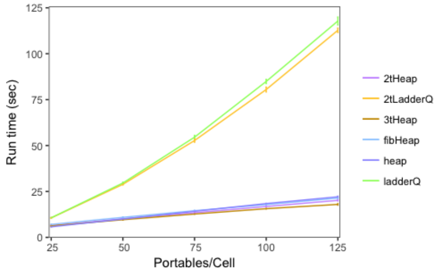


Figure: **Sequential simulation runtimes and peak memory usage with ph3.**

Sequential simulation results - PCS



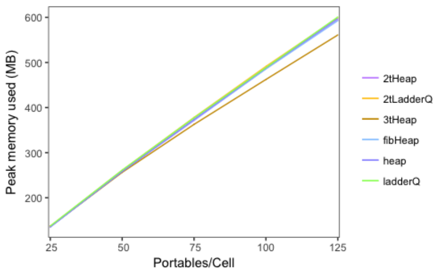


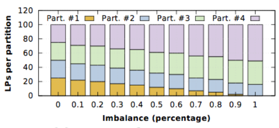
Figure: **Sequential simulation runtimes and peak memory usage with pcs6.**

Simulation Model - PHOLD

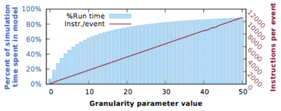
Table: **Parameters in PHOLD benchmark**

Parameter	Description
rows	Total number of rows in model.
cols	Total number of columns in model. $\#$LPs $=$ **rows** x **cols**
eventsPerLP	Initial number of events per LP.
granularity	Additional compute load per event.
%selfEvents	Fraction of events LPs send to self
delay or λ	Value used with distribution – Lambda (λ) value for exponential distribution *i.e.*, $P(x\|\lambda) = \lambda e^{-\lambda x}$.
imbalance	Fractional imbalance in partition to have more LPs on a MPI-process.
simEndTime	GVT when simulation logically ends.

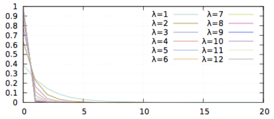
PHOLD - Key Parameters



(a) impact of `imbalance`



(b) impact of `granularity`



(c) impact of λ (`delay`)

- Imbalance parameter influences the partition.
- Granularity impacts the processing time of events.
- λ impacts the distribution of the time stamp values.

Simulation Model - PCS

Table: **Parameters in PCS simulation model**

Parameter	Description
rows	Total number of rows in model.
cols	Total number of columns in model. #Cells/LPs = **rows** x **cols**
portables	The portables represents a mobile phone unit that resides at the Cell for a period of time and then moves to one of four neighboring cells.

Simulation Model - PCS

Table: **Parameters in PCS simulation model**

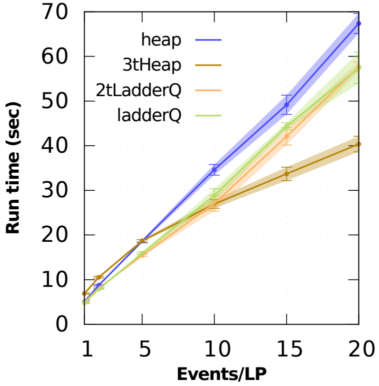
Parameter	Description
moveIntervalMean	Mean value of an exponential random distribution used to generate the time when a portable will move to an adjacent cell.
callIntervalMean	Mean value of an exponential random distribution from where the next call timestamp value is determined.
callDurationMean	Mean value of a poisson distribution used to generate the length/-duration of a call to a portable.

Simulation Model - PCS

Table: **Parameters in PCS simulation model**

Parameter	Description
#channels	The maximum number of channels assigned to each PCS cell.
imbalance	Fractional imbalance in partition to have more LPs on a MPI-process.
simEndTime	GVT when simulation logically ends.

Sequential simulation results - PHOLD



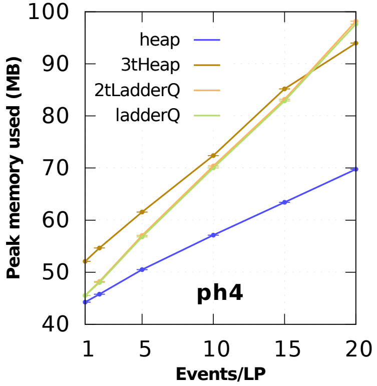
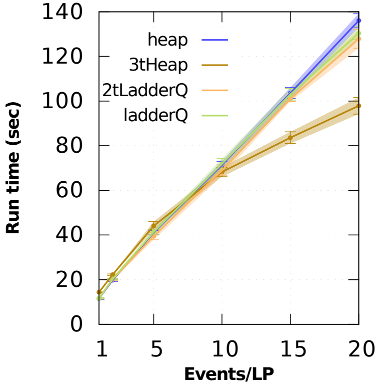


Figure: **Sequential simulation runtimes and peak memory usage with ph4.**

Sequential simulation results - PHOLD



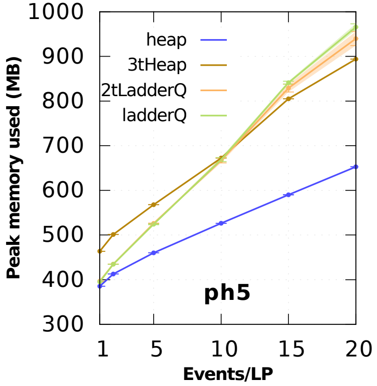
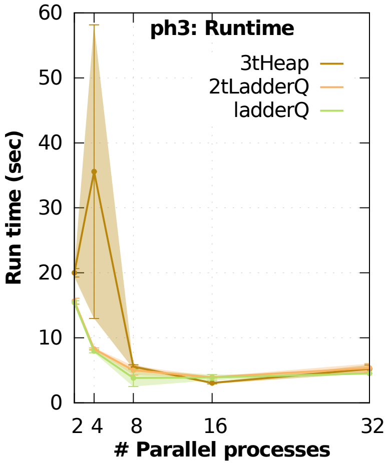


Figure: **Sequential simulation runtimes and peak memory usage with ph5.**

Parallel simulation assessment - Efficient case for **ladderQ**



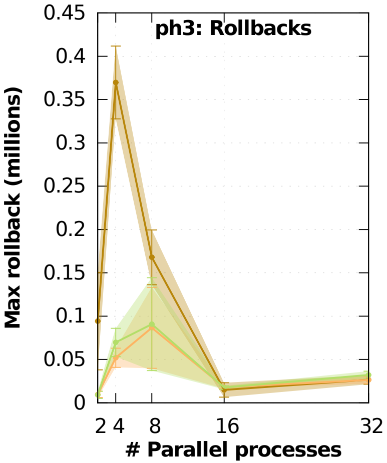
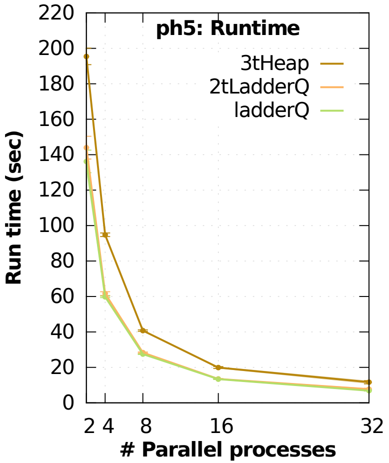


Figure: **Statistics from PH3 configuration of PHOLD parallel simulation with eventsPerLP=2, $\lambda = 1$, %selfEvents=25%**

Parallel simulation assessment - Efficient case for **ladderQ**



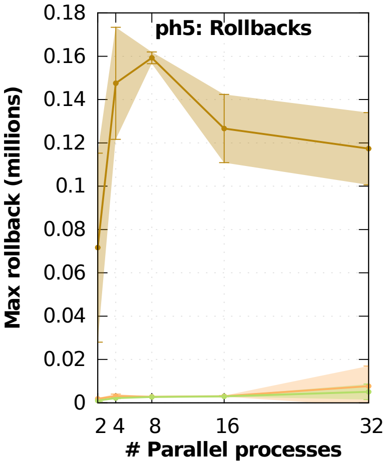
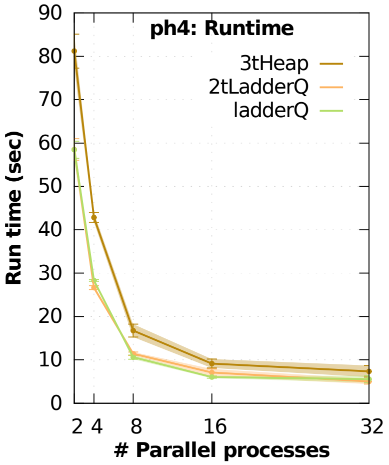


Figure: **Statistics from PH5 configuration of PHOLD parallel simulation with eventsPerLP=2, $\lambda = 1$, %selfEvents=25%**

Parallel simulation assessment - Efficient case for **ladderQ**



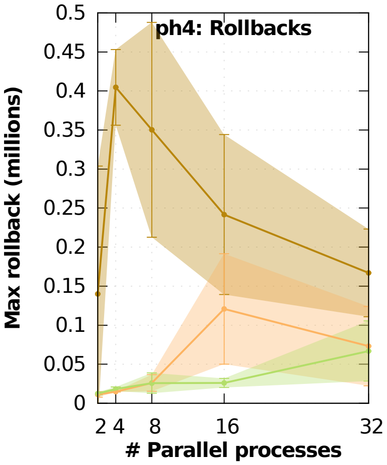
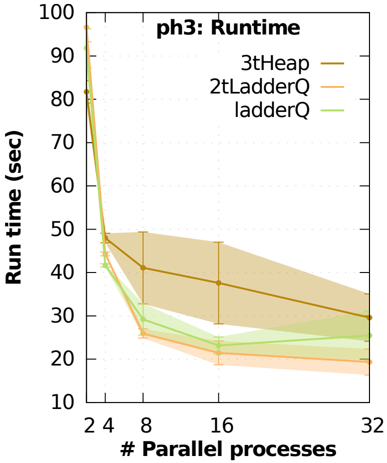


Figure: **Statistics from PH4 configuration of PHOLD parallel simulation with eventsPerLP=2, $\lambda = 1$, %selfEvents=25%**

Parallel simulation assessment - Knee point for **3tHeap** vs. **ladderQ**



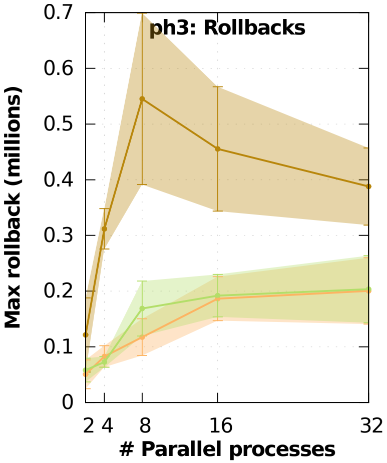
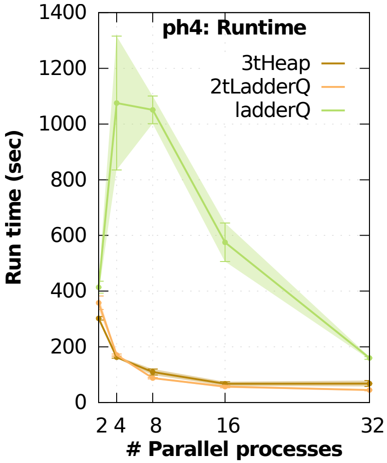


Figure: **Statistics from PH3 configuration of PHOLD parallel simulation with eventsPerLP=10, $\lambda = 10$, %selfEvents=25%**

Parallel simulation assessment - Knee point for **3tHeap** vs. **ladderQ**



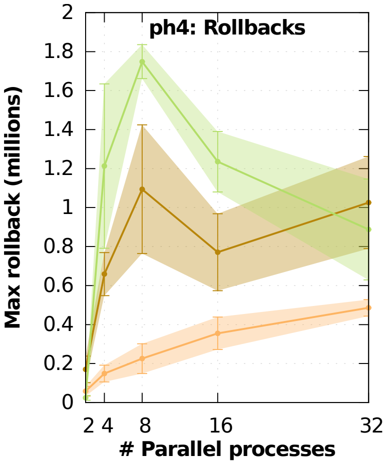
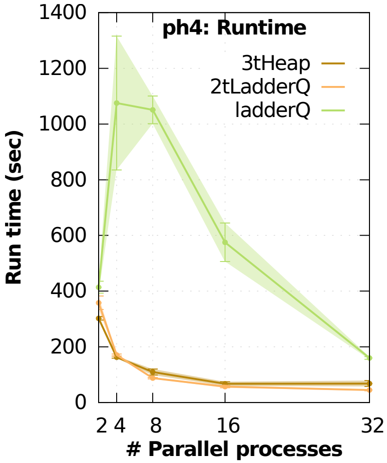


Figure: **Statistics from PH4 configuration of PHOLD parallel simulation with eventsPerLP=10, $\lambda = 10$, %selfEvents=25%**

Parallel simulation assessment - Knee point for **3tHeap** vs. **ladderQ**



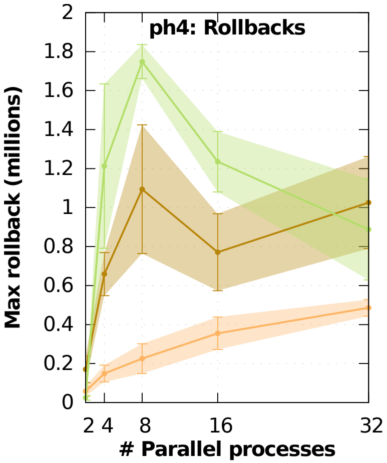
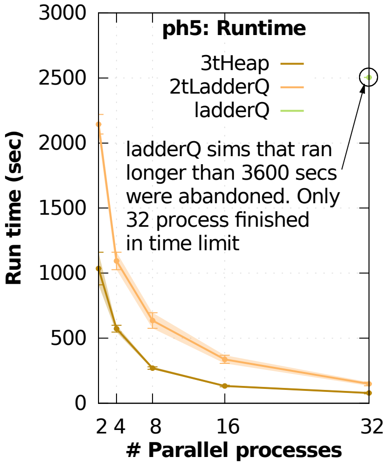


Figure: **Statistics from PH4 configuration of PHOLD parallel simulation with eventsPerLP=10, $\lambda = 10$, %selfEvents=25%**

Parallel simulation assessment - Best case for **3tHeap**



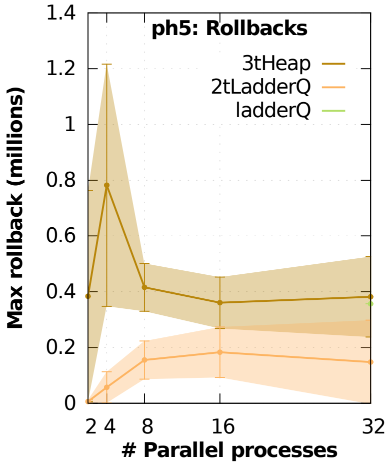
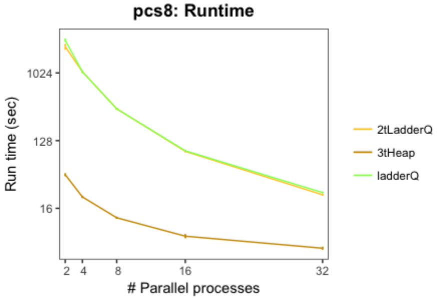


Figure: **Statistics from PH5 configuration of PHOLD parallel simulation with eventsPerLP=20, $\lambda = 10$, %selfEvents=25%**

Parallel simulation assessment - Best case for **3tHeap**



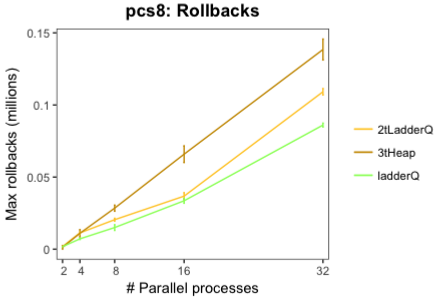
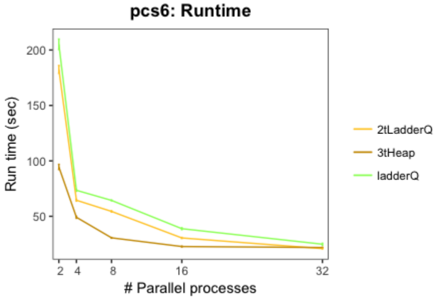


Figure: **Statistics from PCS8 configuration of PCS parallel simulation with portables per cell = 75**

Parallel simulation assessment - Best case for **3tHeap**



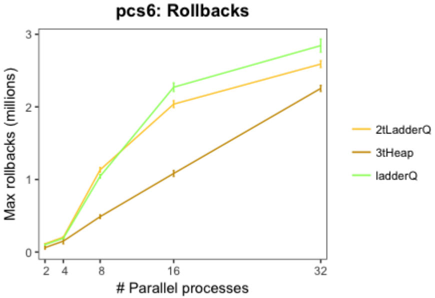
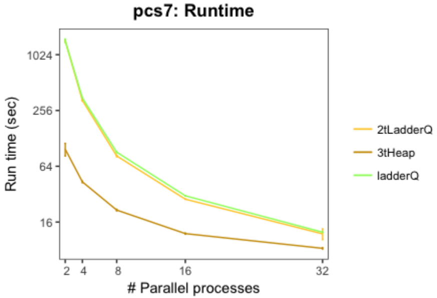


Figure: **Statistics from PCS6 configuration of PCS parallel simulation with portables per cell = 75**

Parallel simulation assessment - Best case for **3tHeap**



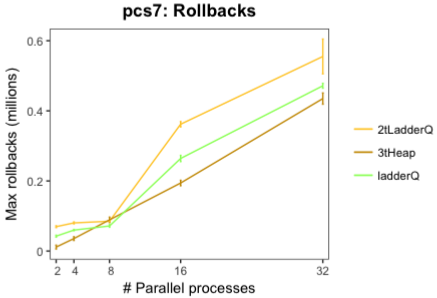
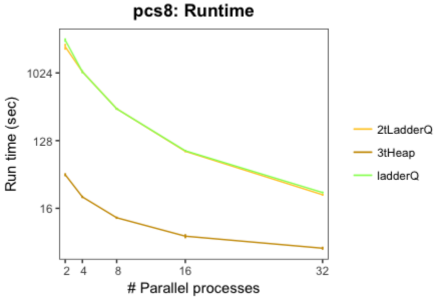


Figure: **Statistics from PCS7 configuration of PCS parallel simulation with portables per cell = 75**

Parallel simulation assessment - Best case for **3tHeap**



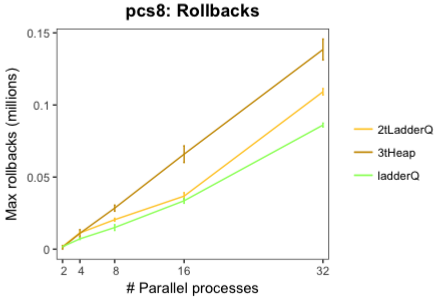


Figure: **Statistics from PCS8 configuration of PCS parallel simulation with portables per cell = 75**