Current state of (distributed) TLC

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Outline

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A distributed model checker algorithm (master)

Data: SQ, FPS, $TRACE$, ϕ, $WORKER$, n

```
1  begin
2      SQ ⟵ initStates() ;          // Generate init states once
3      foreach w ∈ WORKER do concurrently
4          while SQ ≠ ∅ do
5              S ⟵ subset(SQ, n) ;              // Worklist size n
6              Succ ⟵ successors(w, S) ;              // remotely
7              SQ ⟵ SQ \ S ;                 // Mark states S done
8              if isViolation(Succ) then
9                  SQ ⟵ ∅ ;                                  // End
10                 return path(s', TRACE), φ ;          // Path to s'
11             end
12             SQ ⟵ SQ ∪ Succ ;          // Add new succ. to SQ
13             append(TRACE, Succ) ;          // Maintain TRACE
14             H ⟵ hashes(Succ) ;            // Prev. calculated
15             addToSegment(FPS, H) ;       // Into corresp. FPS
16         end
17     end
18 end
```

A distributed model checker algorithm (worker)

Data: ϕ, *FPS*

1 **begin**
2 $Succ \longleftarrow \emptyset$
3 **foreach** $s \in States$ **do**
4 $s' \longleftarrow genSucc(s)$; // Generate succ. states
5 $Succ \longleftarrow Succ \cup \{\text{hash(s')},\text{s'},\text{s}\}$; // Calculate hashes
6 **end**
7 **foreach** $h \in segment(FPS, h)$ **do** concurrently check known
8 $Succ \longleftarrow Succ \setminus \{\text{h},\text{s'},\text{s}\}$; // Remove known states
9 **end**
10 **foreach** $s' \in Succ$ **do** check safety props
11 **if** *violates(s, s', ϕ)* **then**
12 *signalViolation*(s', ϕ) ; // End
13 **end**
14 **end**
15 **return** *Succ*
16 **end**

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Basic topology

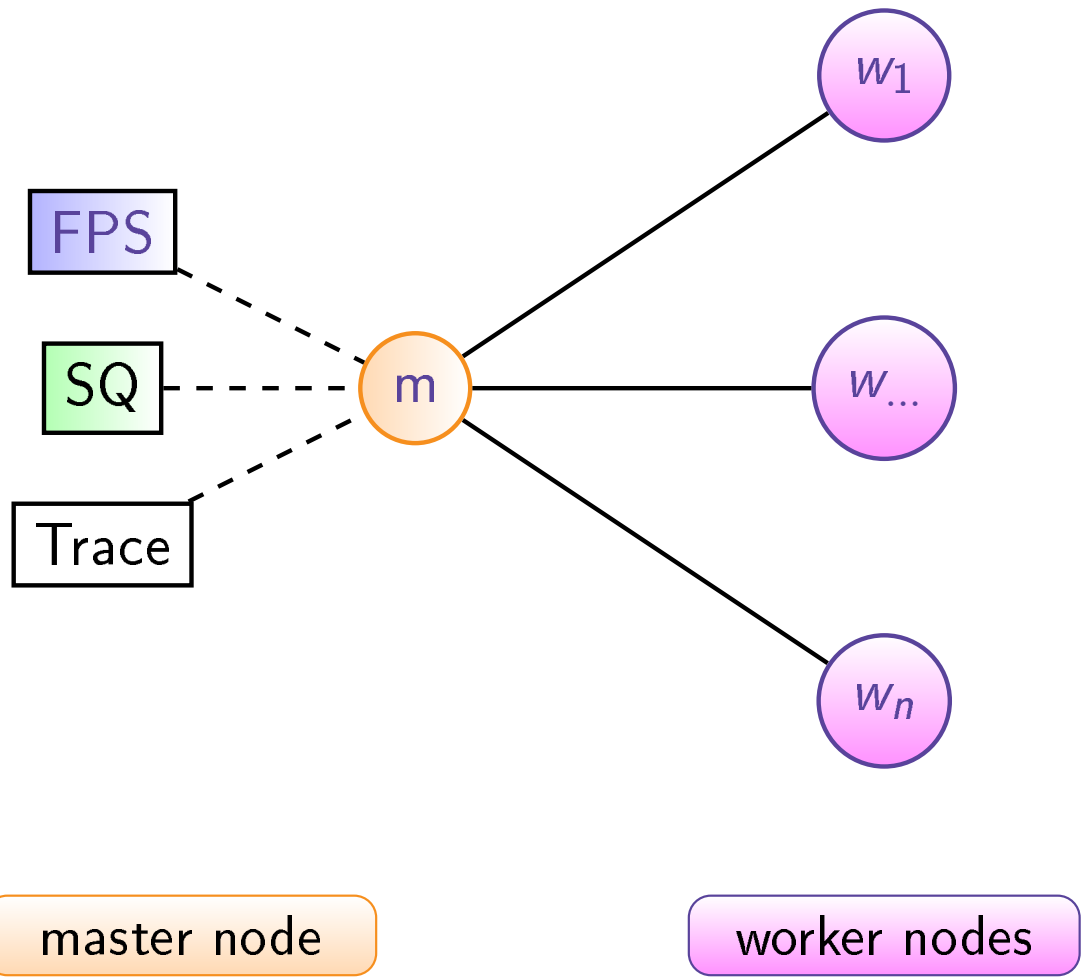

Figure: basic setup

Advanced topology

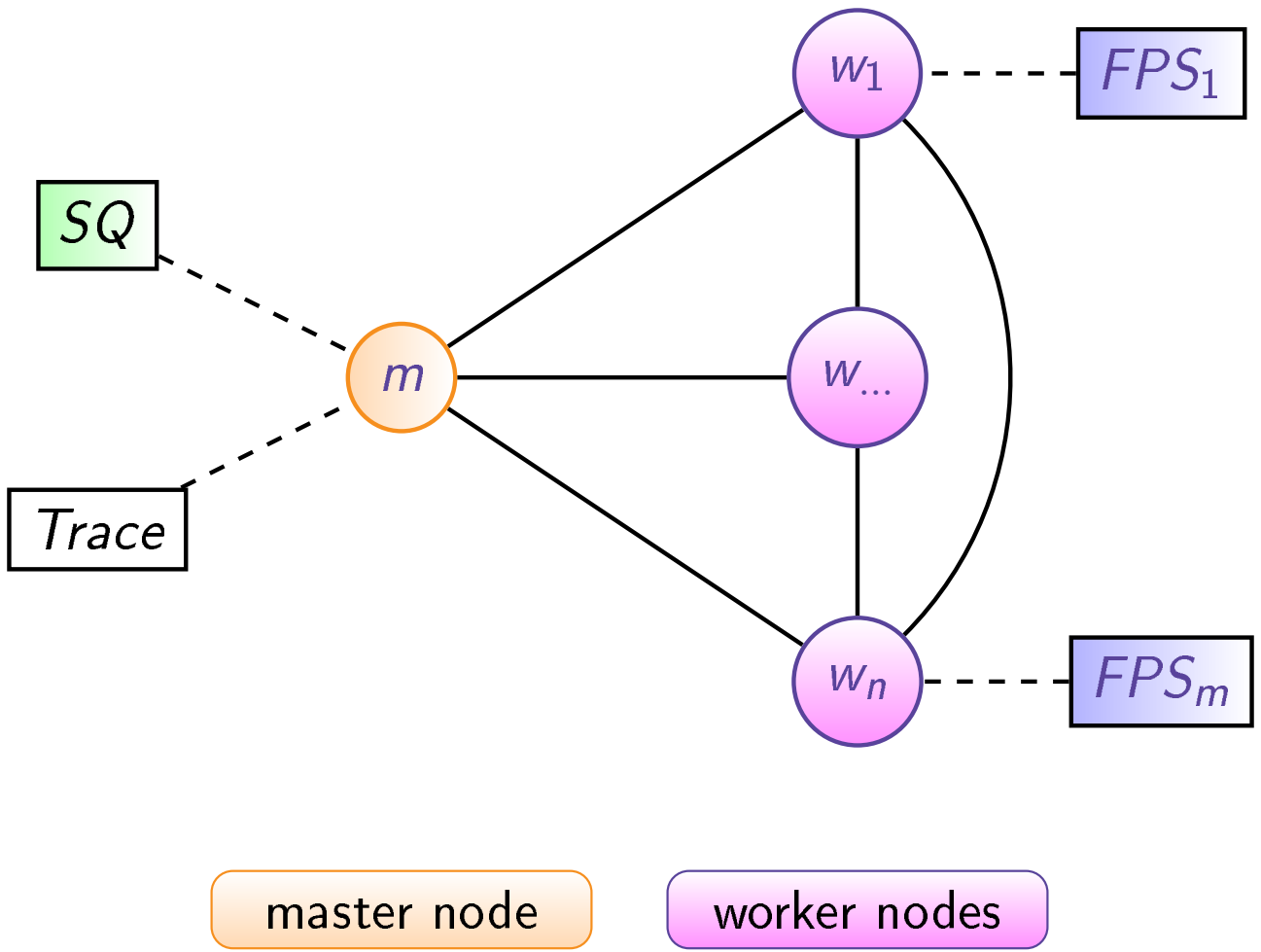

Figure: advanced setup

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Fault tolerance

- 1...n workers (w)
- 1...m fingerprint sets (FPS)
  - Lost fingerprint set means corresponding states will be re-explored
  - FP collision probability will be off
- Can neither compensate loosing SQ nor $Trace$ (yet)
  - Chkpt only provides fault tolerance against program errors
  - Workaround: Keep remote backups of .chkpt files

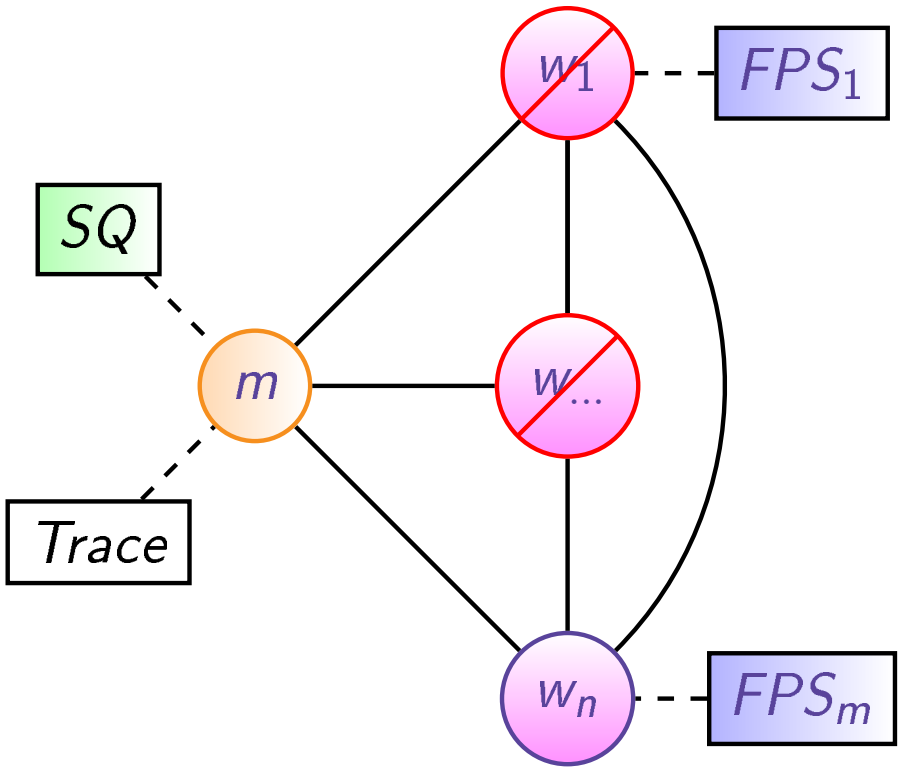

Figure: broken setup

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Does (distributed) TLC perform?

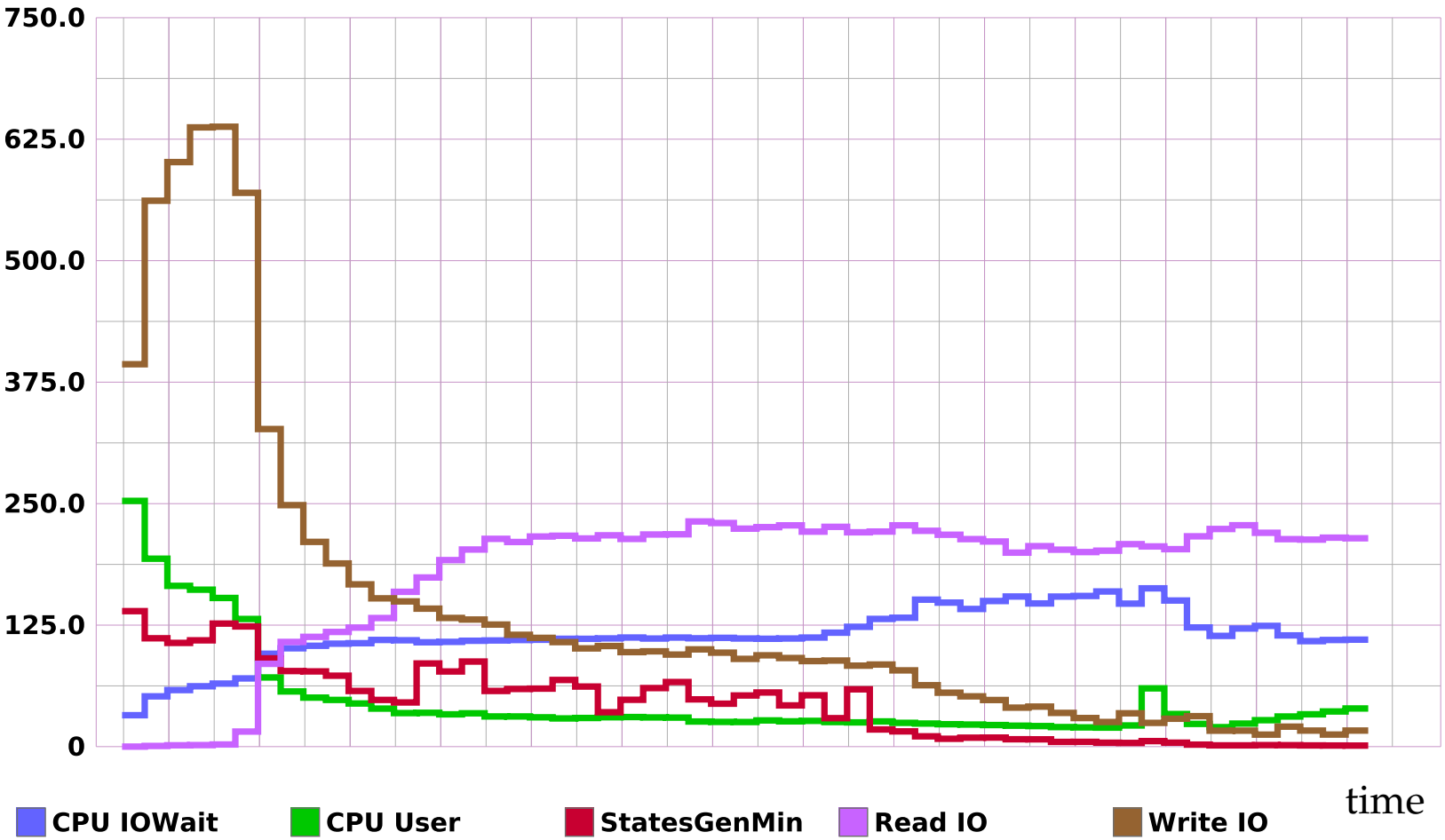

Figure:
EC2-69-xmxms60G-w32-nodes08-cDef-l1_n32_k2-RHead-fpmem08

Does (distributed) TLC perform?

- Problems
  - Performance degrades as soon as TLC goes to disk (expected)
    - I/O bound
    - (Solid state) disks order of magnitude slower compared to RAM
    - vs. much greater storage size
  - FPS memory utilization is suboptimal

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Big Memory

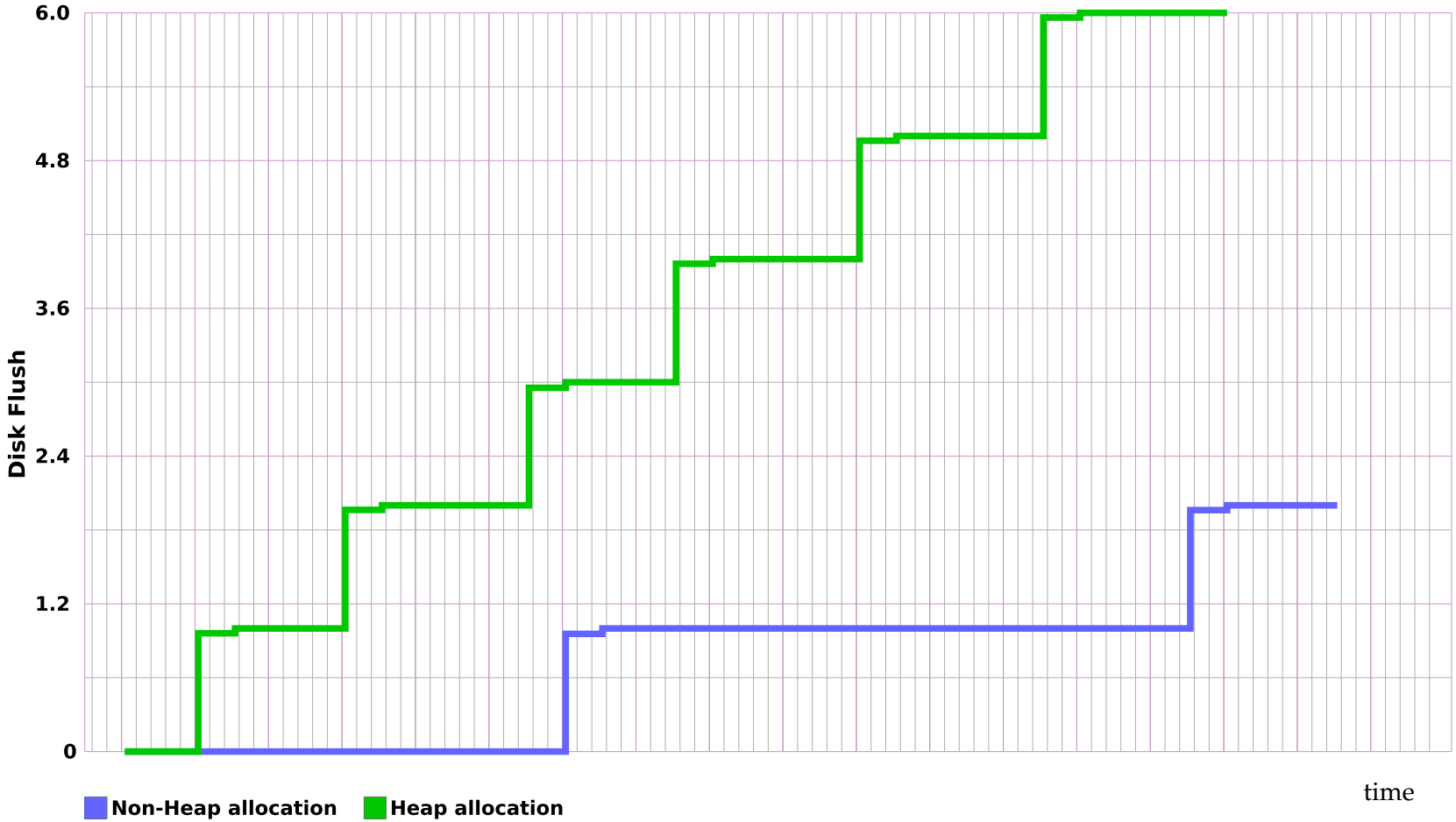

Figure: Heap and non-heap

Big Memory contd.

Allocates on heap & LSB

- long[][] (multidimensional)
  - 22% initial overhead
  - Length, class schema, pointers
- long[tblCnt] as temporary sort array during disk flush
  - 50% storage overhead
  - Sorting overhead
  - int addressing hard limit for (a single) DiskFPSet
- Sums up to net efficiency approx. 40%
- Exposed to GC
  - Fingerprints cannot gc'ed

Allocates on non-heap & MSB

- Replaces multidim. array with static continuous memory
  - No overhead
  - Initial bootstrap cost to statically allocate
- Half memory consumption by removing long[tblCnt] array completely
  - Presort in-memory FP based on most significant bits (MSB)
  - Requires on-heap 2nd level collision bucket (fix by e.g. re-probing)
- Removes GC cost completely

FPSet concurrency

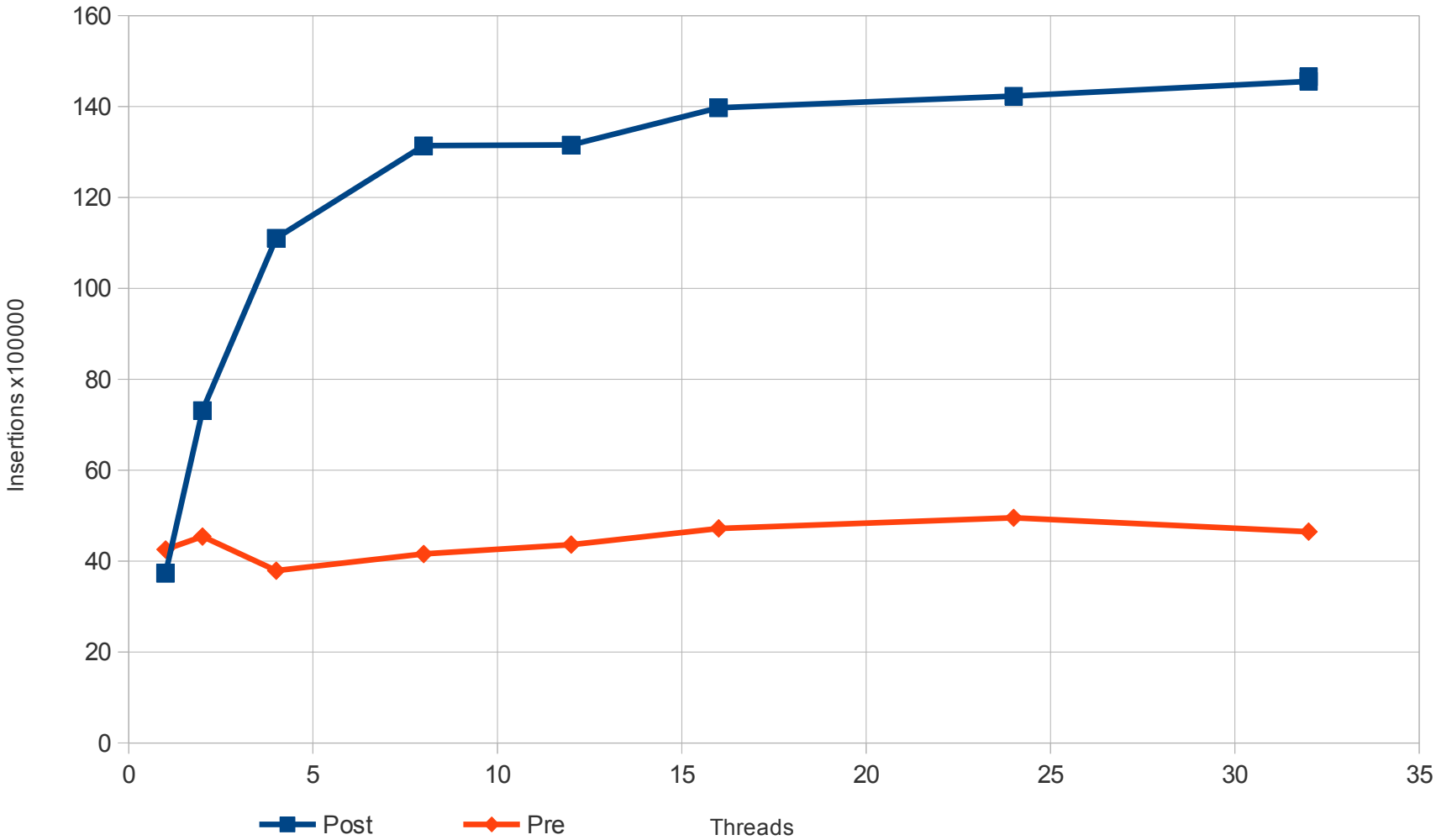

Figure: FPS memory ops concurrency pre and post e. (16 virtual cores)

FPSet concurrency contd.

- Concurrent memory read access (exclusive writes)
- Striped locks to increase concurrency/fine grained locking
  - Only lock corresponding part of hash table during memory writes
- Disk locking remains untouched (I/O is dominant cost)

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Scale horizontally - Distributed TLC

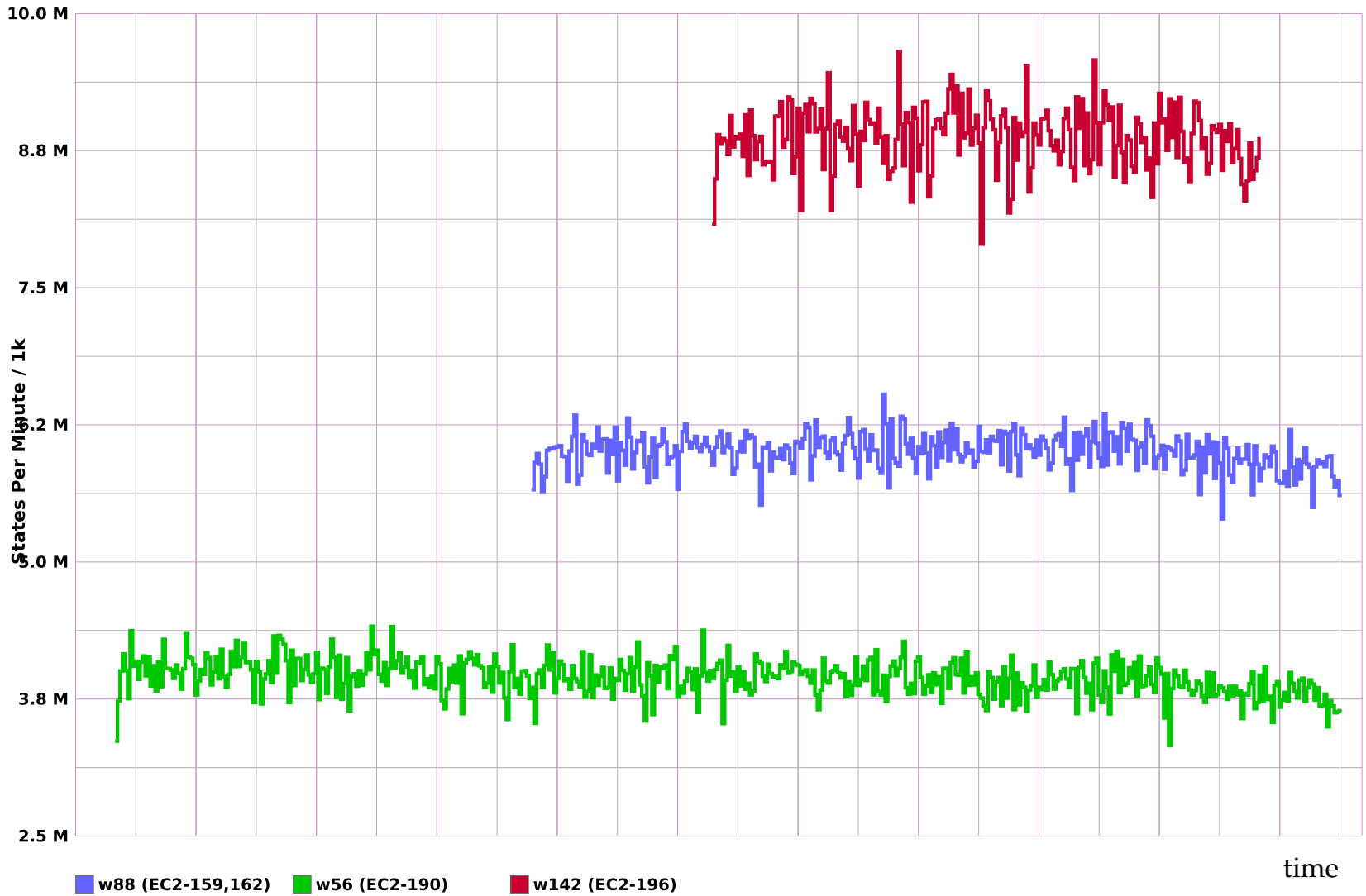

Figure: 56/8, 88/12 and 142/19 workers/nodes (l12_n10_k8)

Scale horizontally - Enhancements

- Distributed FPS!!!
  - Remote memory still faster compared to local (solid state) disk
- Distributed FPS put and contains ops concurrently
- "BlockSelector" based on network stats to assign big chunks of work at once
  - Degraded breadth-first search
- Calculate fingerprint collision probability concurrently during end-game phase
  - Full pass over all fingerprint sets
- Node-local worker cache (1MiB) keeps 5 to 10% lookups from fingerprint sets
- (Ordered put and contains to reduce page seeks)
  - Sort executed on worker

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Performance comparison

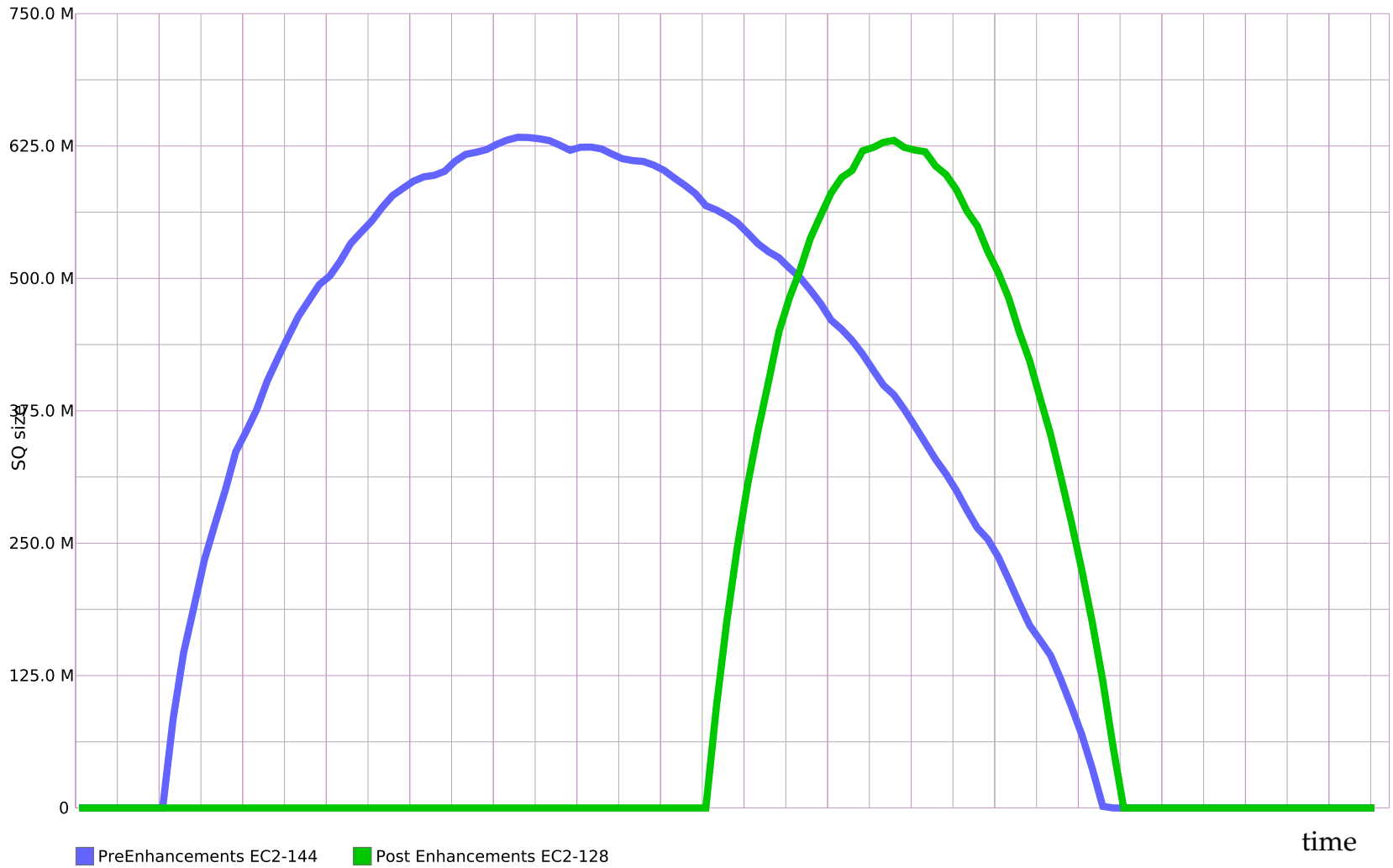

Figure: Pre and post e. SQ size over time

Summary

- Increased TLC performance
- Made distributed TLC scale to many machines (primarily due to distributed FPS)
  - Preliminary results show approx. 0.7 scalability factor
  - Tests need to be extended to higher node counts
- Toolbox based distributed deployment

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Outlook

- Dynamic distributed FPS and bug free recovery
- StateQueue & Trace scaling and fault tolerance
- “AutoScaling” based on actual machine load
- Increased locality by partitioning/segmenting on state properties different from fingerprints
- Better support for large scale deployments (based on Jenkins scheduler?)
- Mathematical performance model

Acknowledgment

- Microsoft Research & MSR Inria Joint Lab
- Amazon AWS
- Experiments presented in this paper were carried out using the Grid'5000 experimental testbed, being developed under the INRIA ALADDIN development action with support from CNRS, RENATER and several Universities as well as other funding bodies - `https://www.grid5000.fr`
- Dr. Cliff Click "Scaling Up a Real Application on Azul" 2006 (JavaOne) - `http://www.stanford.edu/class/ee380/Abstracts/070221_J1_ScalingUp.pdf`

Q&A

Thank you for your attention

References

- eMail: `mailto:tla-workshop-2012@lemmster.de`
- Slides: `https://www.lemmster.de/uploads/CurrentStateDistributedTLC_MarkusAKuppe.pdf`
- tlc-perf repository: `https://github.com/lemmy/tlc-perf`
- memopt builds: `http://tla.msr-inria.inria.fr/kuppe/memopt/`

Additional material

Test model parameters

l	n	k	distinct states (k^n)	size (MiB)	cost/state (2^l)
10	6	8	2^{18} (262.144)	2	1024
10	8	8	2^{24} (16.777.216)	128	4096
10	10	8	2^{30} (1.073.741.824)	8.192	16.384
12	6	8	2^{18}	2	1024
12	8	8	2^{24}	128	4096
12	10	8	2^{30}	8.192	16.384
14	6	8	2^{18}	2	1024
14	8	8	2^{24}	128	4096
14	10	8	2^{30}	8.192	16.384
1	32	2	2^{32} (4.294.967.296)	32.768	2
1	33	2	2^{33} (8.589.934.592)	65.536	2

SQ buffer size

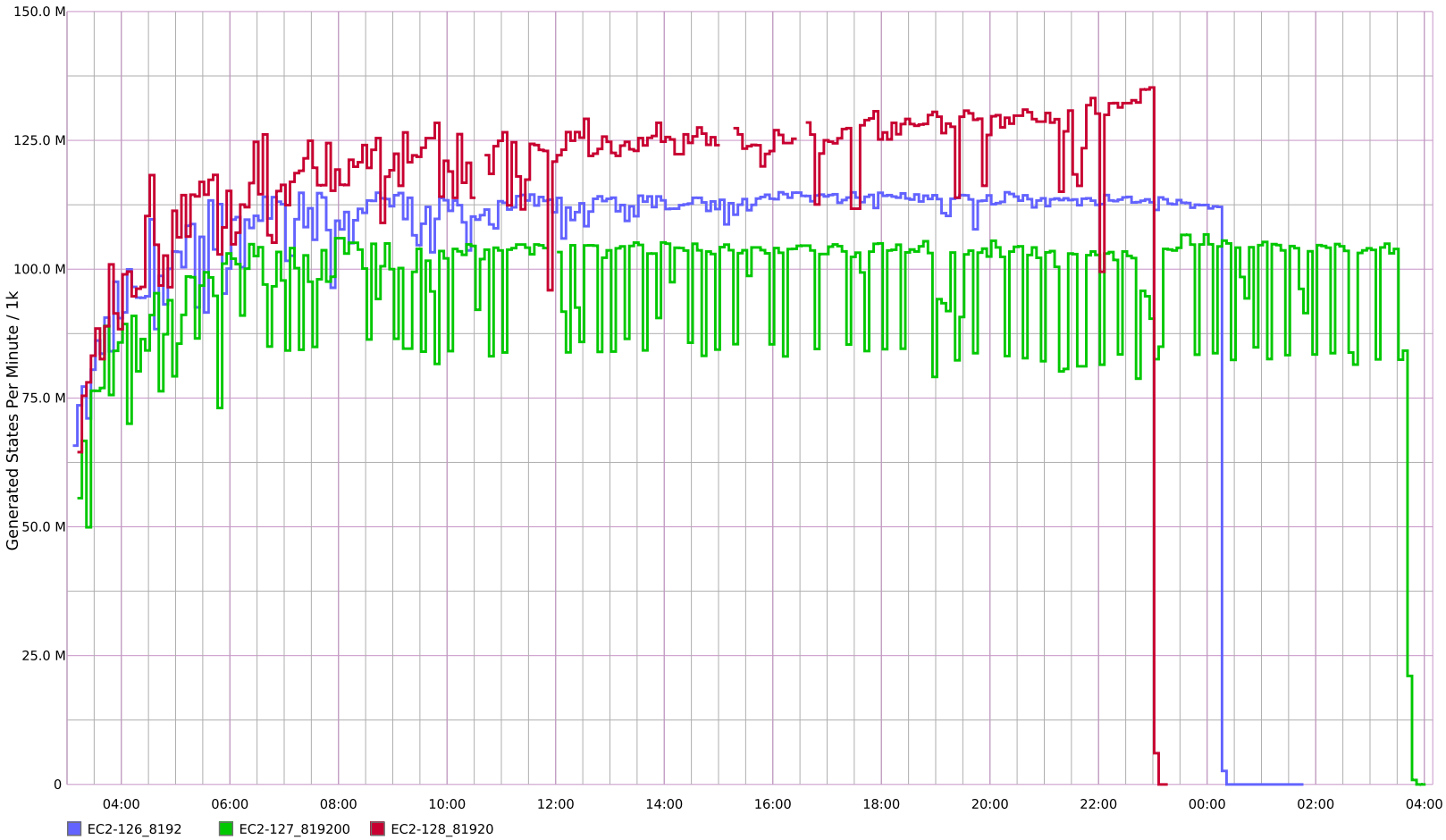

Figure: SQBufferSize

Ordered fingerprint operations

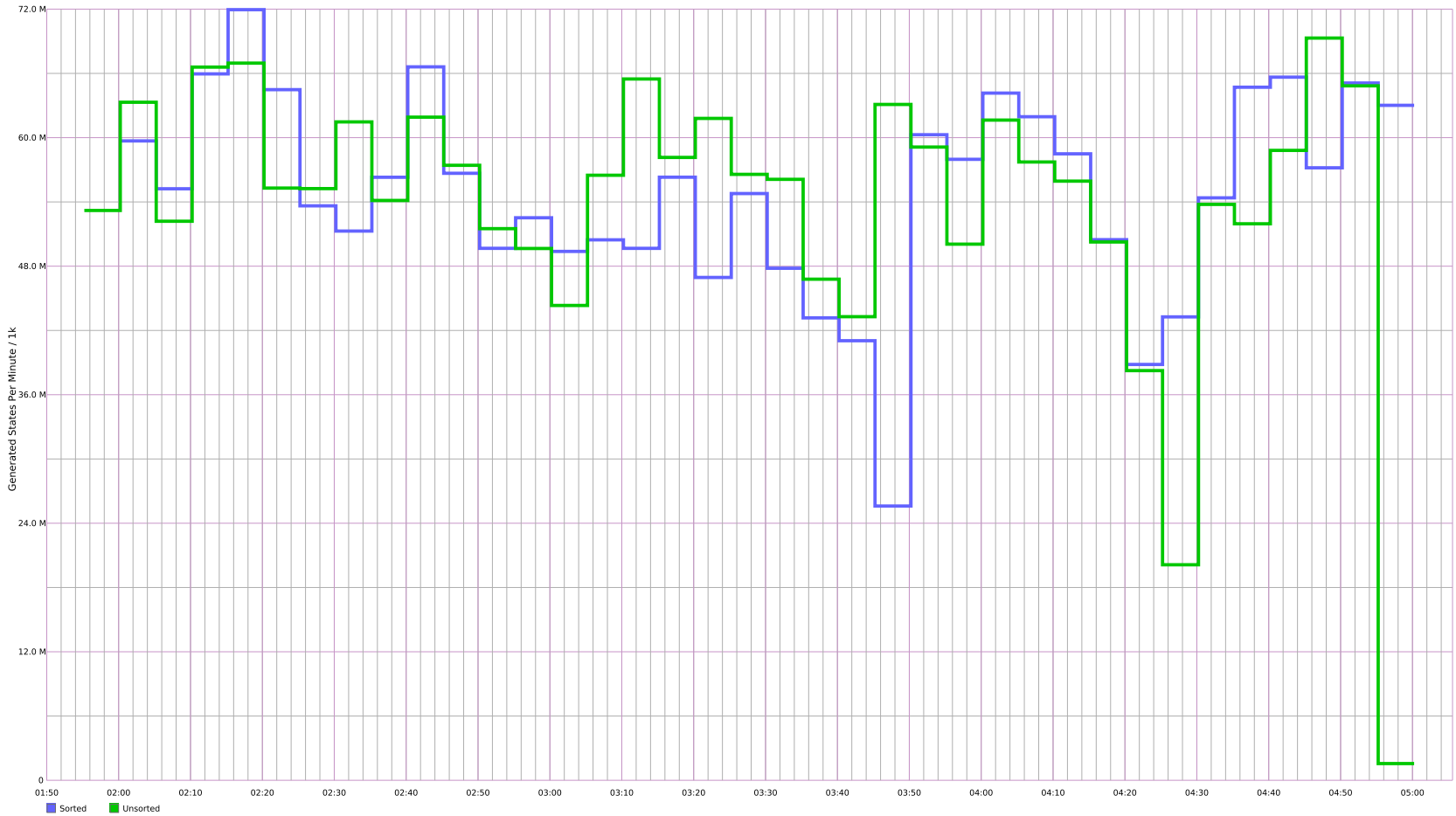

Figure: Ordered FP ops