LPC 2011

Improving "global" scheduler decisions

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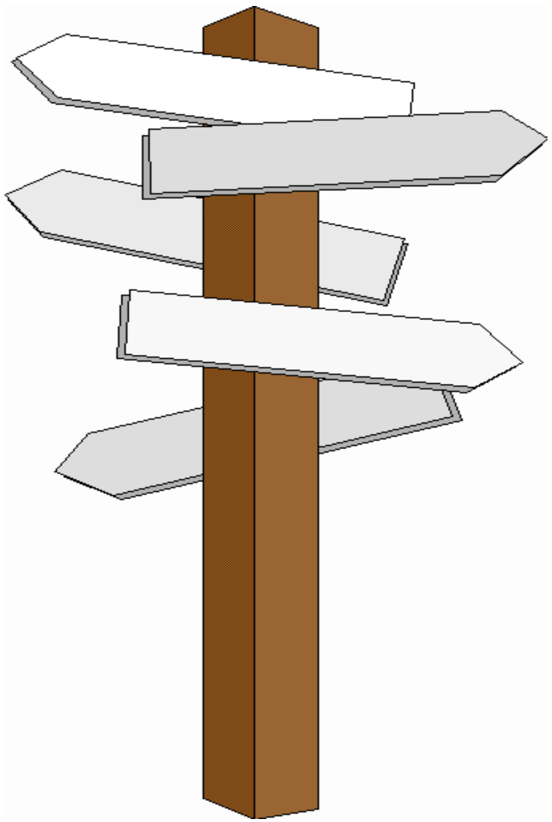
Overview

- Some CPU scheduling fundamentals
- Challenges
- Results



Linux CPU Scheduler

Linux uses the *Completely Fair Scheduler (CFS)*

History & Overview

- Merged in 2.6.23, replaces previous *O(1)* scheduler.
- Weighted fair queuing scheduler; strong roots in where multiple packet flows must share a link.
- No "queues", uses red-black trees to track *timelines*.

CFS: Basics

Basics

- "Weight based fair-scheduler"; allocate CPU cycles across period in proportion to each entity's weight.

How does this work in practice?

- Fix a unit period of time (the scheduling period *P*)
- Divide this period amongst tasks proportionally by weight

CFS: Weight-based scheduling

Basic Example

- 3 equivalent tasks **A**, **B**, **C**

Could choose: **A**, **B**, **C**

P

Or: **C**, **B**, **A**

P

Or even: **A**, **B**, **C**, **B**, **A**, **B**, **C**..

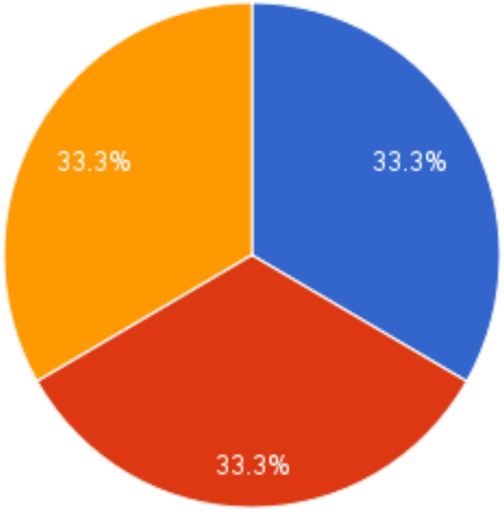
.... Not even going to try and draw this one

CFS: Weight-based scheduling

More generally:

$$\sum time(A) = \sum time(B) = \sum time(C) = \frac{P}{3}$$

Note: *P* is ~25ms on most systems



But, we assumed everyone had equal weight. **Hmm.**

CFS: Weight-based scheduling

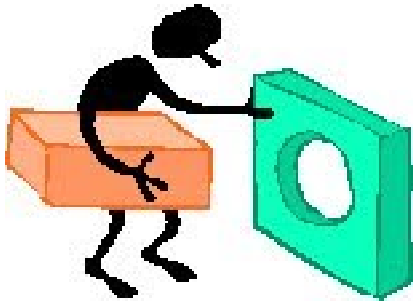
Previous example assumed weights were uniform, how do we handle asymmetric weights?

By virtualizing time.

CFS: Virtual time

How do we fold weight into time?

Moderate its advancement.

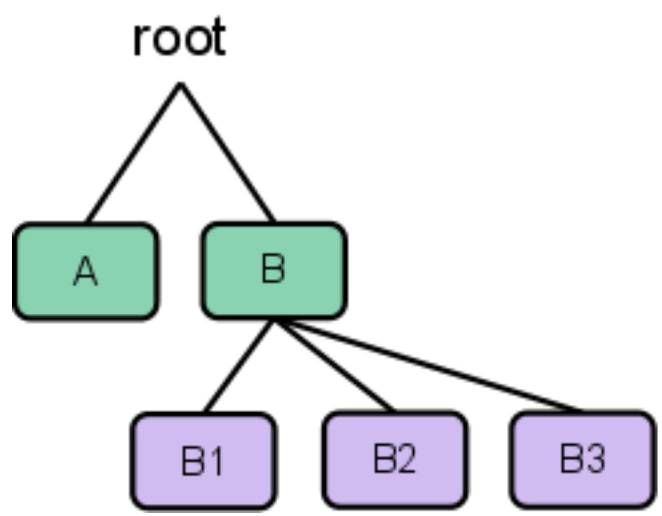


For smaller entities
Time accumulates more quickly.

For larger entities
Vice versa, time accumulates more slowly.

CFS: Hierarchical scheduling

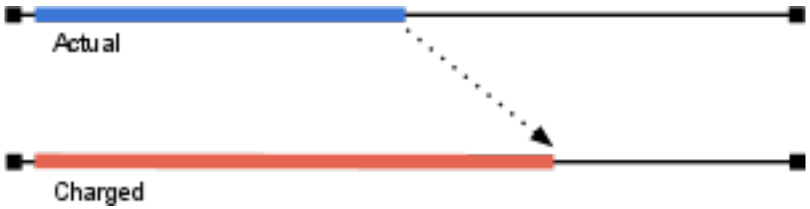
CFS supports the collection of tasks into a group, these groups can be nested to form a hierarchy.



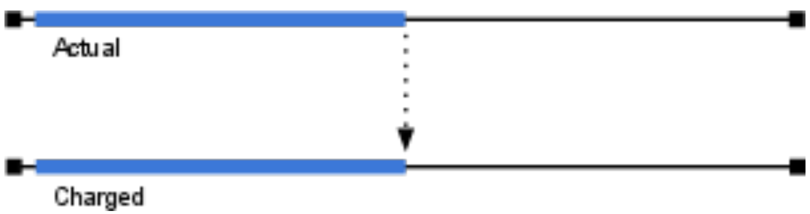
Scheduling decision becomes recursive.

CFS: Timelines

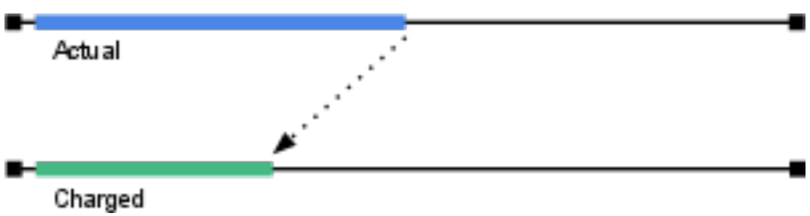
For a **smaller** entity, virtual time proceeds more quickly



For a **unit** entity, virtual time proceeds normally



For a **larger entity**, virtual time proceeds more slowly



CFS: Accounting virtual time

How is vtime (virtual time) defined?

Linear scale:

$$v_{time} = \frac{u}{w} \cdot time = \frac{1024}{w} \cdot time$$

e.g. Consider 5 elapsed seconds at weight=512

$$v_{time} = \frac{1024}{512} \cdot 5s = 2 \cdot 5s = 10s$$

Note: "Unit" weight is 1024

CFS: Virtual time

Recall:

$$\sum time(A) = \sum time(B) = \sum time(C) = \frac{P}{3}$$

Becomes:

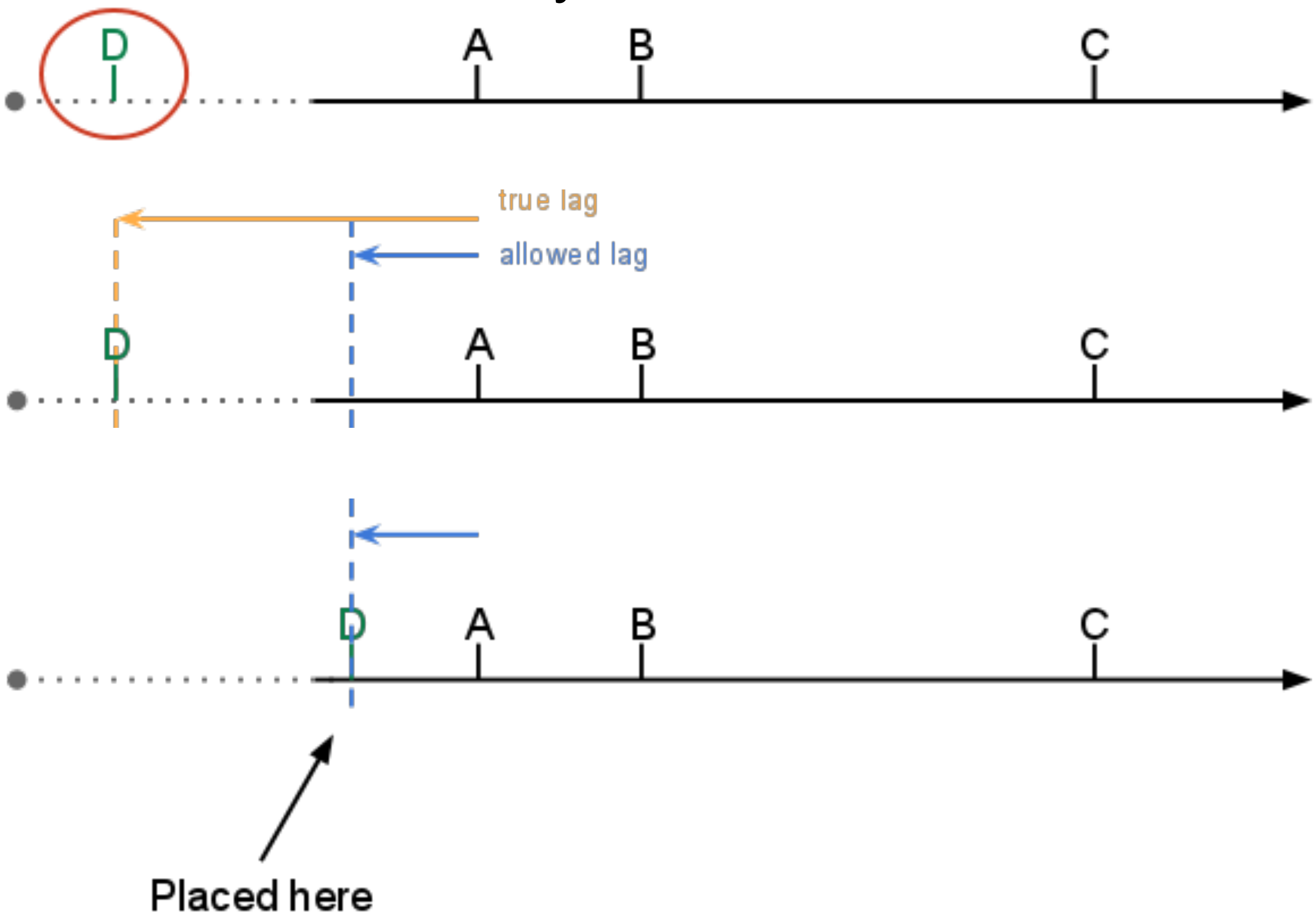
$$\sum v_{time}(A) = \sum v_{time}(B) = \sum v_{time}(C) = \frac{P}{3}$$

CFS: Timelines

As mentioned before, CFS maintains a timeline of all entities, ordered by vruntime. This is represented as a red-black tree.

CFS: Wake-up placement

Introduction of a new entity:



CFS: Pre-emption

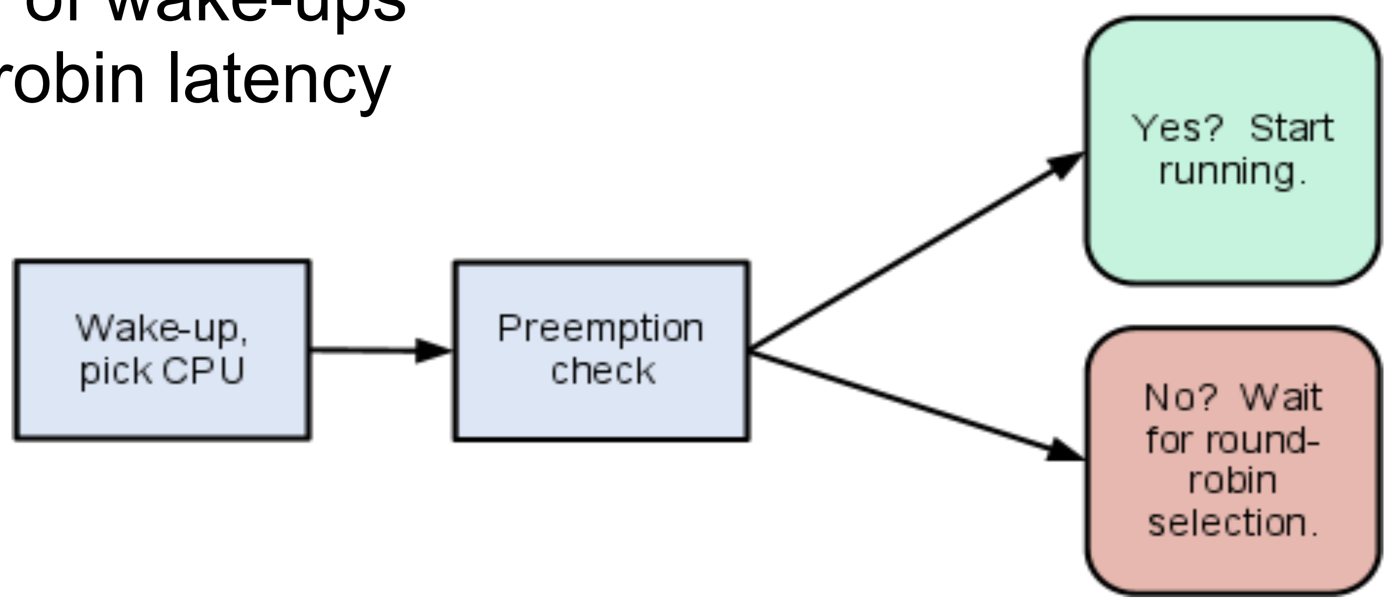
Also based on timeline

Scheduling Latency

What is scheduling latency?

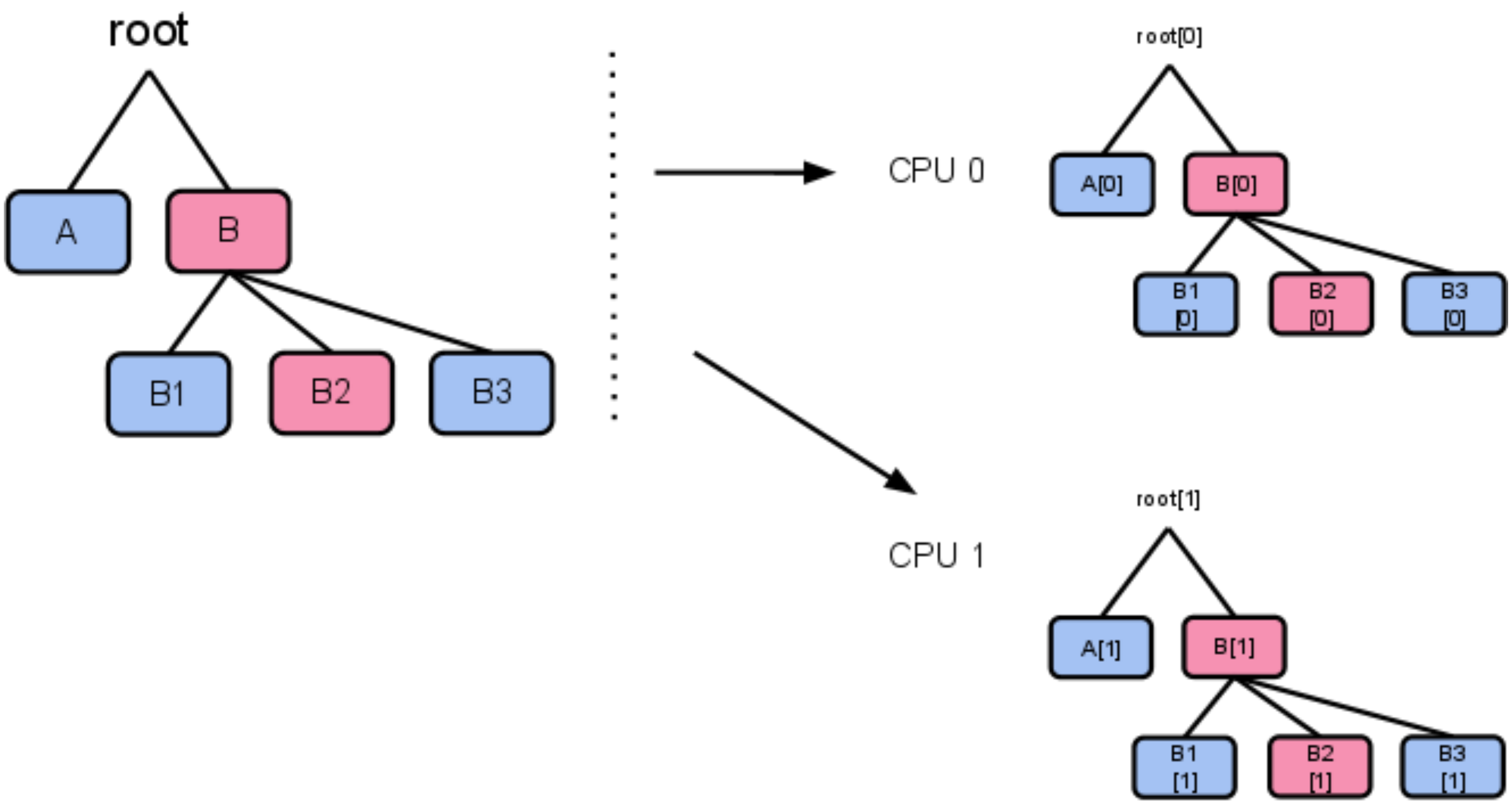
Two cases we care about:

- Latency of wake-ups
- Round-robin latency



SMP: Group scheduling

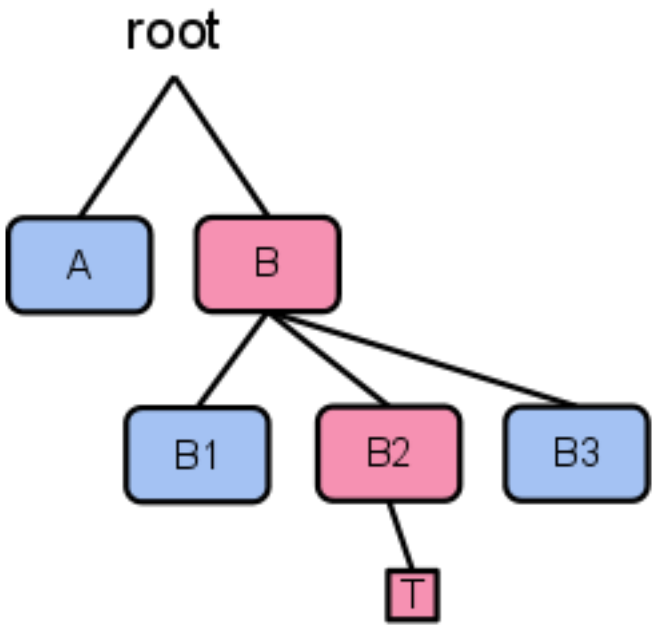
Consider the previous hierarchical scheduling example.



CFS: Hierarchical scheduling

Example

1. Using **root** time line, □Pick □**B**
2. **B** is a group entity, recurse.
3. Pick **T** from **B**'s virtual timeline.
4. ***T*** is a task, we're finished!



SMP ... makes everything harder.

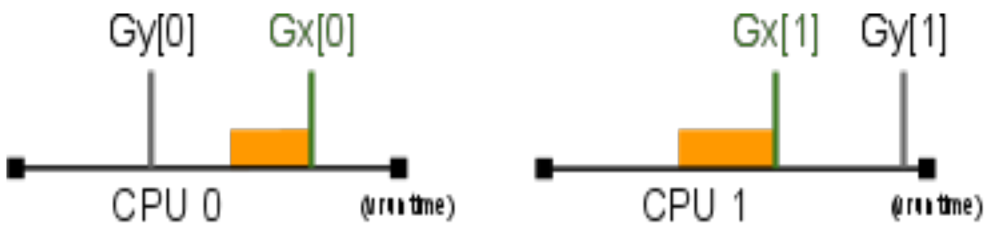
Turns out scaling frequency is **hard**.

Solution: Scale parallelism! Many cores!

This adds tangles to everything we just talked about. **:(**

SMP-Group: Pre-emption

Problem:



The pre-emption decision is inconsistent. Had we chosen to run on CPU0, we would have pre-empted yet on CPU1 we are forced to wait.

Which of these is right?

We'll come back to this.

SMP: Group scheduling

The problem, more generally:

Group entities participate in more than one timeline.

- What weight do we assign each?
- How does the lag of one affect another?
- What does pre-emption between groups look like?

SMP-Group: Weight distribution

Group entities have a weight. But this is a global weight, their entities need a local weight when participating on each CPU's timeline.

Can't we just use the global weight?

Breaks under asymmetric competition :(

SMP-Group: Weight distribution

Suppose *A* has 3 tasks of equal weight:

1. *A[0]* parents two tasks.
2. *A[1]* parents one task.

Note: *A[i]* is the entity for group *A* on *cpu i.*

Then,

A[0] should be weighted at 2/3 of *A*.
A[1] should be weighted at 1/3 of *A*.

We call the weight assigned to a group-entity its *"shares".*

SMP-Group: Shares distribution

Generalizing this:

$$A[0]_{weight} = A_{shares} \cdot \frac{load_0}{\sum load_n}$$

But,
This is hard to compute.

- Sum(load_n) is O(n)!
- One load changing affects everyones' weight.
- Haven't even nested groups under groups here!

Shares: Initial approach

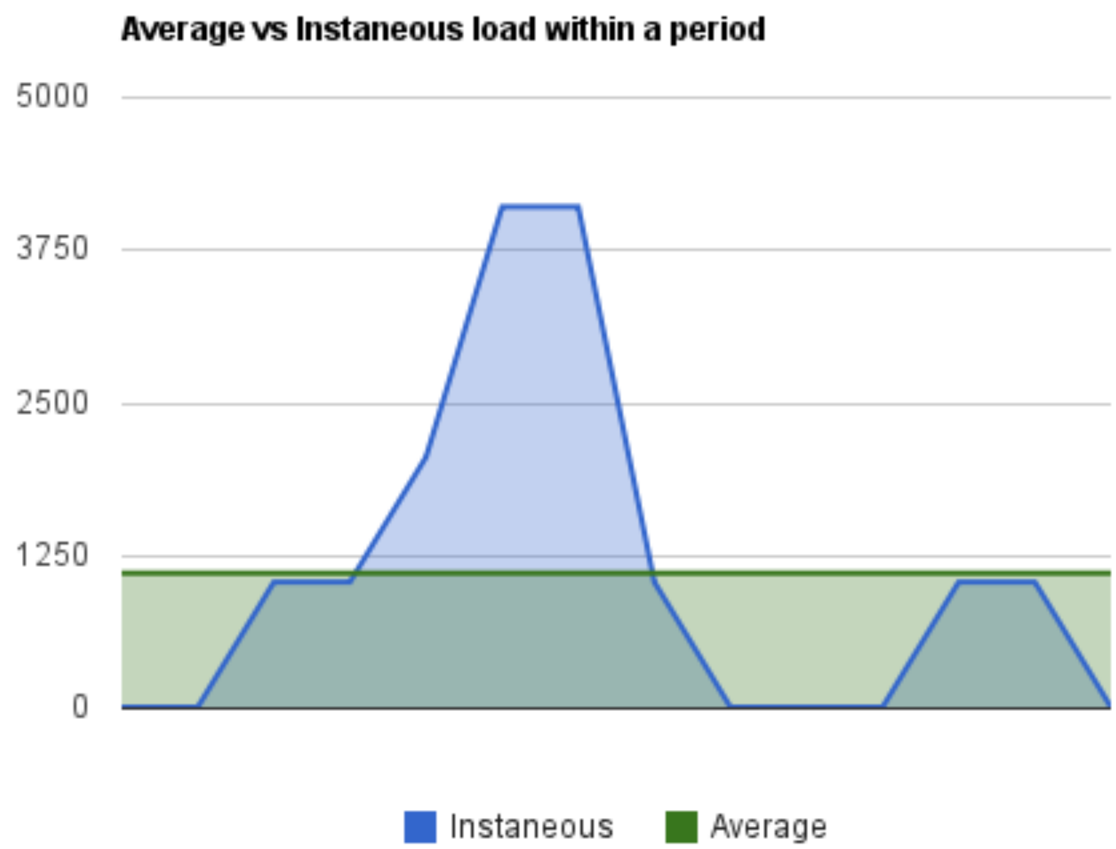
- Periodically evaluate this sum explicitly
  - Compute Sum(load_n)
  - Cache and divide each load_i against this.

Previously accounted in the top 20 of all CPU cycles (by C/C++ function) consumed at Google.

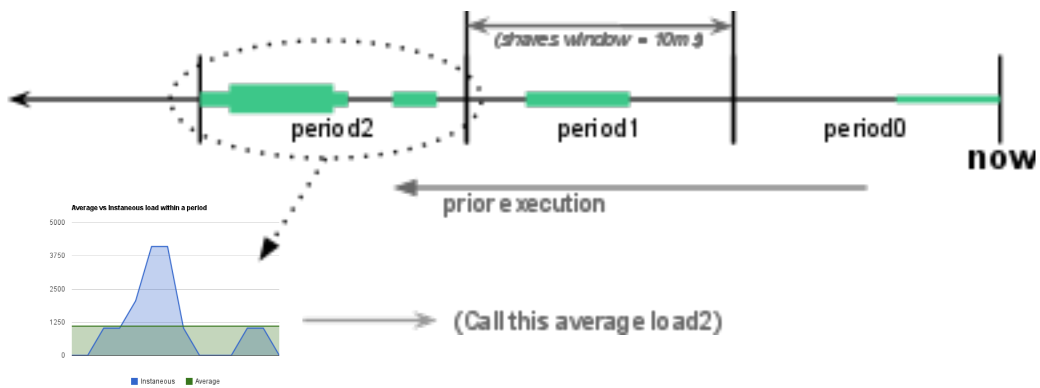
Shares: Current approach

Key idea
Load varies, instead of tracking the instaneous sum, let's track the average observed load and assign weights against that.

Shares: Current approach



Shares: Average history



Then,

Average everything together (with exponential decay)

$$load_{\overline{A[0]}} \doteq load_0 + \frac{load_1}{2^1} + \frac{load_2}{2^2} \dots$$

Shares: Using average history

Used today, works fairly well... but..

Caveat:

No good way of accounting for load migrated due to load-balancing.

Other pitalls:

Ratios versus current contribution are inconsistent.

Shares: Improving tracking

Each (per cpu) group entity tracks the average sum of its child load.

=> Can't determine a child's load contribution when moving it to another cpu!

Revised
What if each entity tracked its own runnable contribution? A group entities load would then be the sum of its childrens' contributions.

Shares: Improving tracking

So why didn't we do this in the first place?

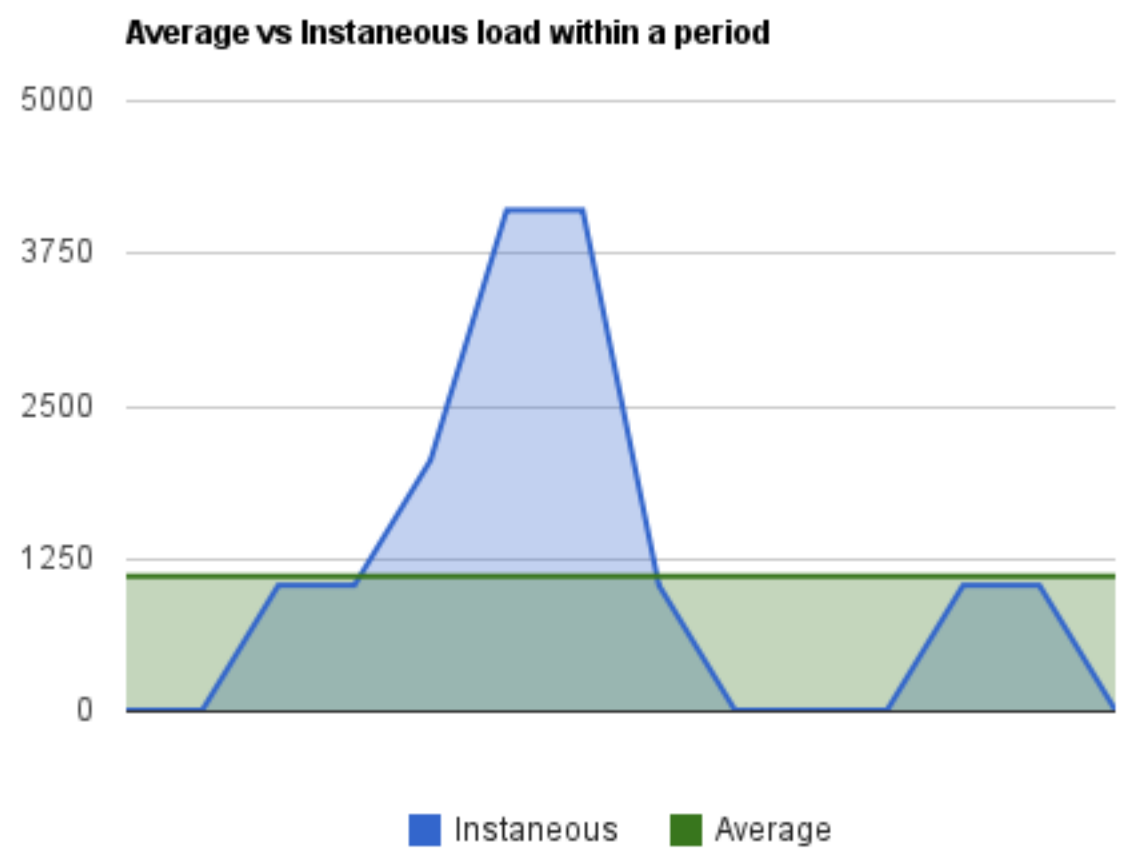
Hard to get right!

- We don't hold the right locks around wake-ups
- Hard to update sleeping entities
- Higher overheads

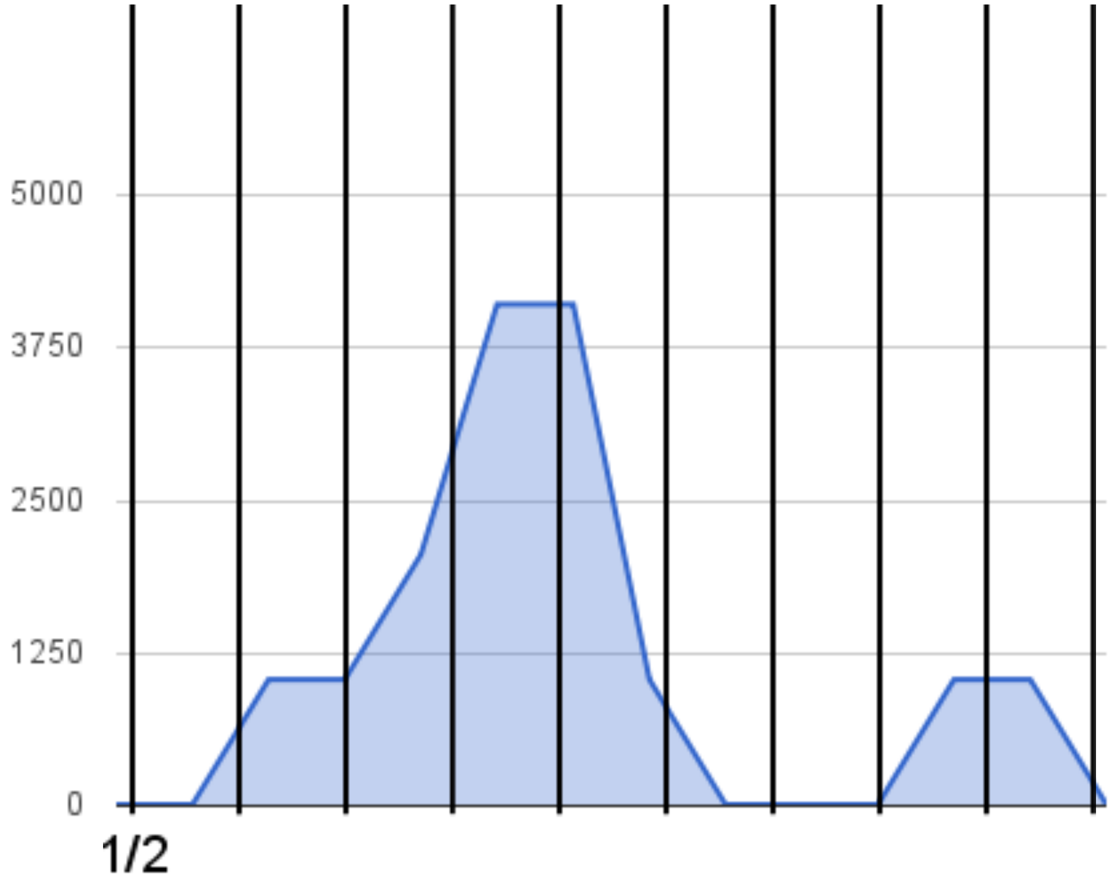
Shares: Tracking at the entity level

Instead of tracking the average of **children**, now tracking a contribution to **parent**.

Re-thinking shares averaging



Re-thinking shares averaging



Shares: Tracking at the entity level

How do we compute an entity's contribution?

$$A[0]_{\overline{load}} \doteq load_0 \cdot y^0 + load_1 \cdot y^1 + load_2 \cdot y^2 + \ldots$$

Then normalize against period:

$$A[0]_{period} = \sum p \cdot y^i$$

Finally:

$$A[0]_{\overline{contrib}} = \frac{A[0]_{\overline{contrib}}}{A[0]_{period}}$$

Shares: Updating blocked entities

Still a problem
How do we handle updates against blocked entities?

Previously:

$$A[0]_{\overline{load}} \doteq \sum load_i \cdot y^i$$

But, if idle, load_0 = 0! **So..**

$$A[0]'_{\overline{load}} \doteq \sum load_i \cdot y^{i+1} = y \cdot A[0]_{\overline{load}}$$

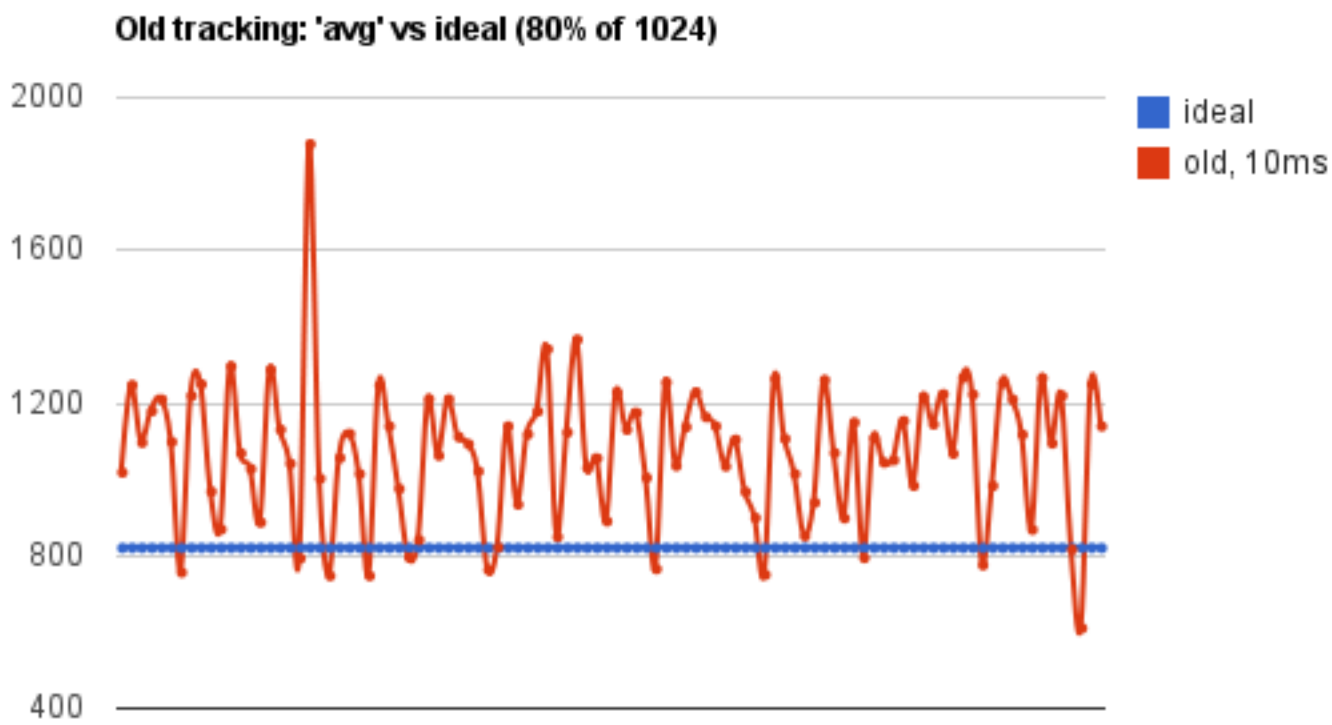
Shares: Updating blocked entities

Separate the sums maintained on a group entity into ***runnable*** and ***blocked***.

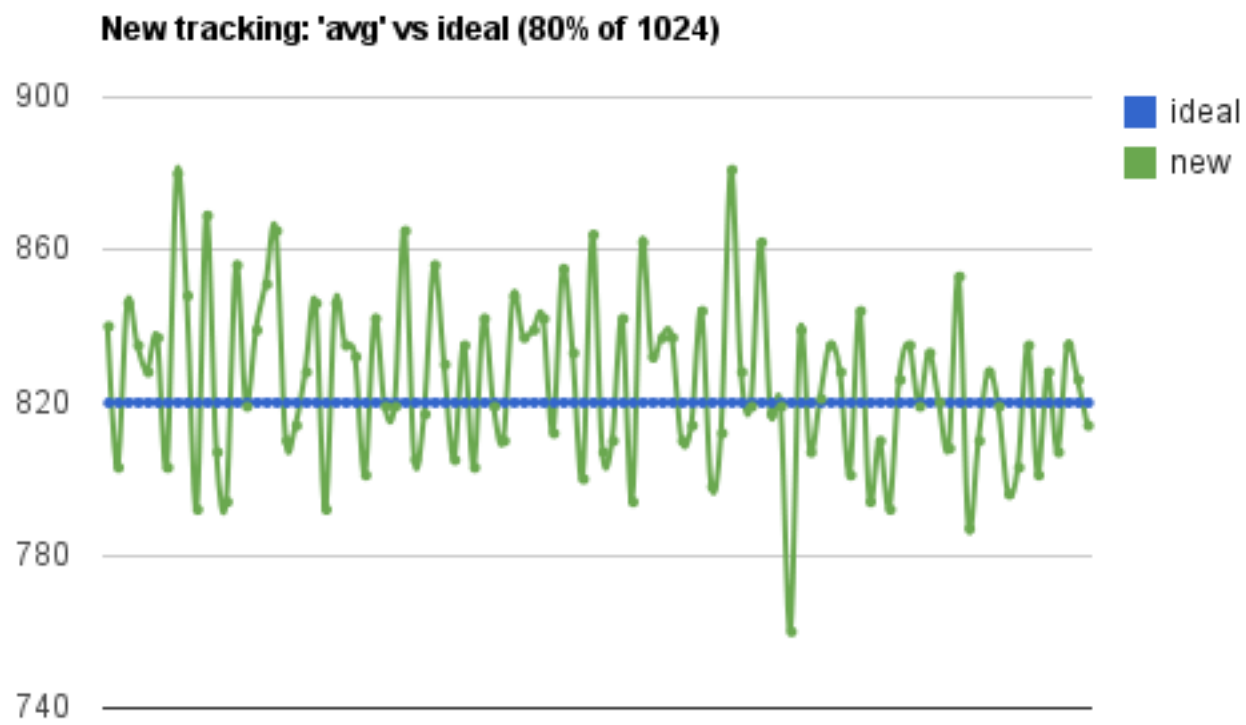
The ***runnable*** sum is updated by the *active* entities making the contribution.

The ***blocked*** sum is updated periodically, using the previous decay trick.

What does this get us?



Load tracking: New

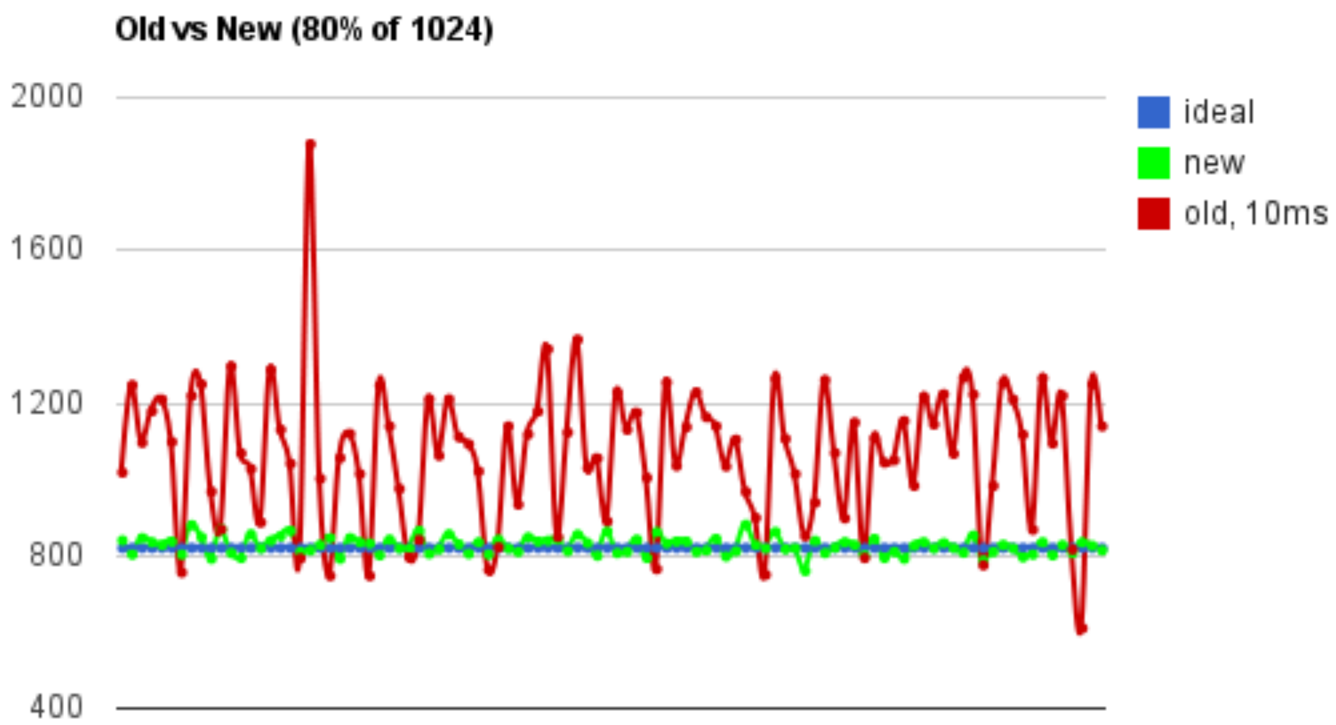


Well..

That wasn't very exciting.

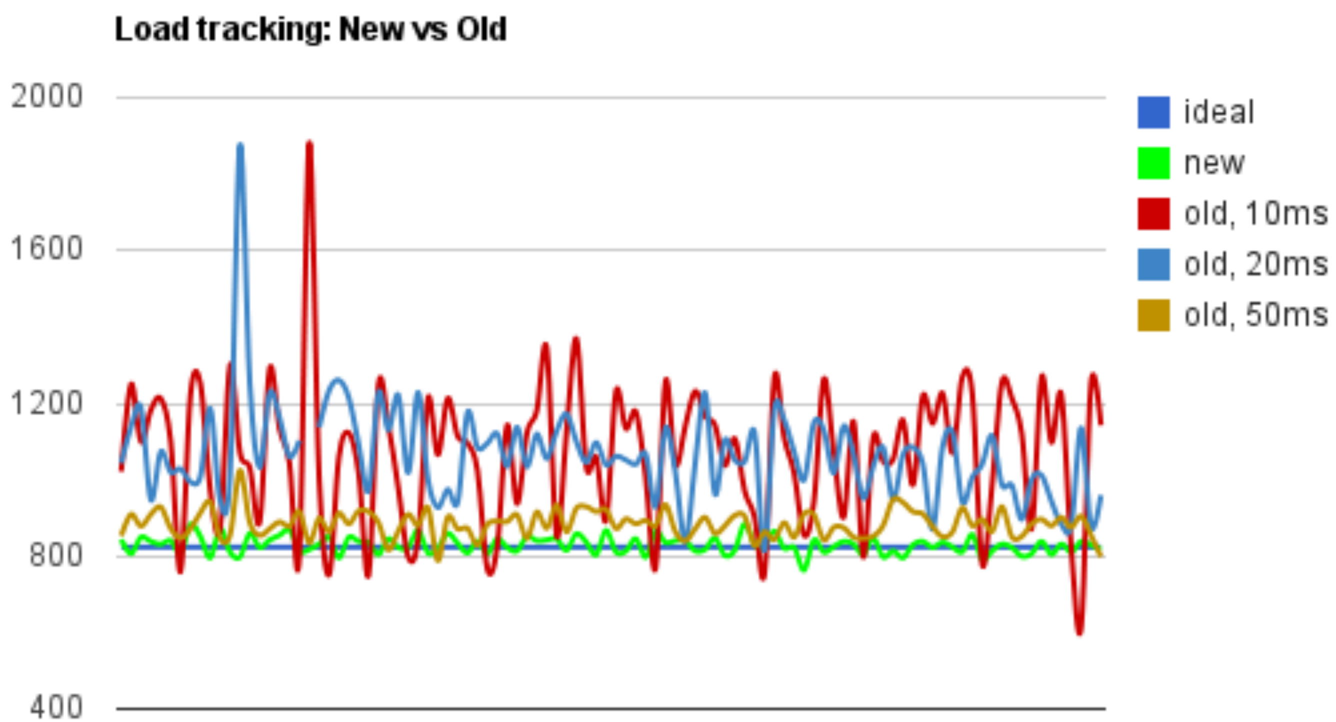
But wait, what about the axes, let's overlay the two.

Load tracking: New vs Old

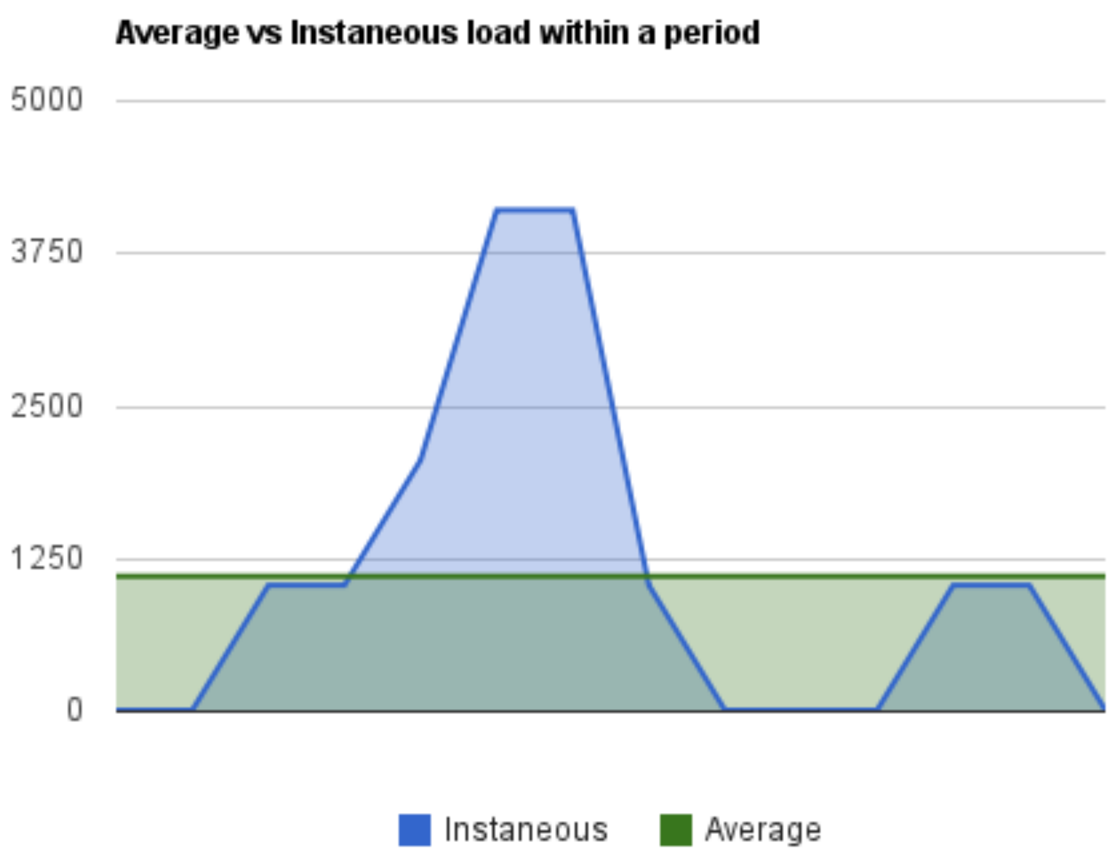


	Min	Max	Median	Avg	Stddev
old	760	983	828	827	27.3
new	610	1878	1097	1070	183.5

Increasing the old shares window

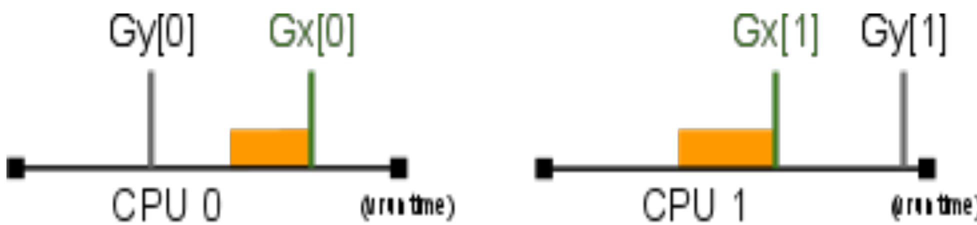


Re-thinking shares averaging



SMP-Group: Pre-emption

Problem:

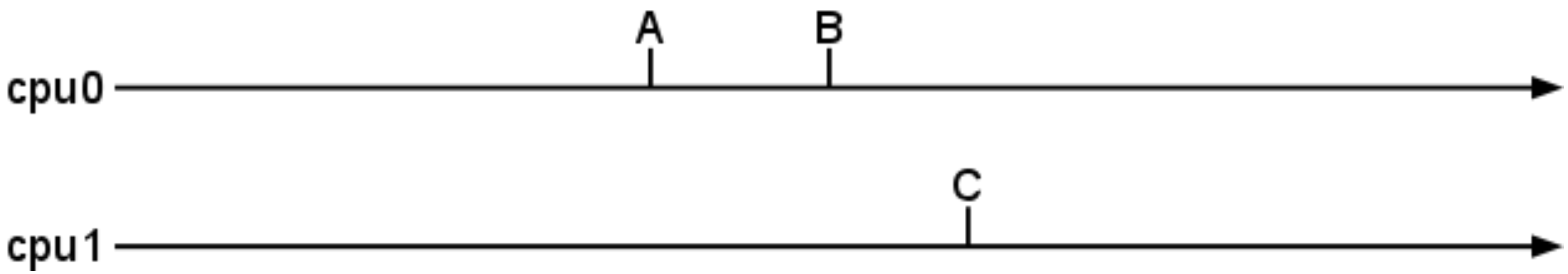


Still don't have an answer as to which choice was right!

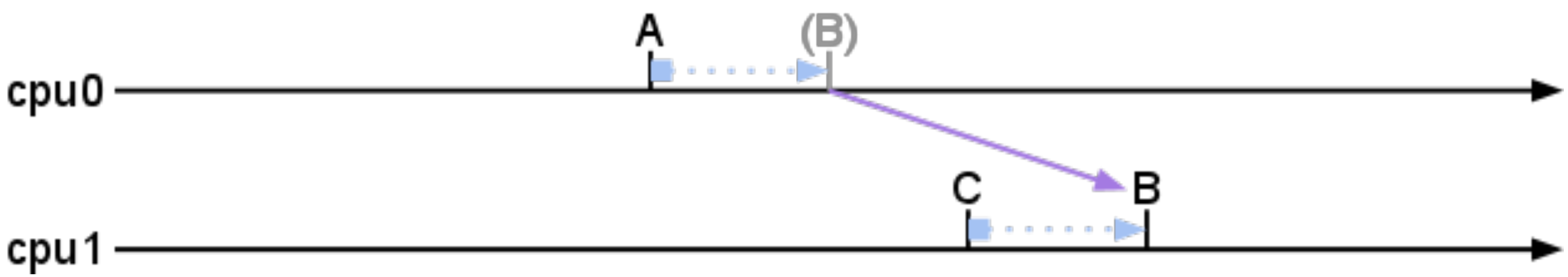
Possibly worse: Nothing we've covered lets you tune this behavior.

Timeline Spread

Suppose **{A,B,C}** have equal weight



When we move **B** we preserve lag relative to **A**.



But **C** should have **negative lag** relative to both **A** and **B**!

Handling "global" pre-emption?

The root of the problem is that we are using separate entities to track a single object.

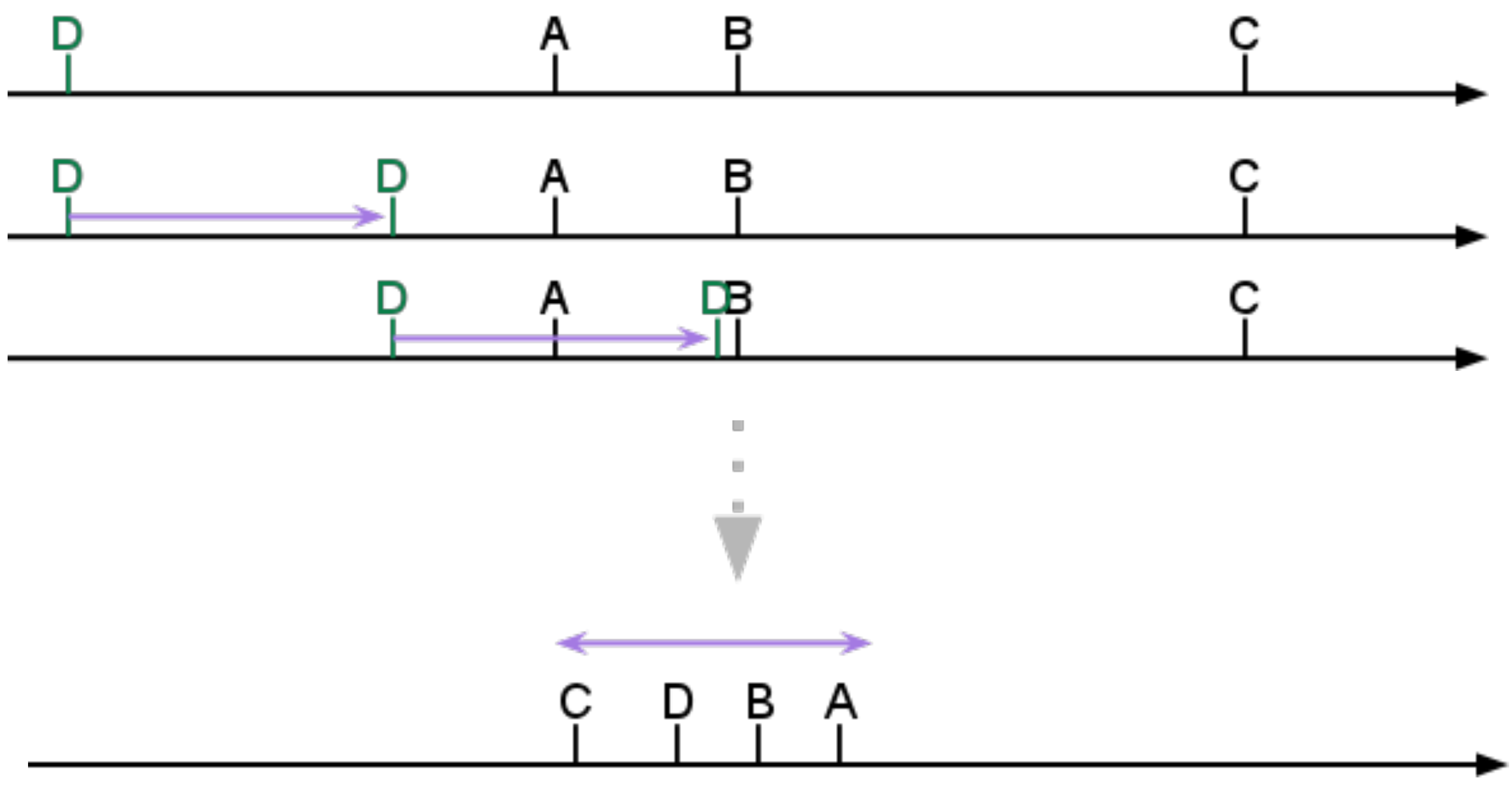
Idea:
Could we use a single (global) entity tree to track groups relative to one another?

Pitfall:
Convergence of the spread within a scheduling level depends on only one entity being able to accumulate run-time.

In the absence of this restriction we are unable to bound latencies or have entities join the tree.

Timeline Spread

CFS latencies are implicitly bounded by vruntime spread:



Take #2

Idea:
Use bandwidth control style tracking of used run-time.

Pitfalls:
- We still want to be work-conserving. (easy)
- We need decay to be continuous... Discrete tracking of accumulated run-time will NOT result in consistent behavior. (really hard)

Take #3

Idea:
Treat group entities as the average behavior of their per-cpu entities.

Pitfalls:
- We need the averages to be accurate / up-to-date.
- May have problems if the distributions are uniformly "odd"
- We need to avoid starvation.

CFS: Virtual time -- Defining "lag"

Lag is the difference between the time that an entity has received and the proportion its weight entitles it to.

$$lag_i = S_i - s_i$$

Where:

- *Si* is the ideal time by weight
- *si* is the actual received time.

Virtual Time: Lag

Positional comparison (wake-up) on time-line is actually trying to approximate lag delta using local information.

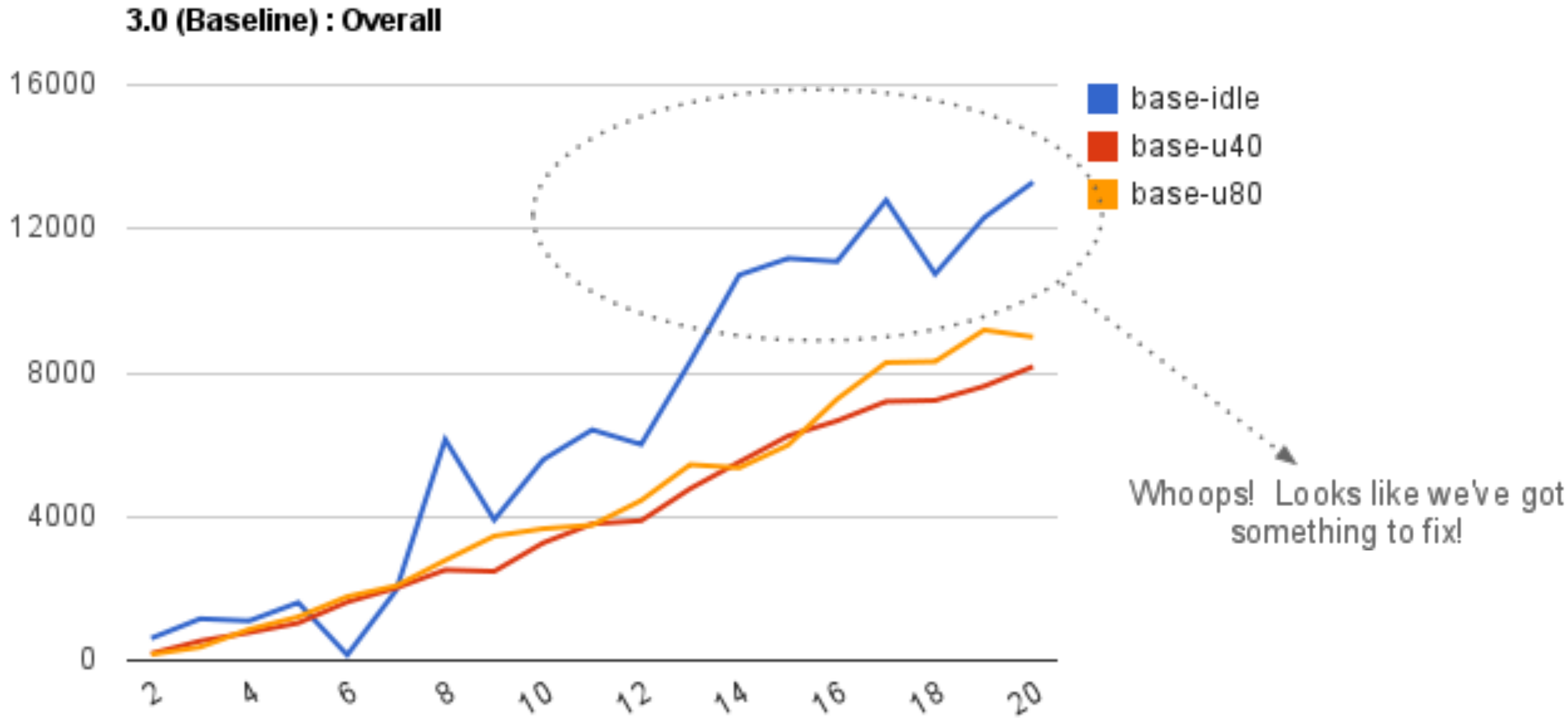
Instead use the global information to re-approximate this as part of placement. Wake-ups happen as before, but with a globally lag preserving placement scheme instead of a local one.

Results

Synthetic latency test (latt)

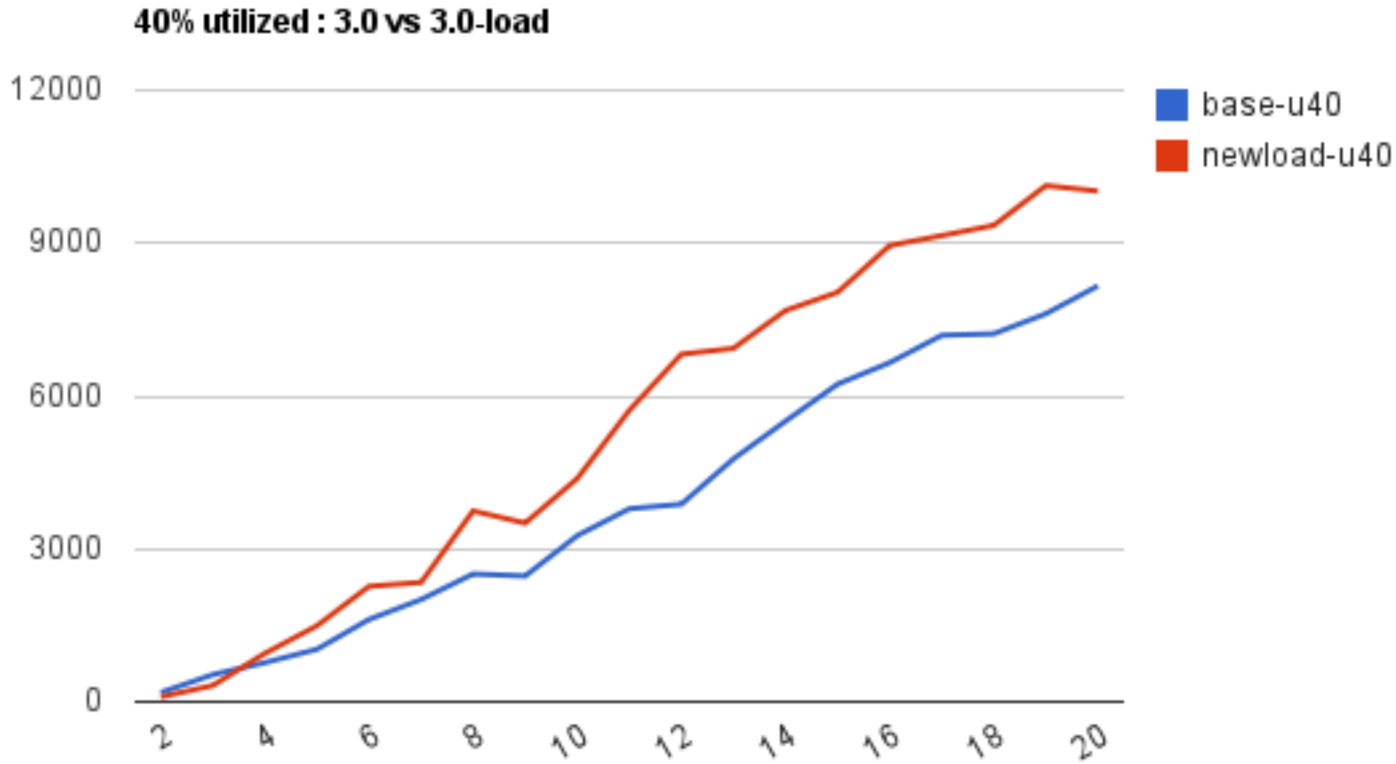
Results: Synthetic latency

Baseline



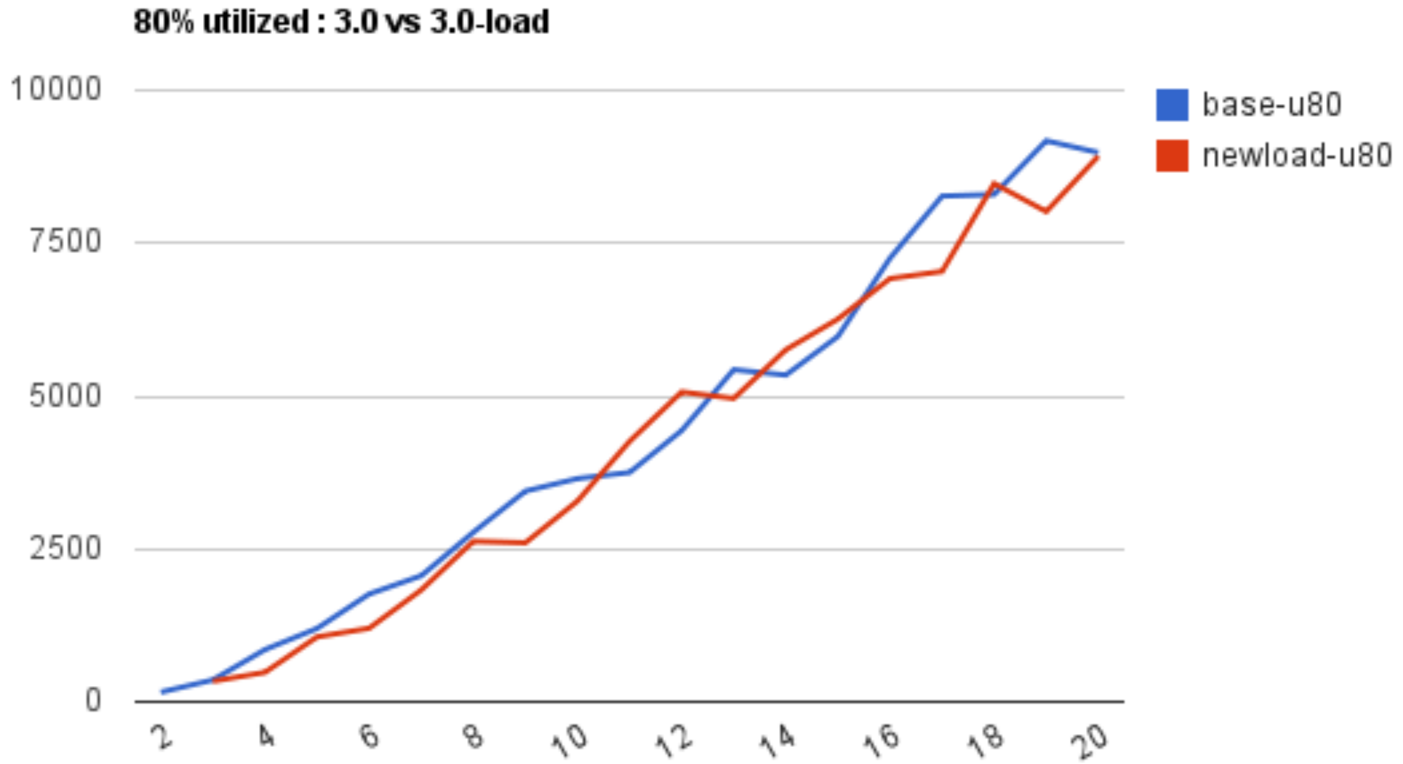
Results: Synthetic latency

New load tracking, 40% utilized



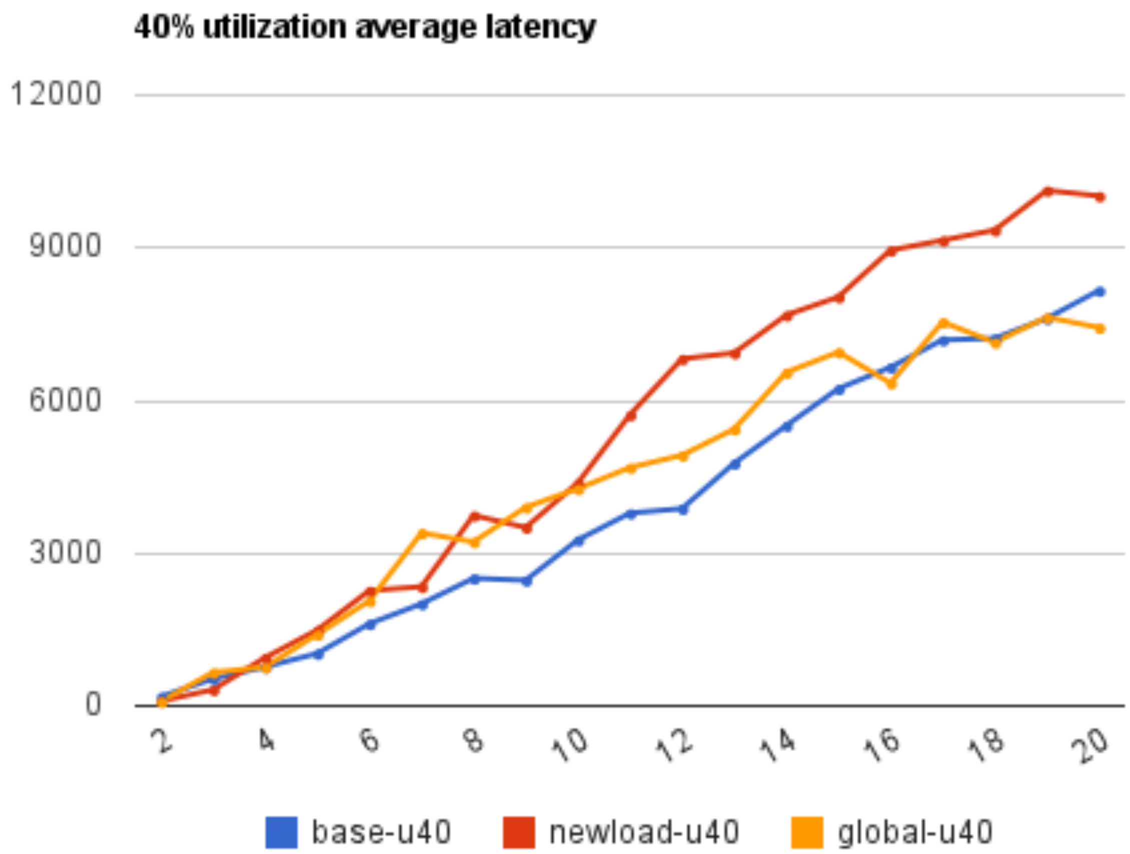
Results: Synthetic latency

New load tracking, 80% utilized



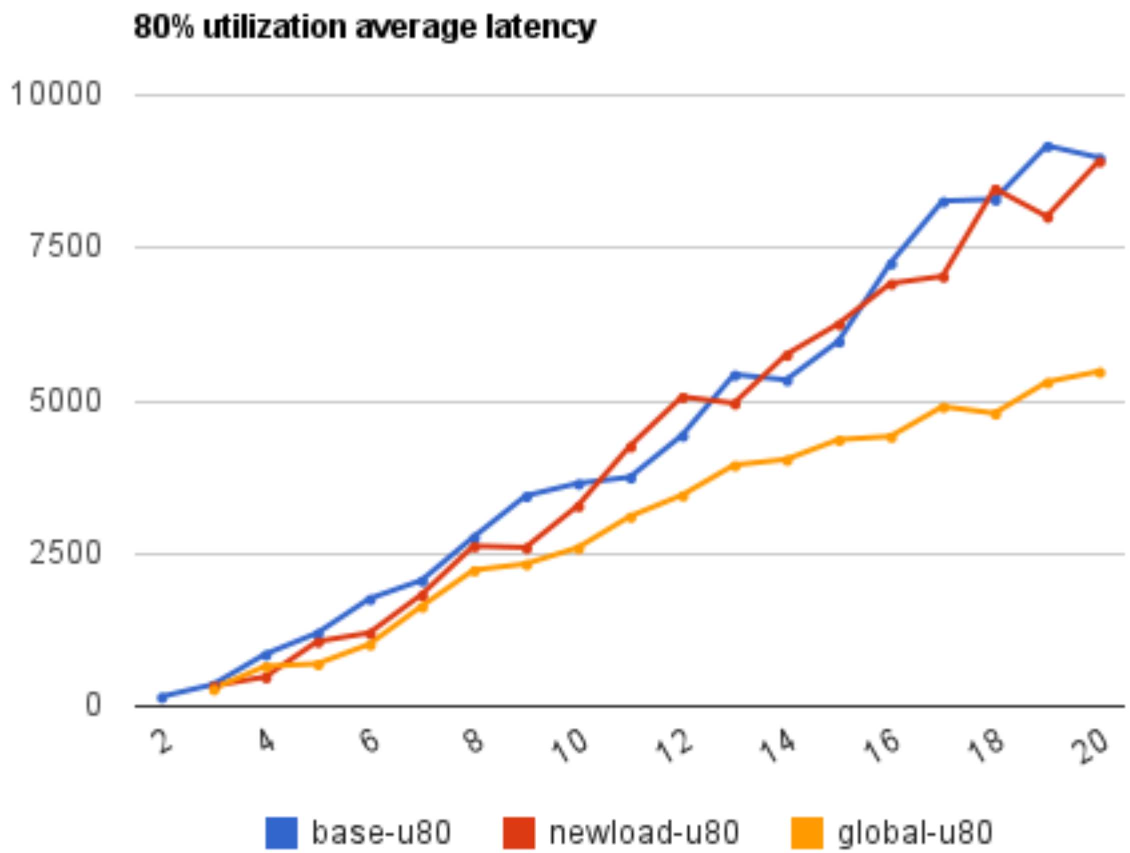
Results: Synthetic latency

Using global lag for entity placement, 40%



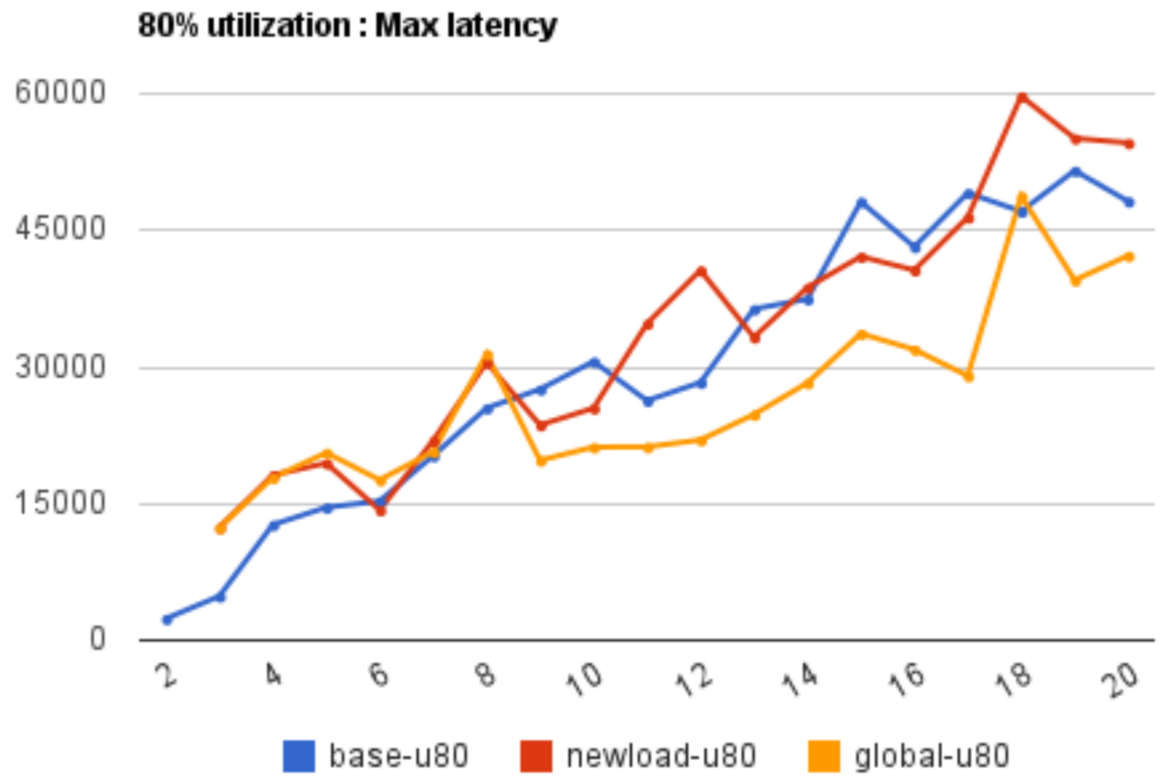
Results: Synthetic latency

Using global lag for entity placement, 80%



Results: Synthetic latency

Tail latencies

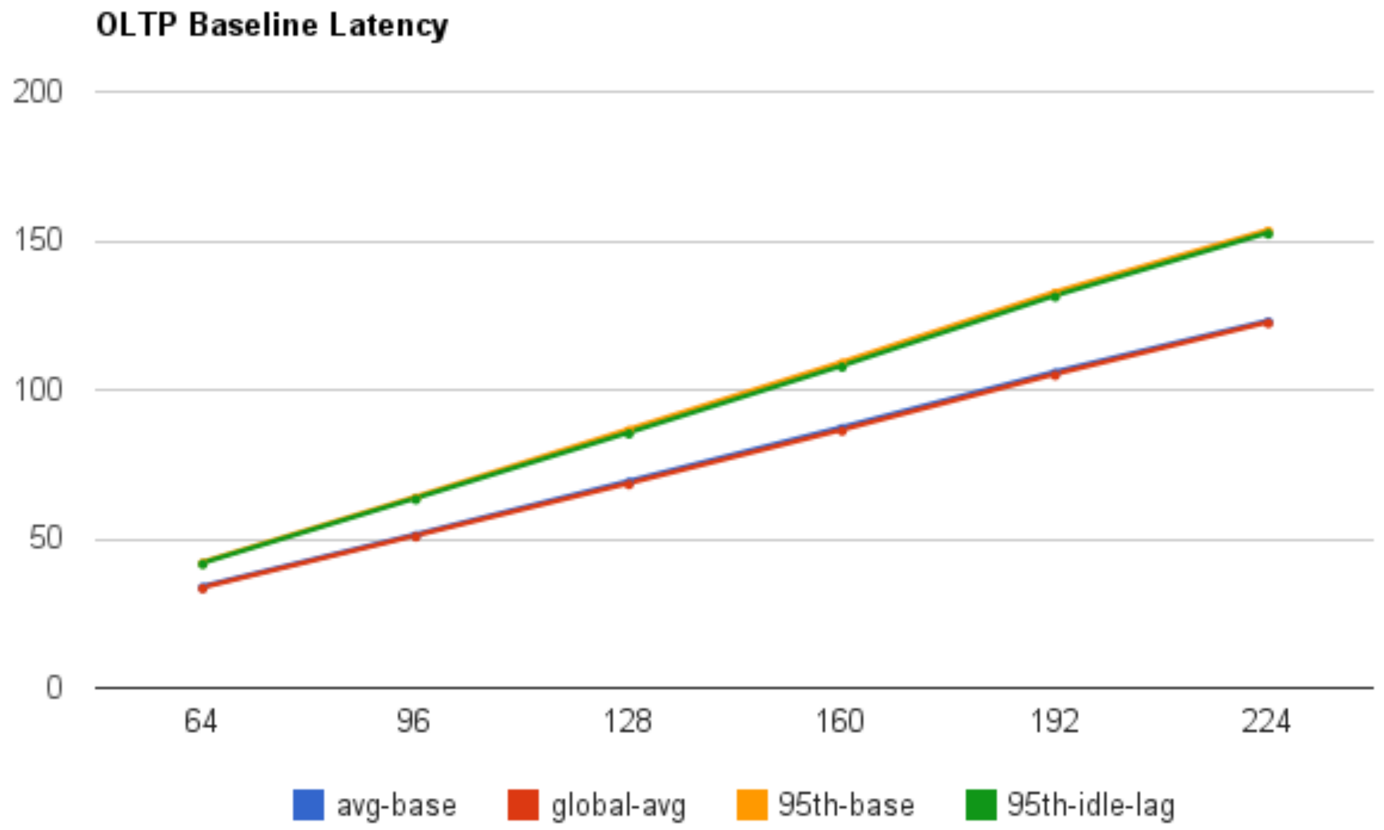


Results

OLTP vs Antagonists

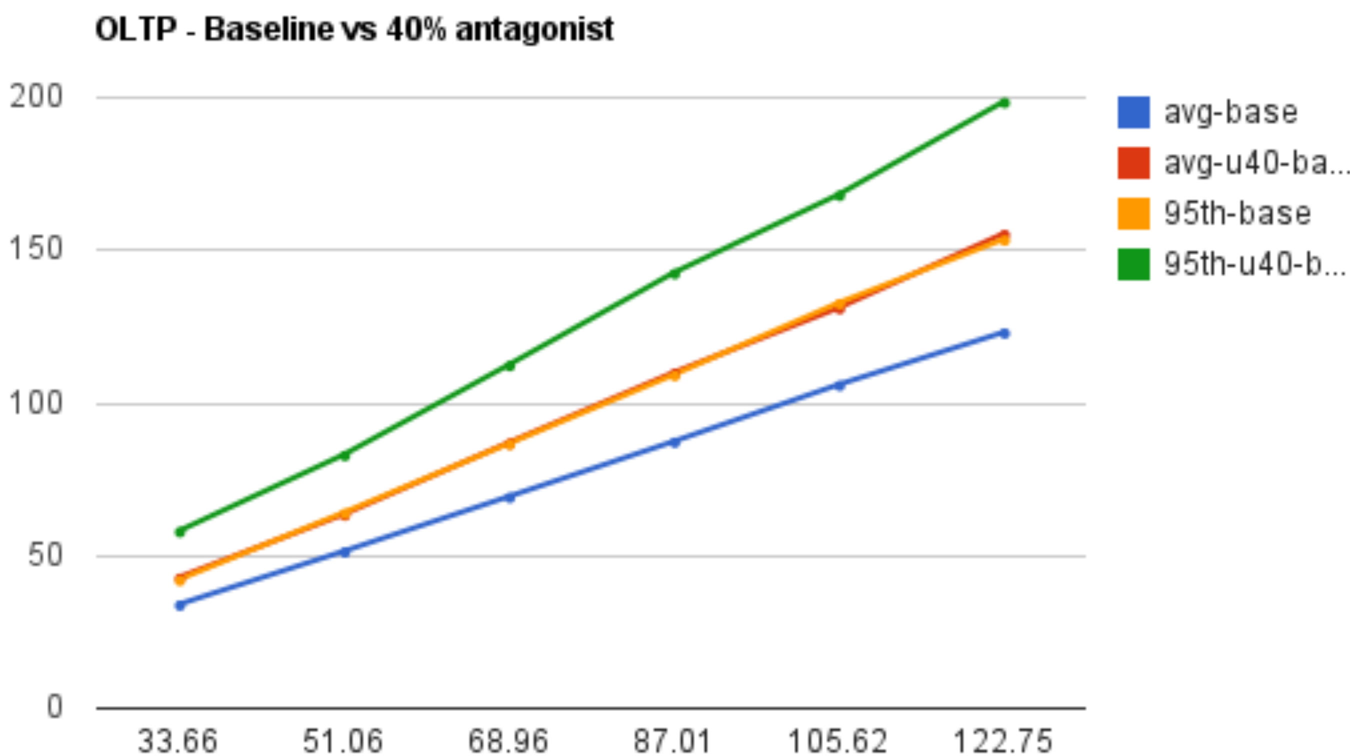
Results: OLTP

Baseline



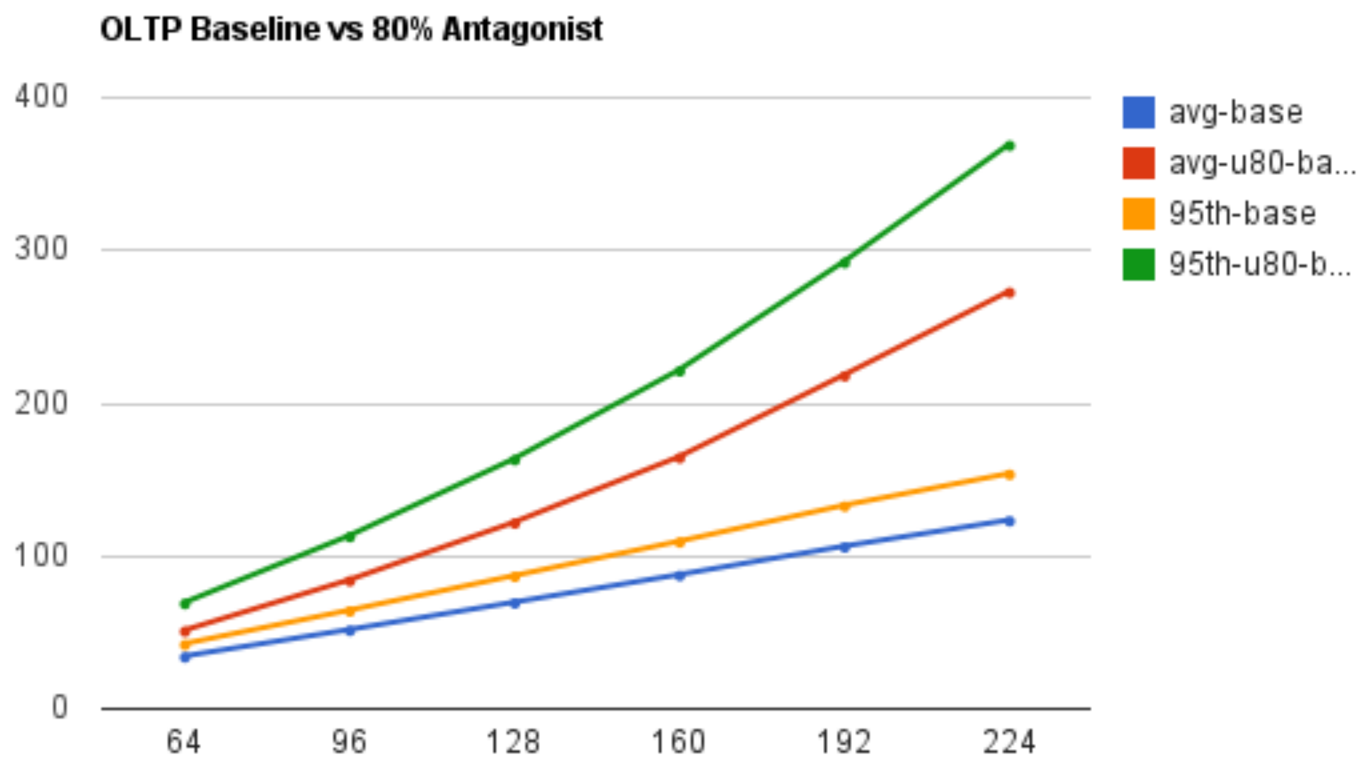
Results: OLTP

Baseline vs 40% antagonist



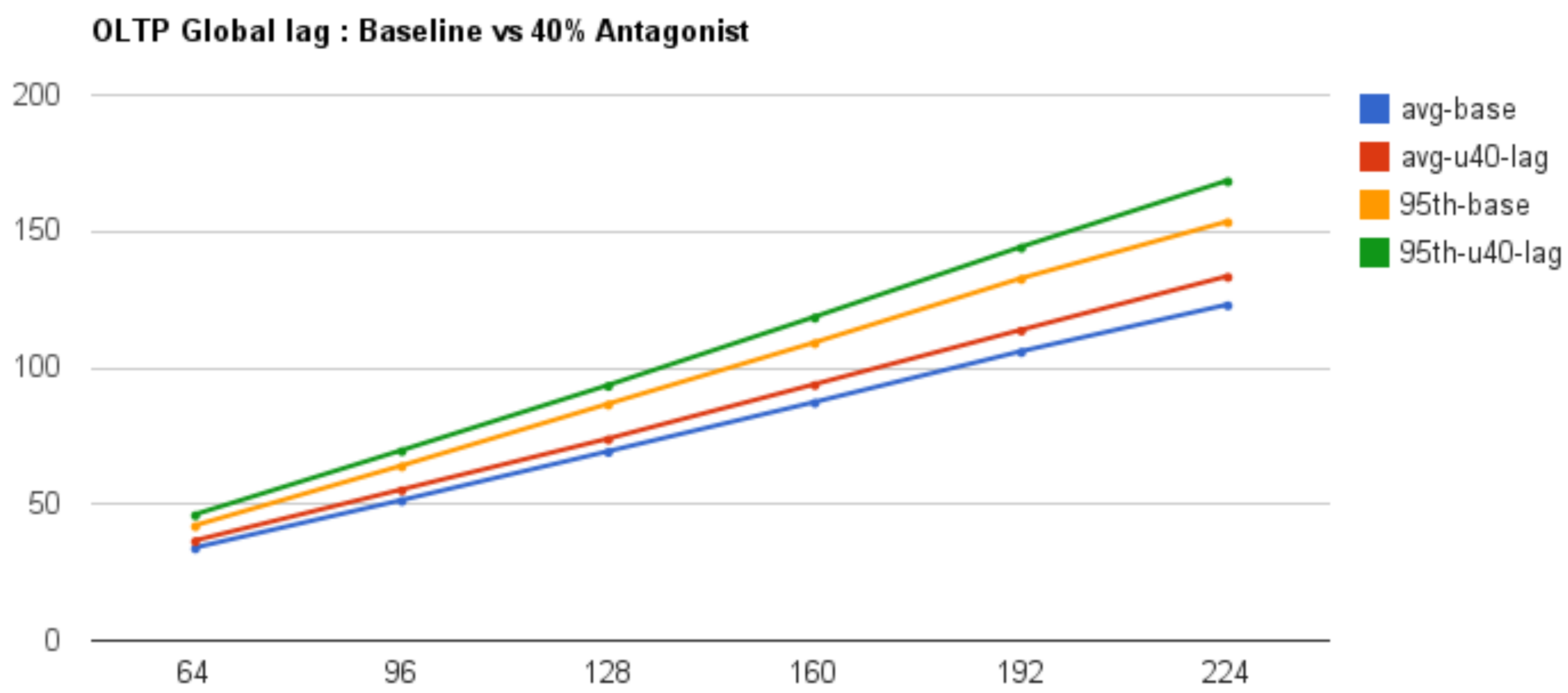
Results: OLTP

Baseline vs 80% antagonist



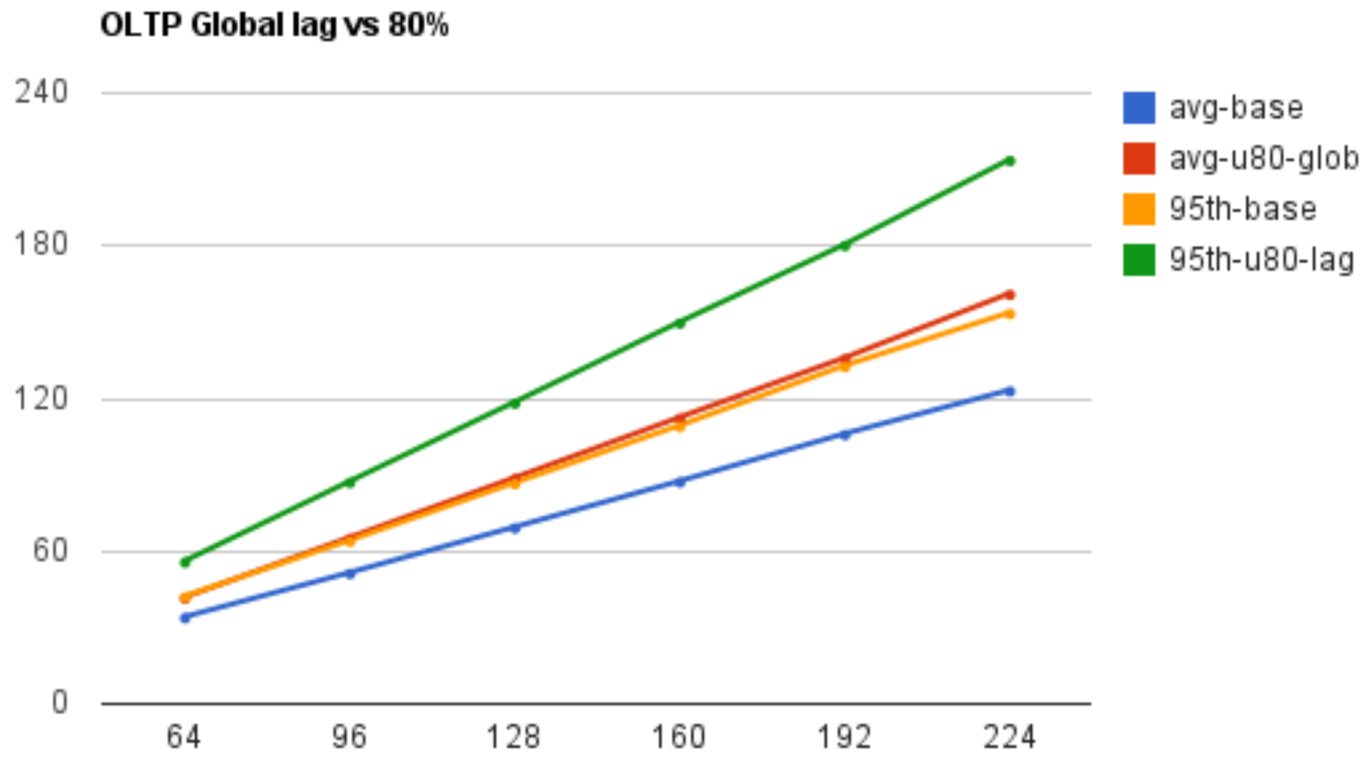
Results: OLTP

Global-lag w/ 40% vs Baseline



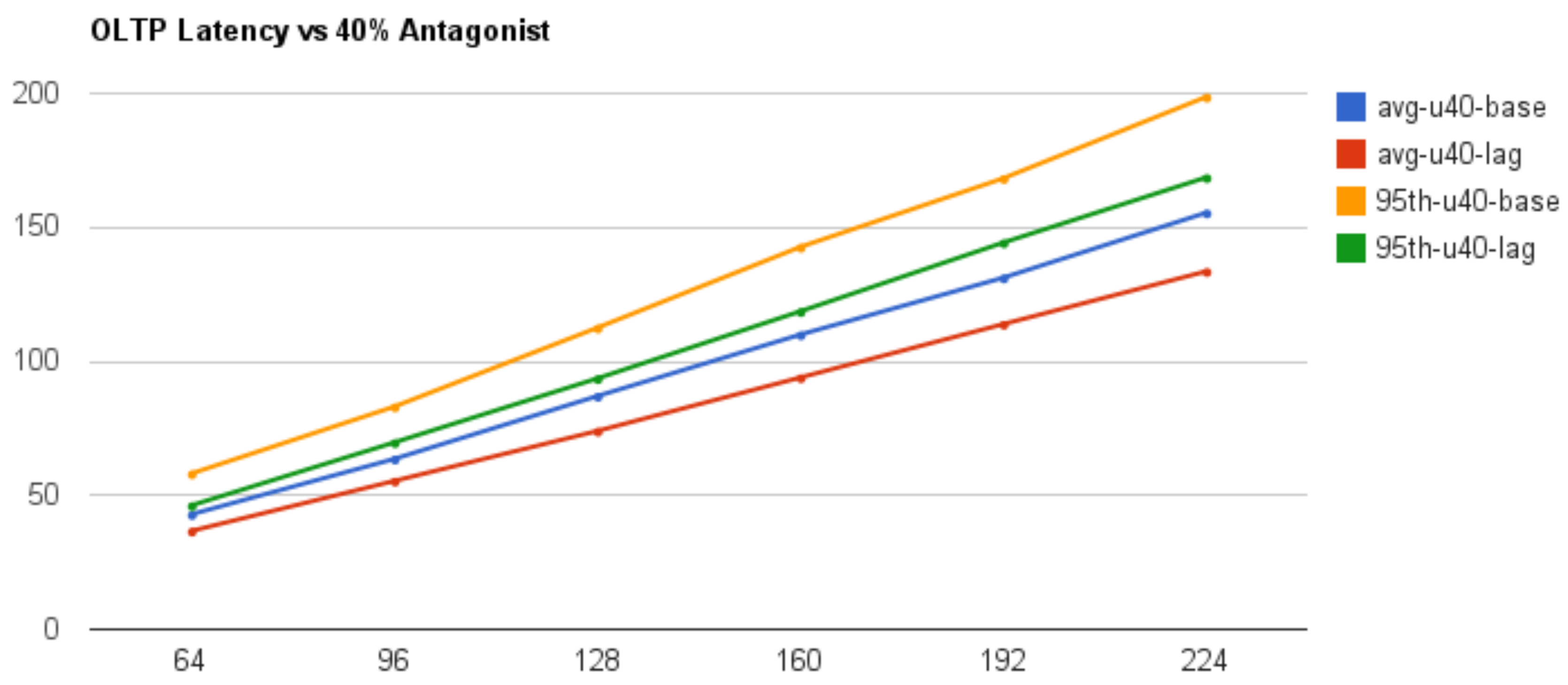
Results: OLTP

Global-lag w/ 80% vs baseline



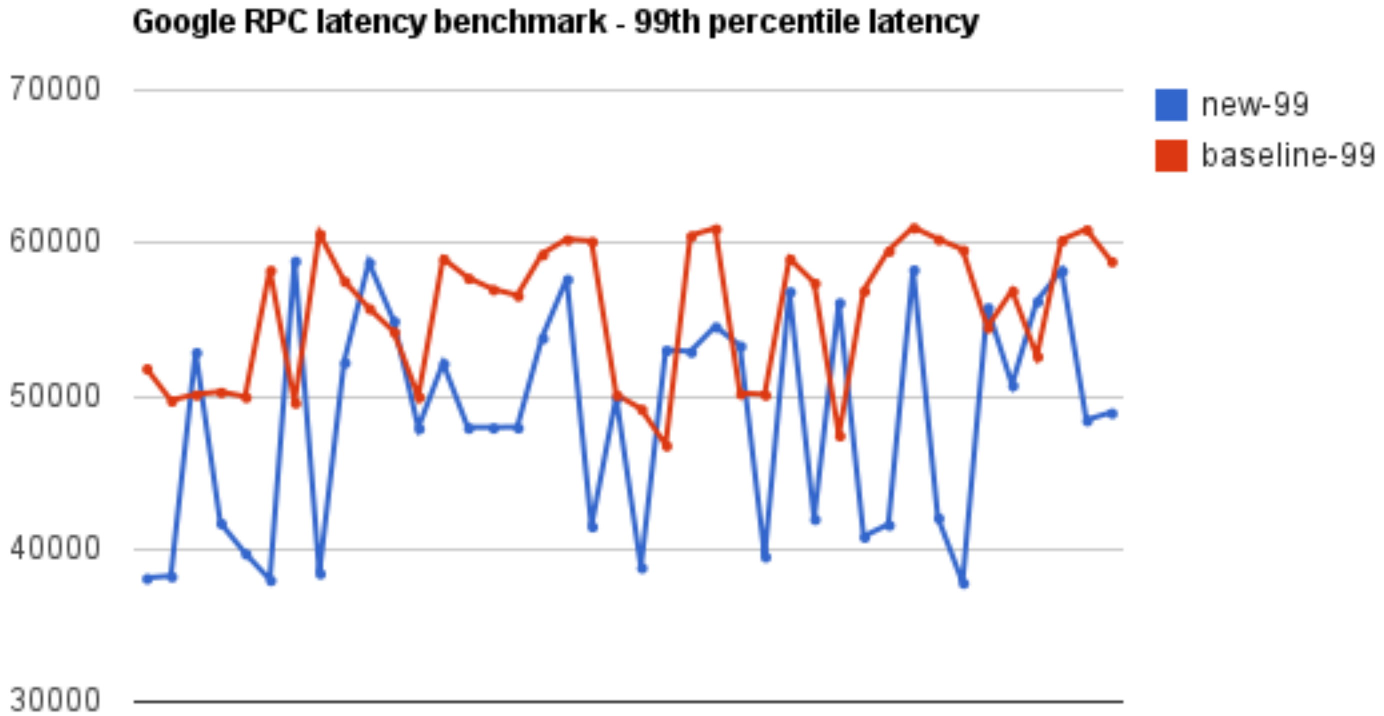
Results: OLTP

Global-lag w/ 40% vs baseline w/ 40%



Results: In group thread lags

Google RPC latency benchmark



Tail latency improved from ~55.4ms to ~48.5ms

What's next?

- Publish/merge load tracking patches
- Continue evaluating latency performance
- Some local fairness evaluations needed

Thanks for attending LPC 2011!

Further questions?

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