THE LINUX SCHEDULER: A DECADE OF WASTED CORES

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  - **Would you ever suspect the scheduler?**

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  - ***We implemented high-resolution tracing tools and saw that some cores were idle while others overloaded…***

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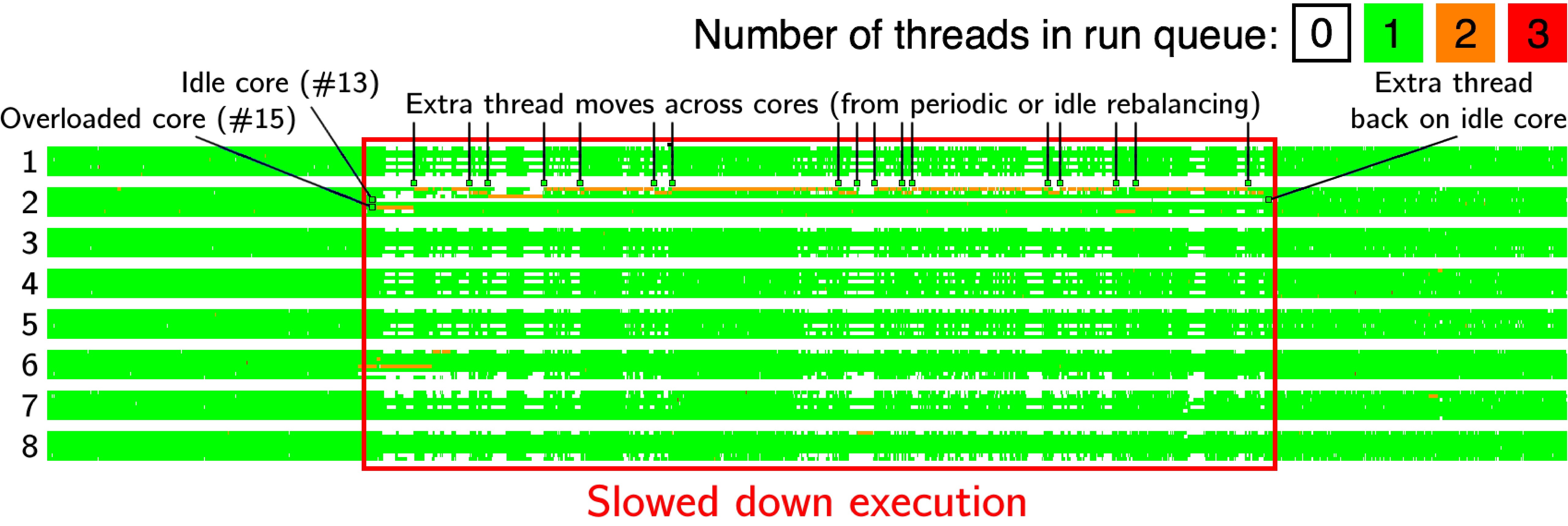

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- **After fixing some of the bugs :**
  - 12-23% performance improvement on a popular database with TPC-H
  - 137× performance improvement on HPC workloads
- **Not always possible to provide a simple, working fix…**
  - Intrisic problems with the design of the scheduler?

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…starting with a bit of background…

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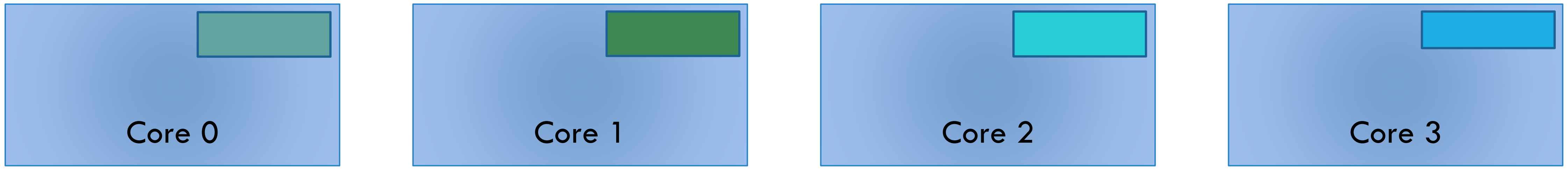

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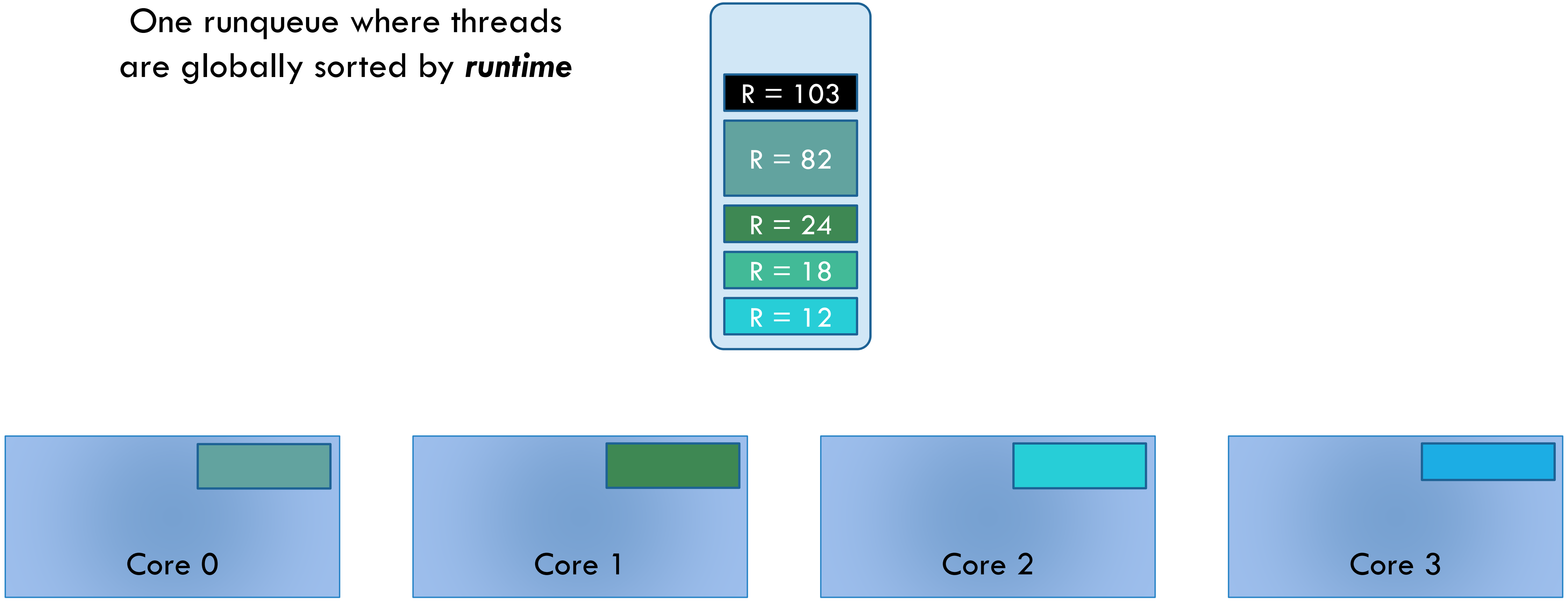
One runqueue where threads are globally sorted by ***runtime***



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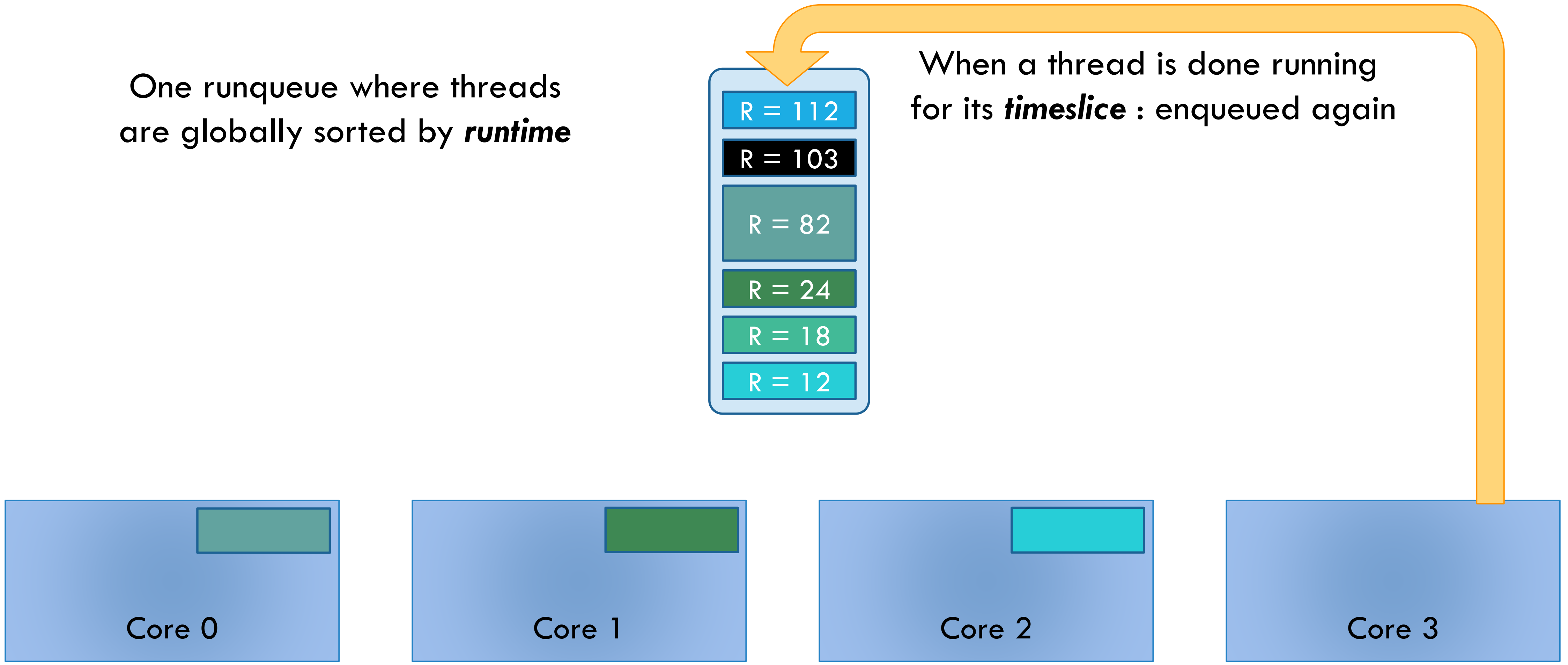

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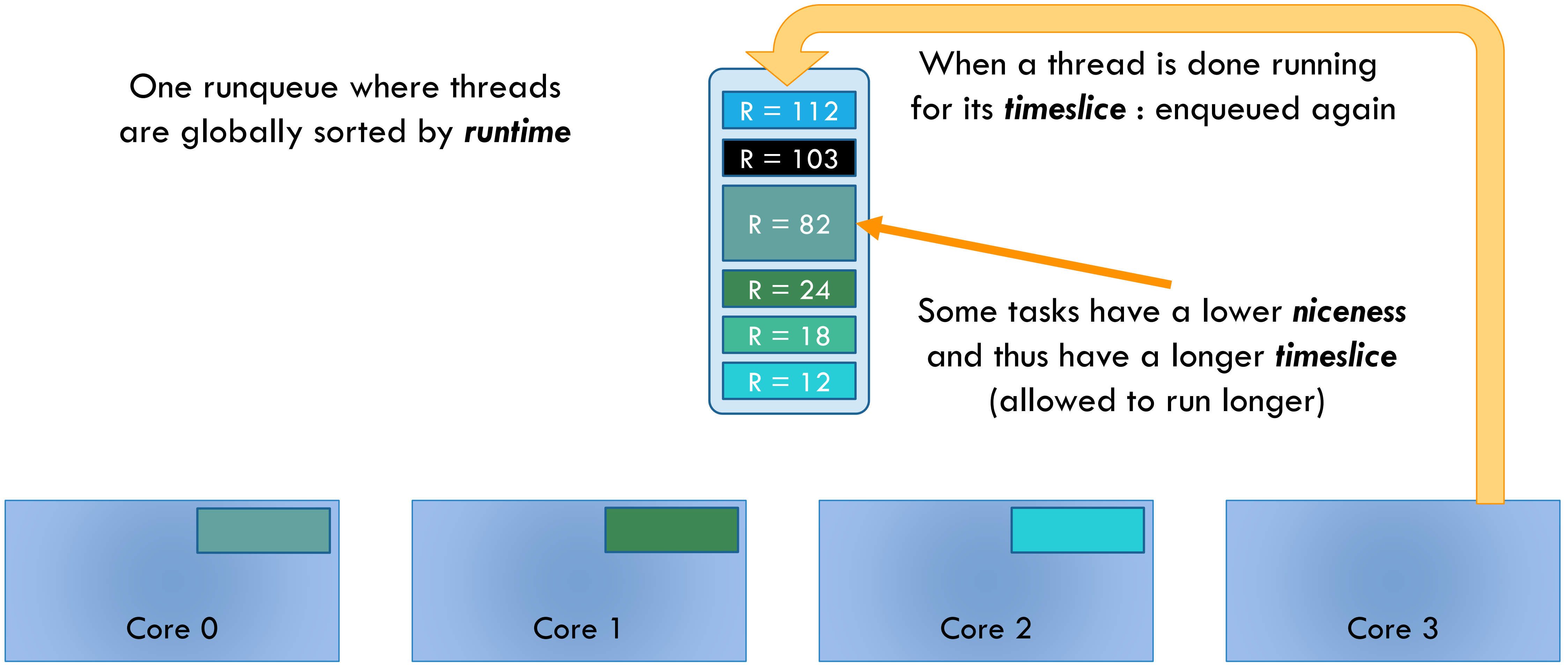

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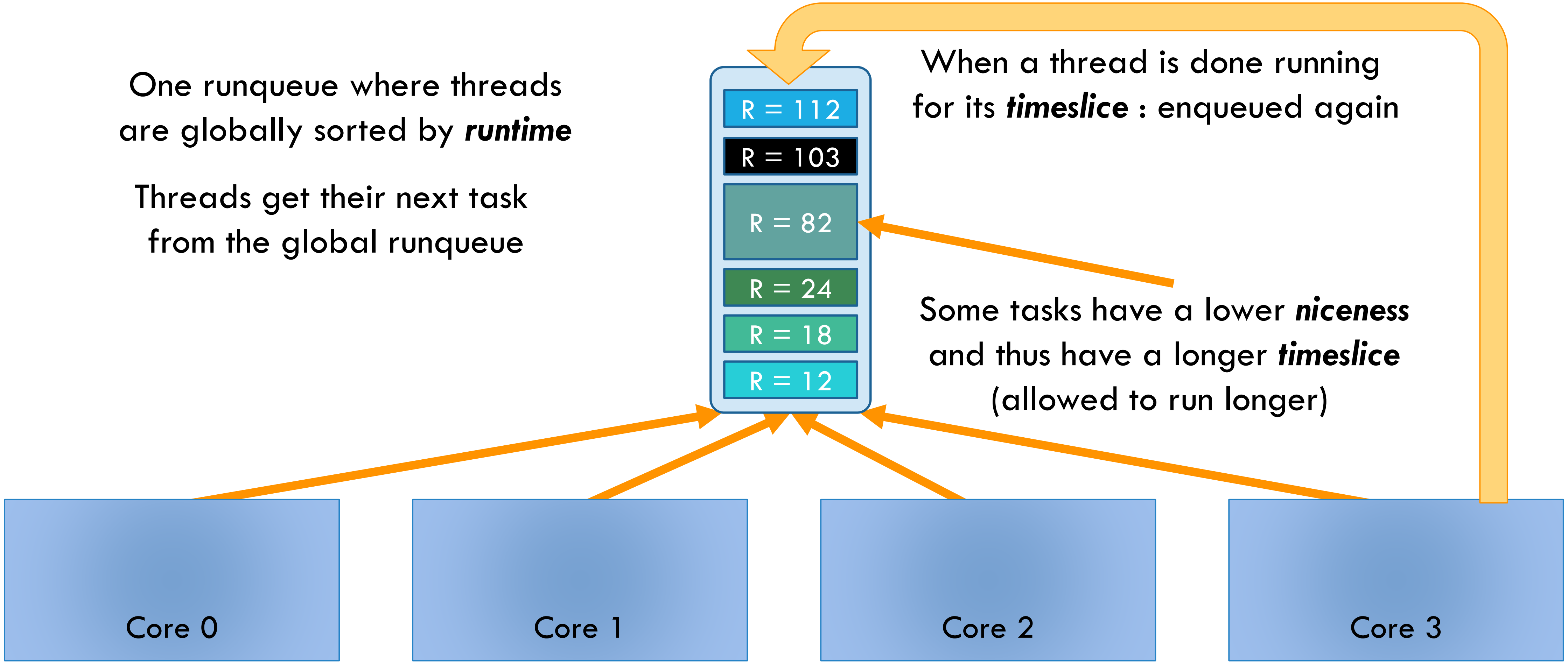

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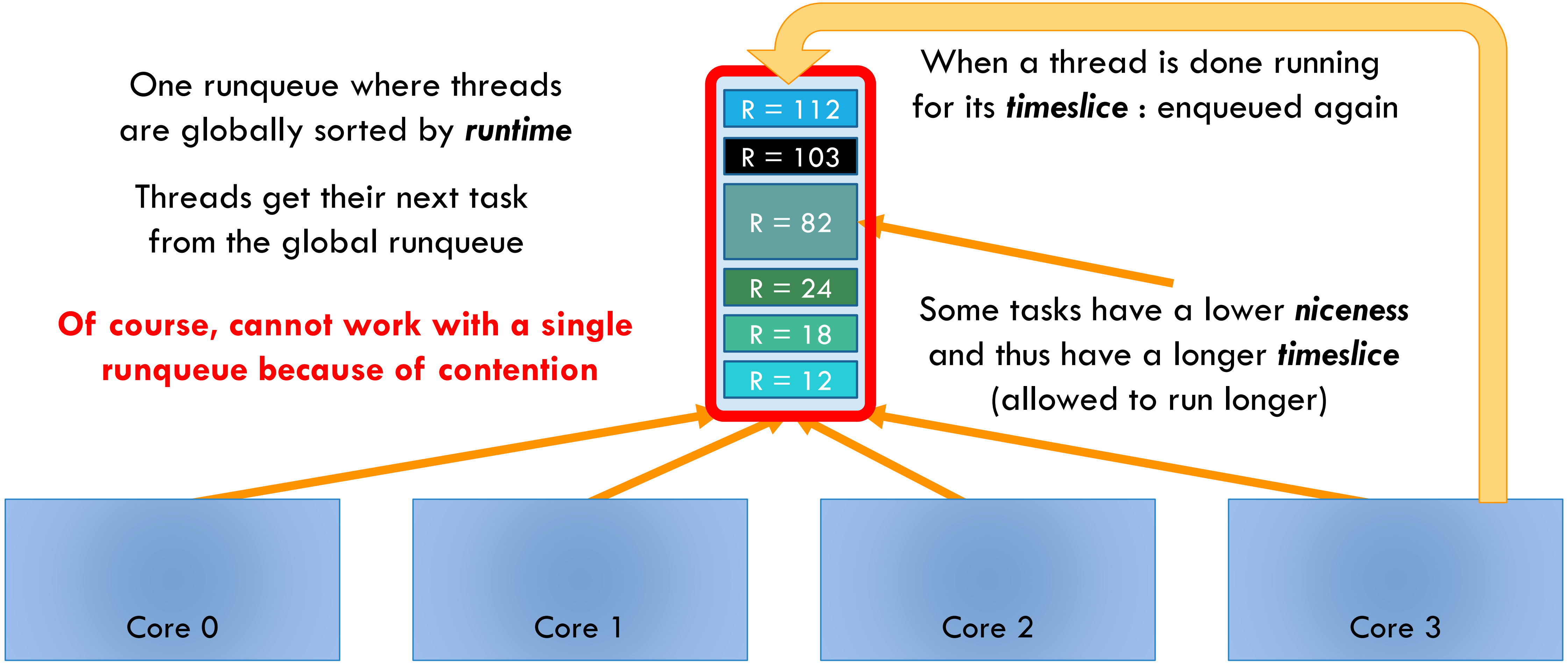
Of course, cannot work with a single runqueue because of contention



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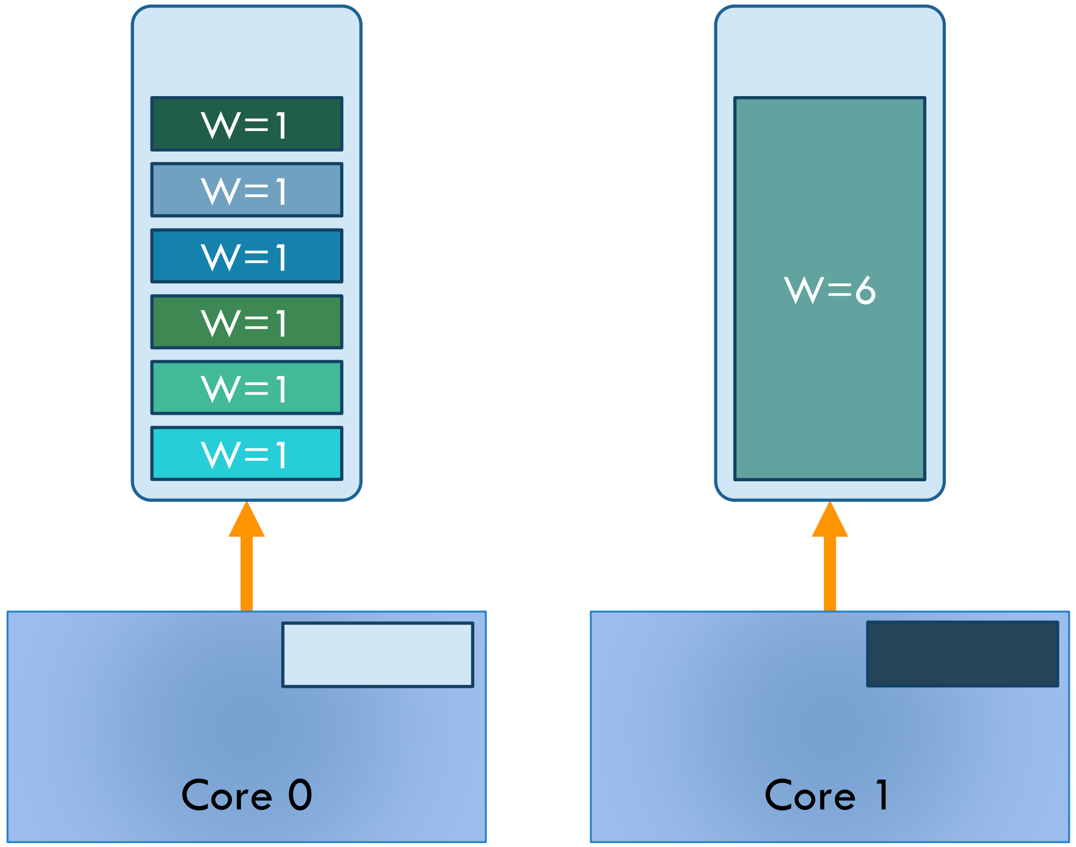

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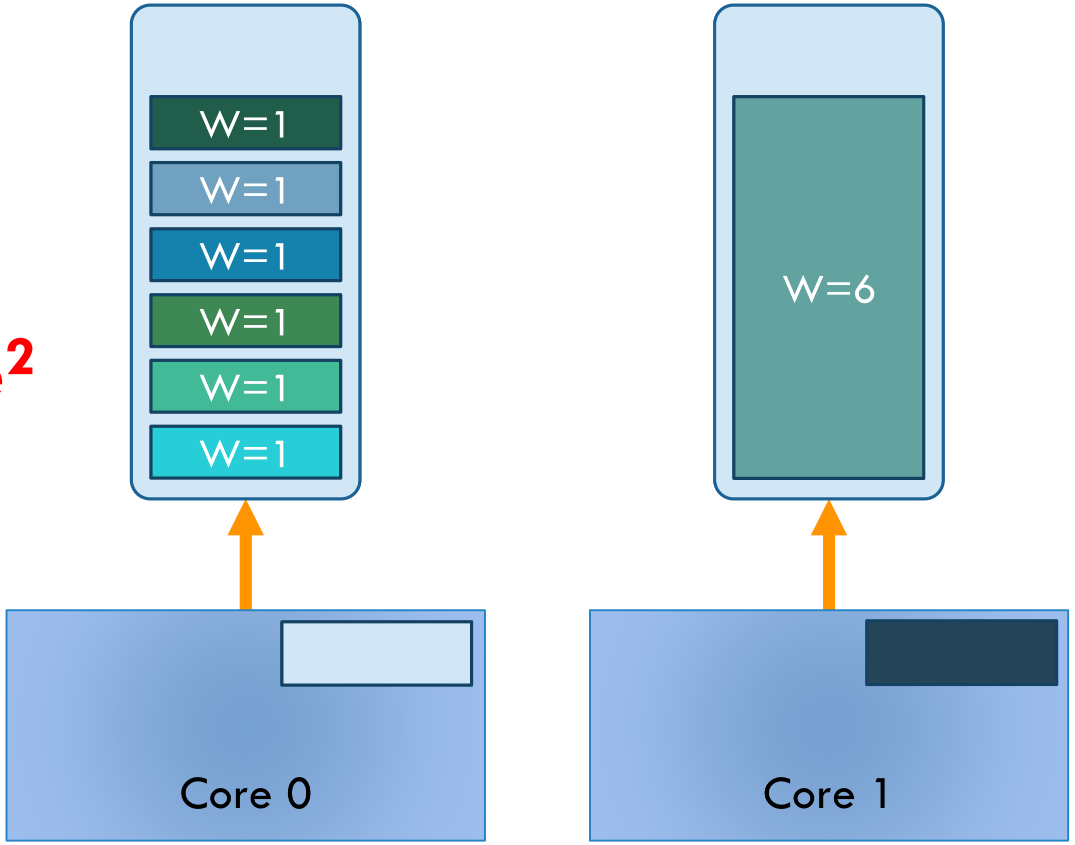

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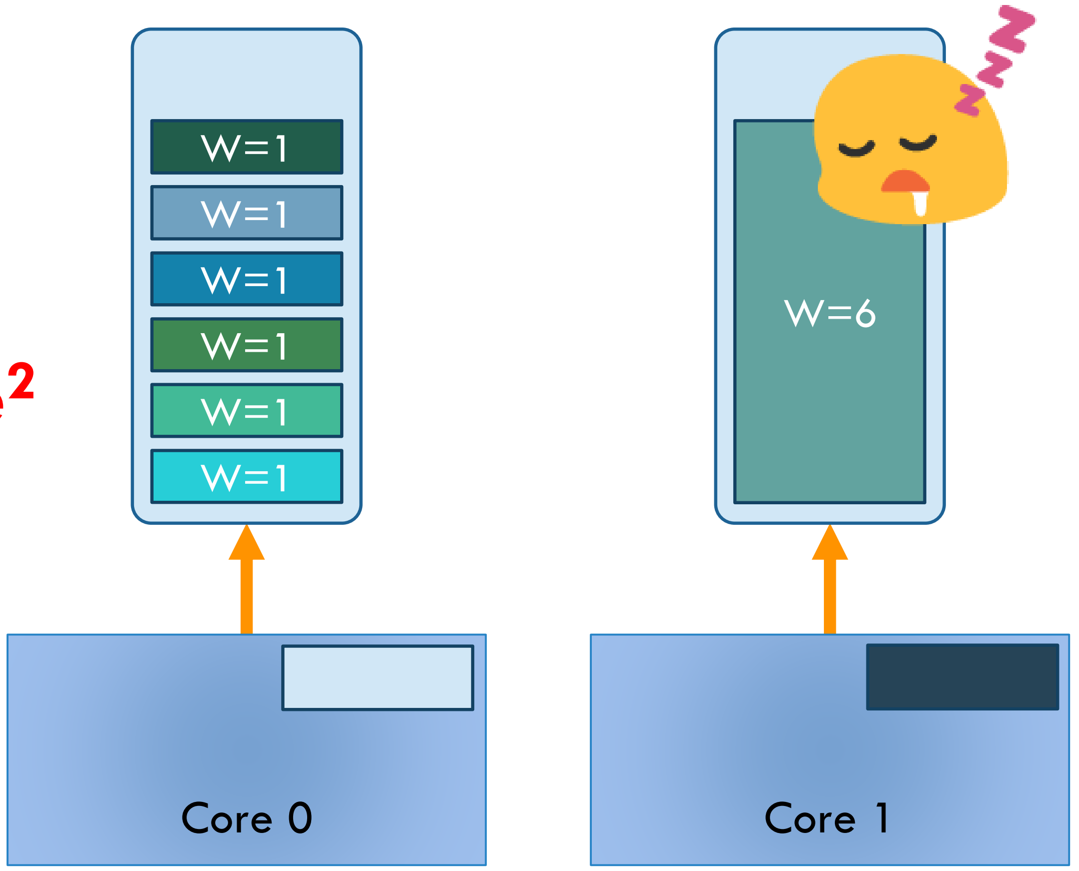

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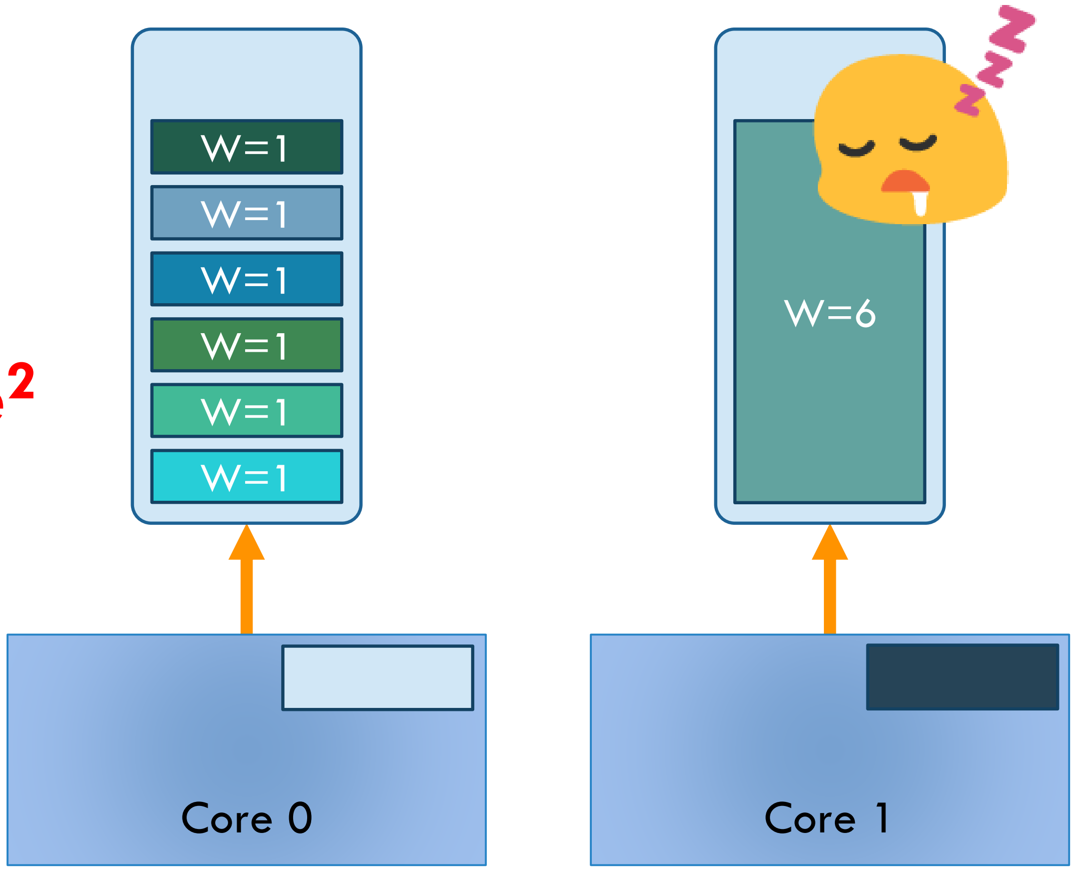

- **Since there can be many cores: hierarchical approach!**

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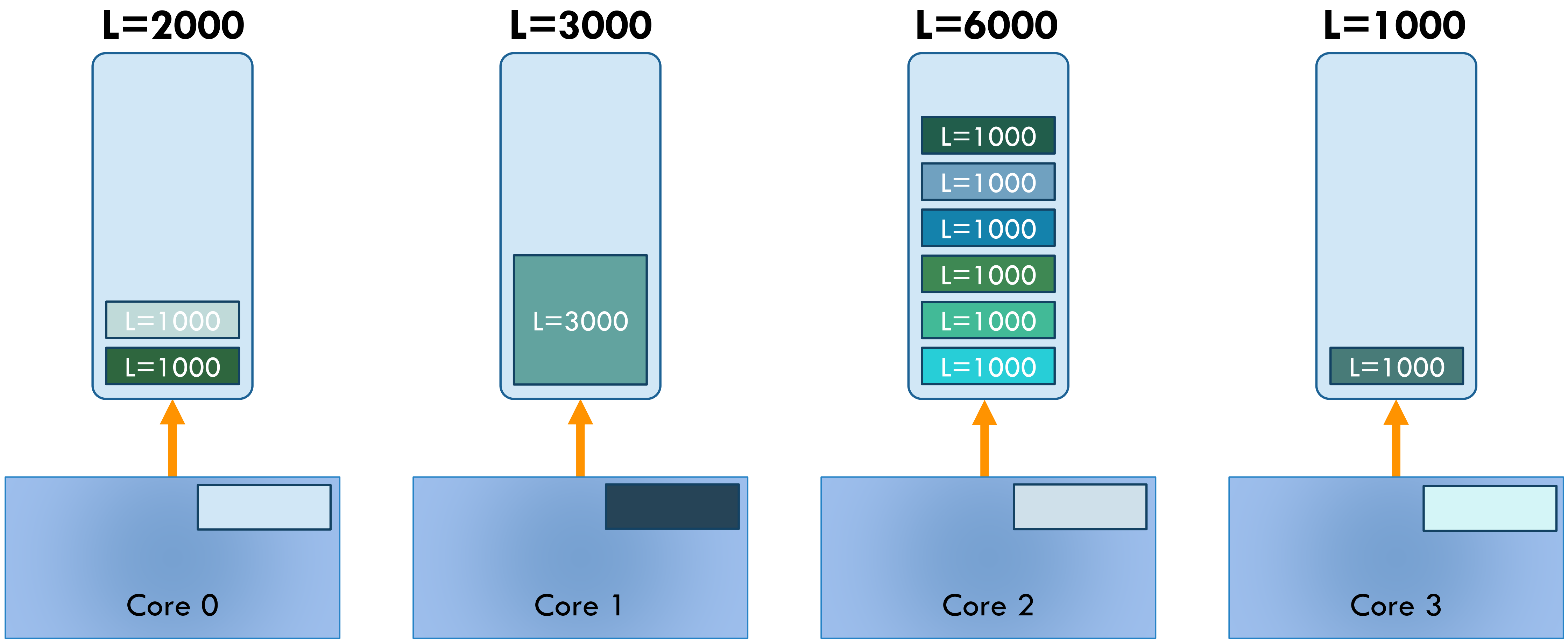

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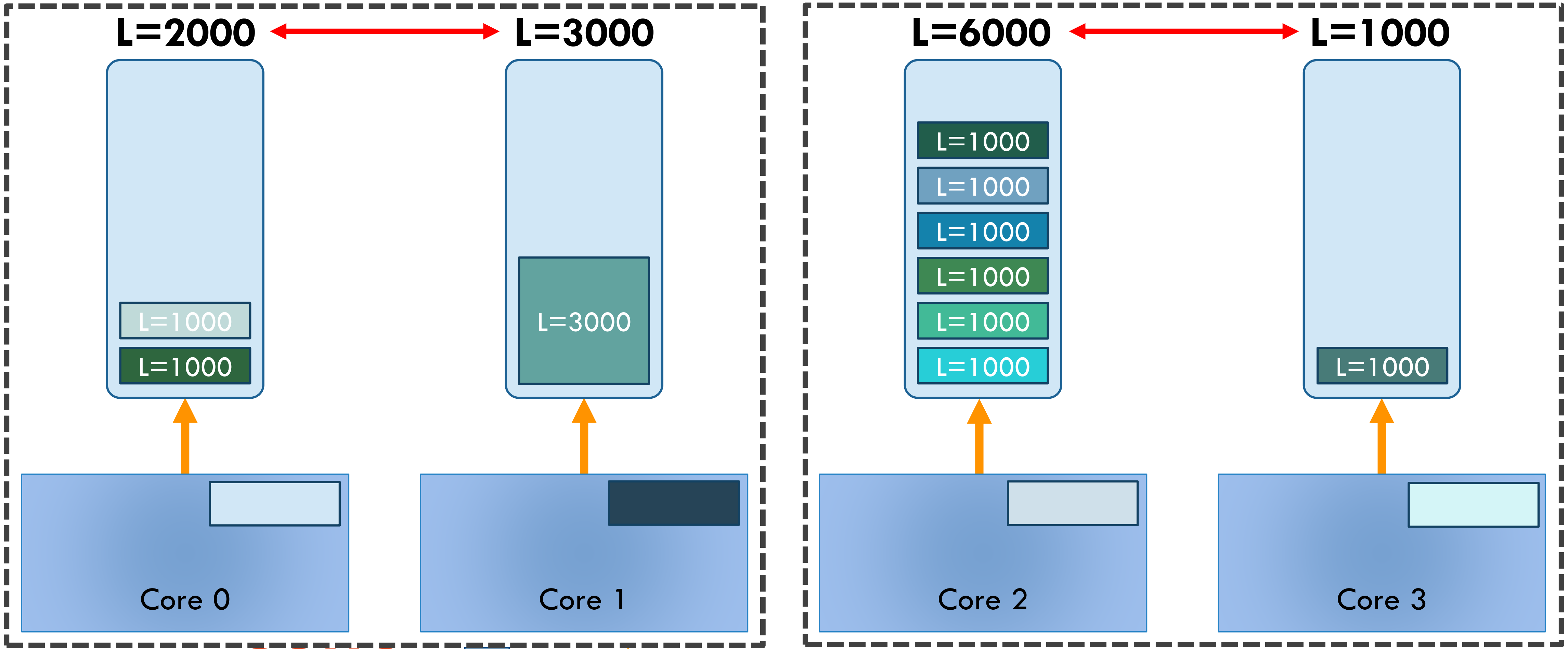

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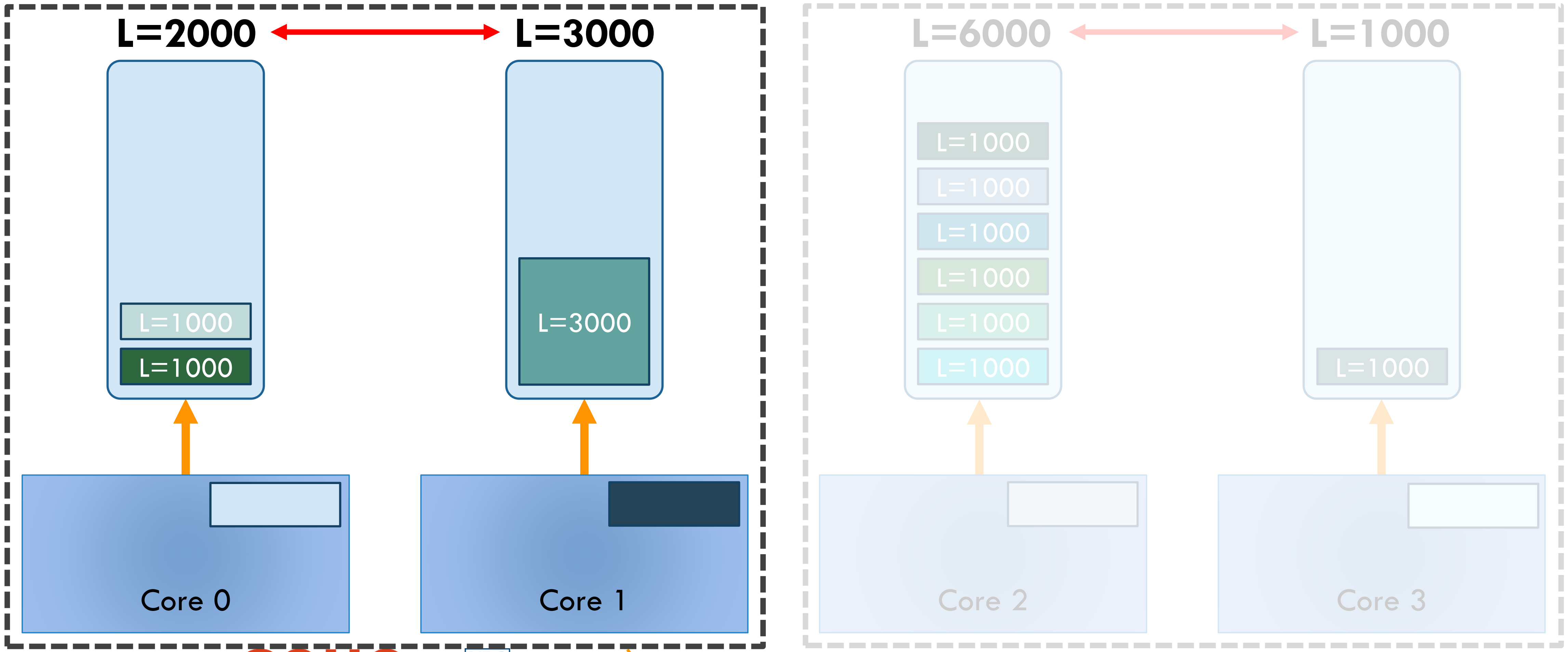

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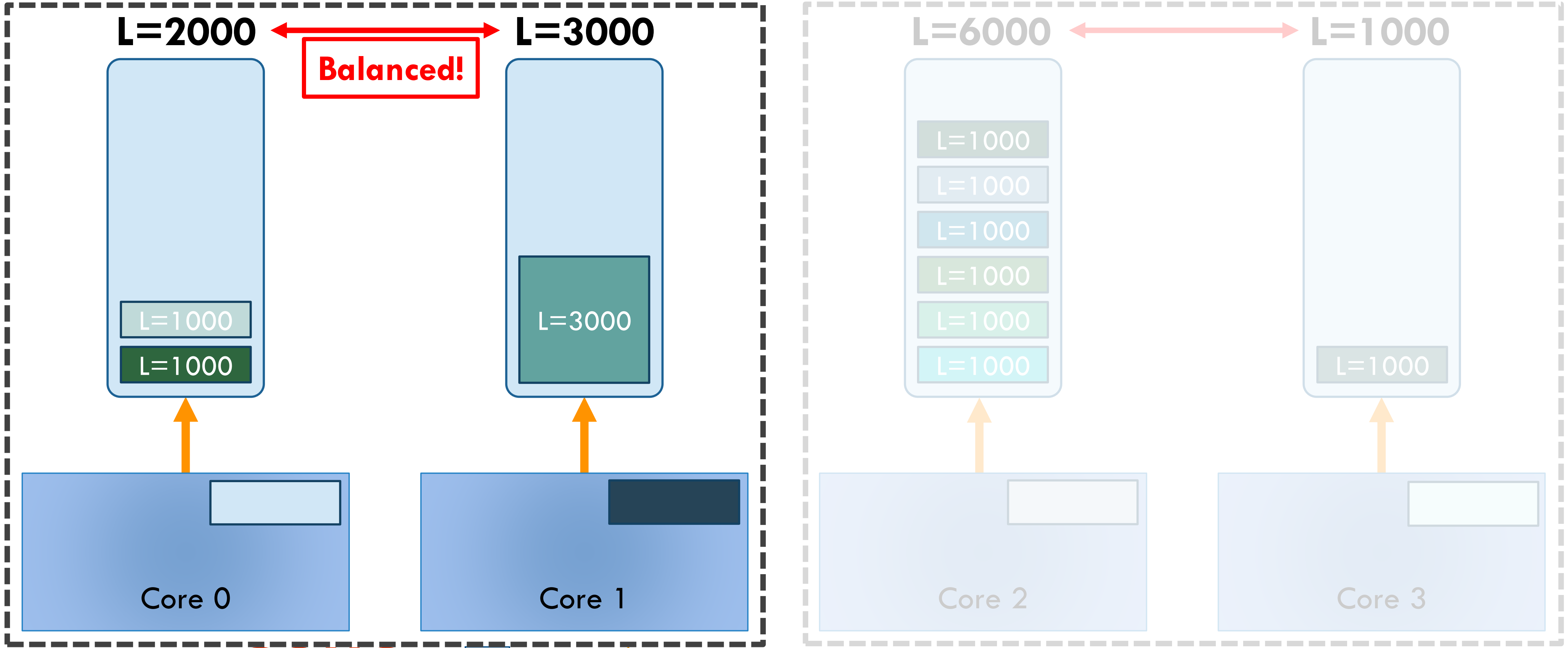

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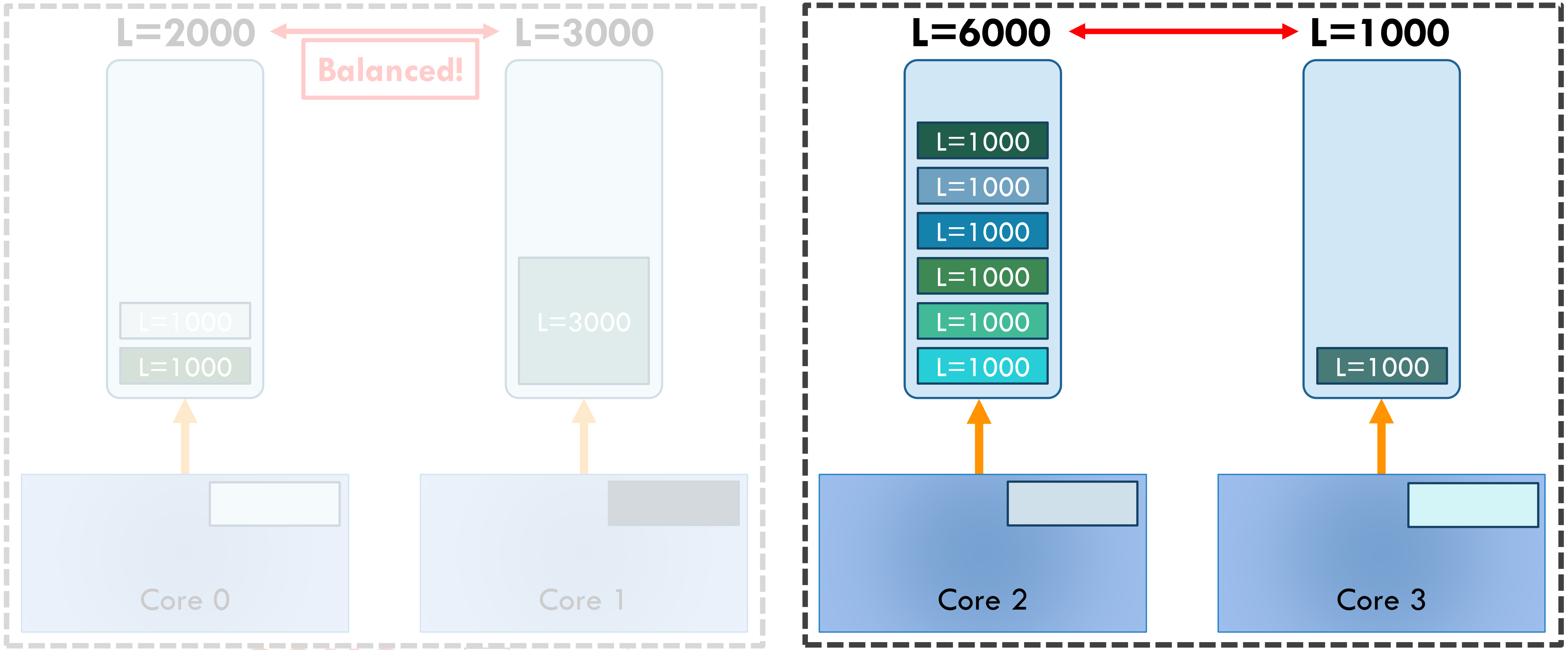

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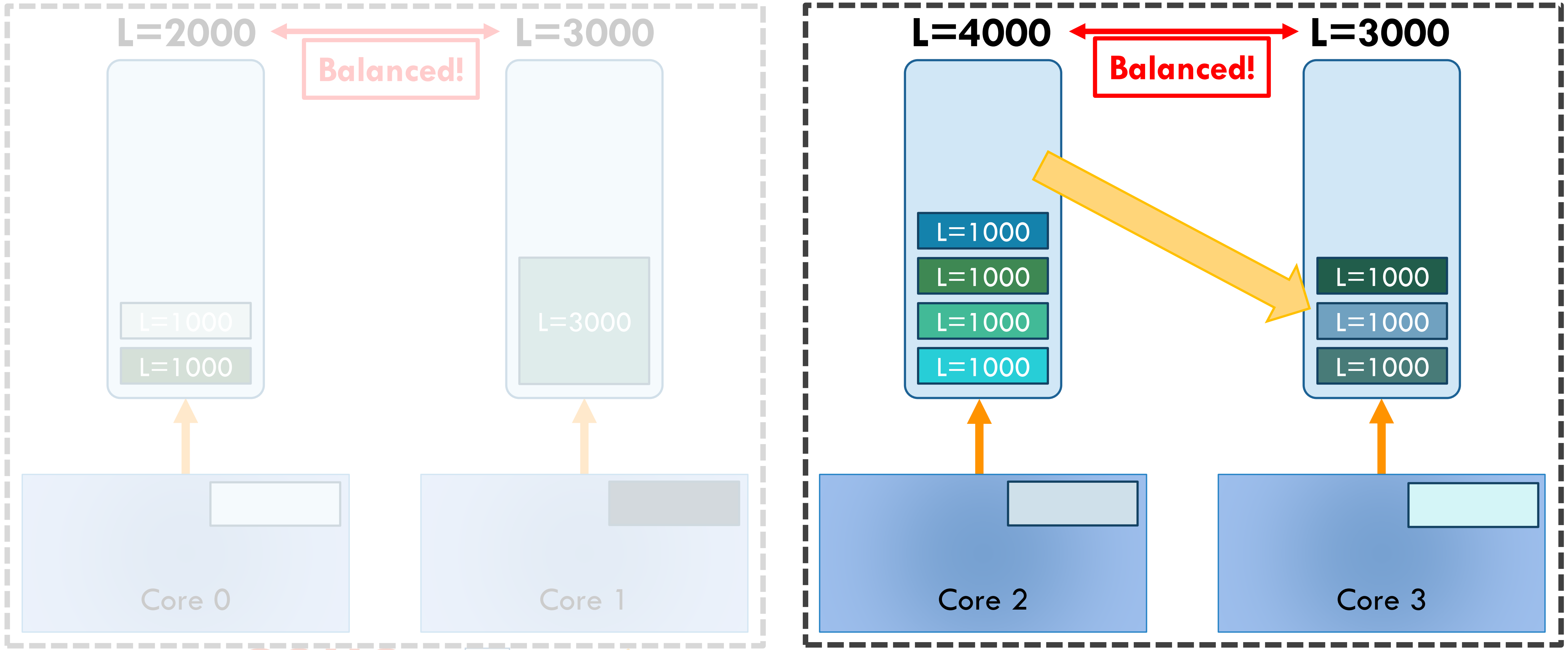

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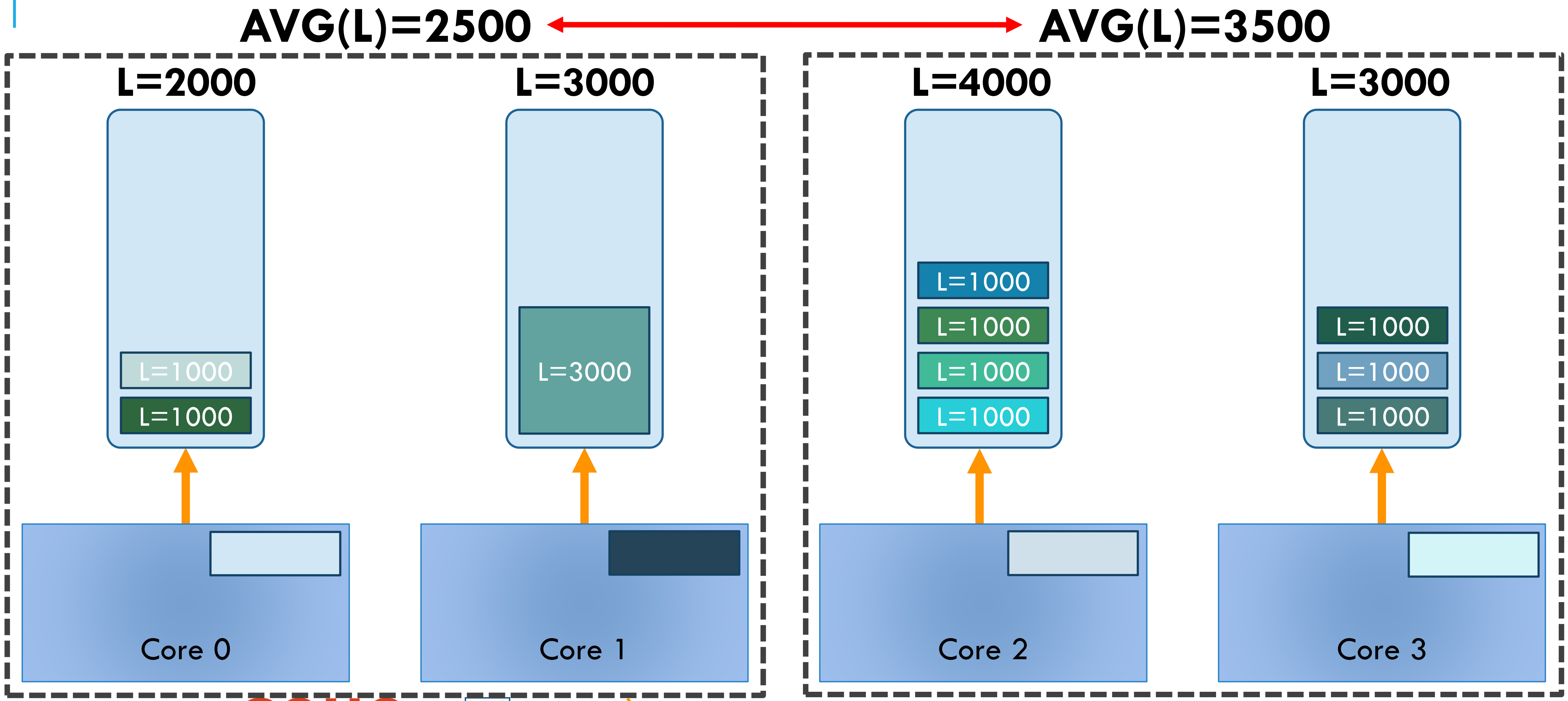

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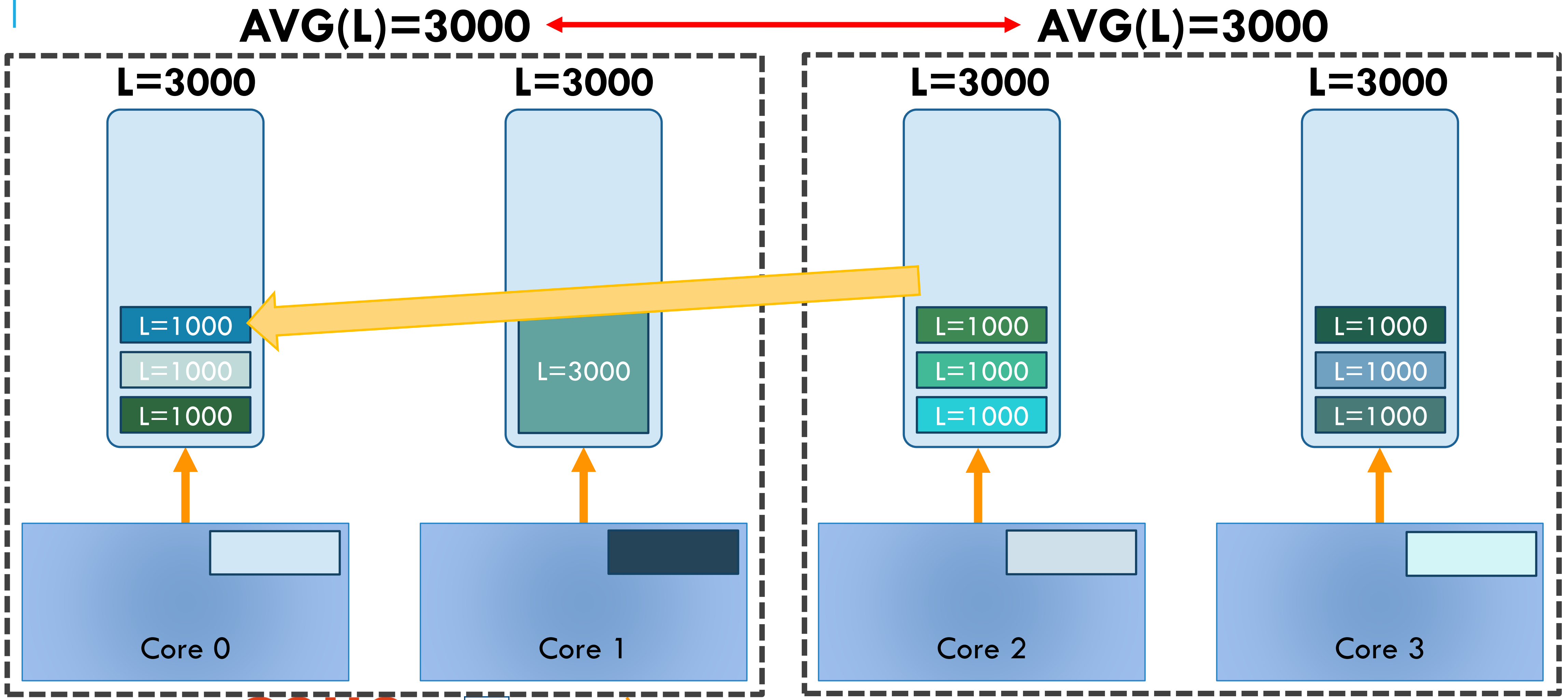

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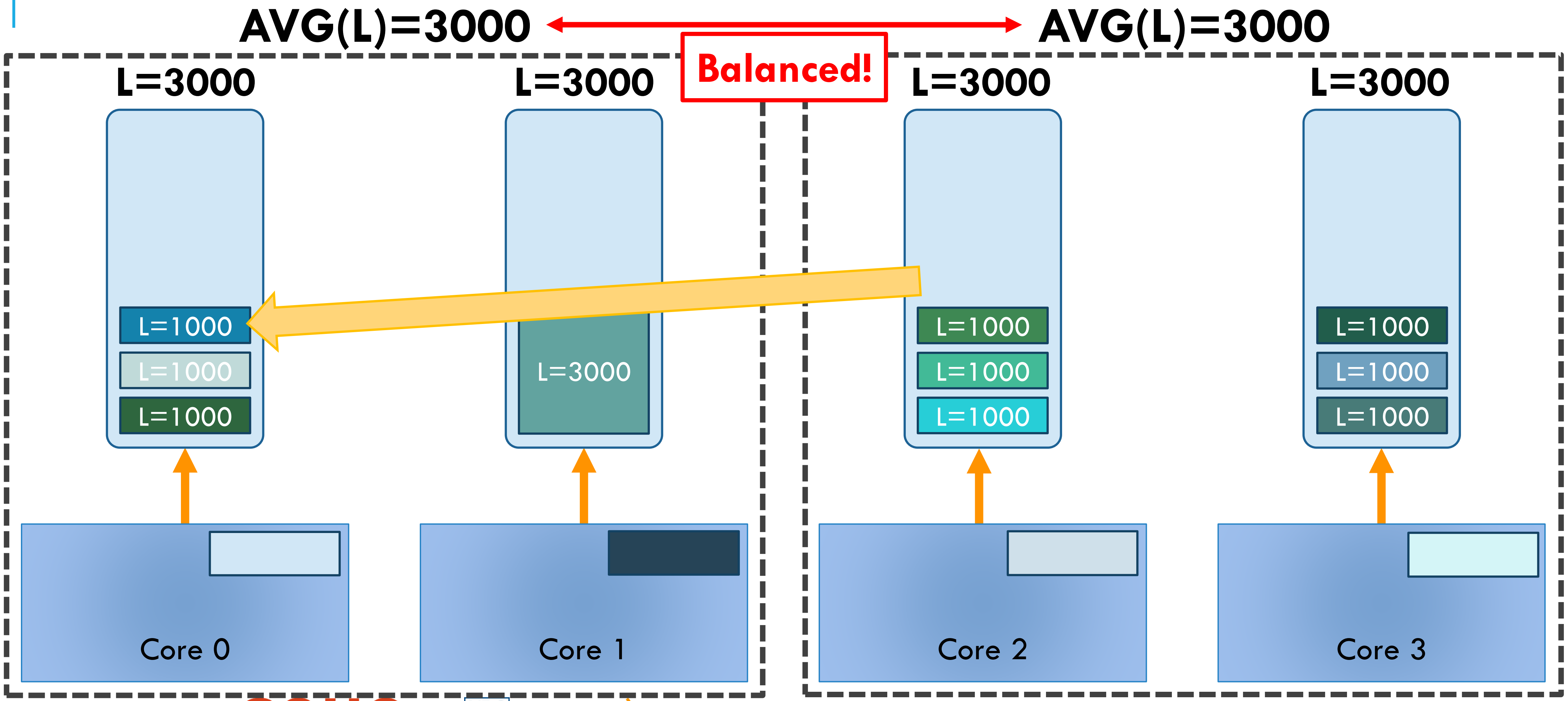

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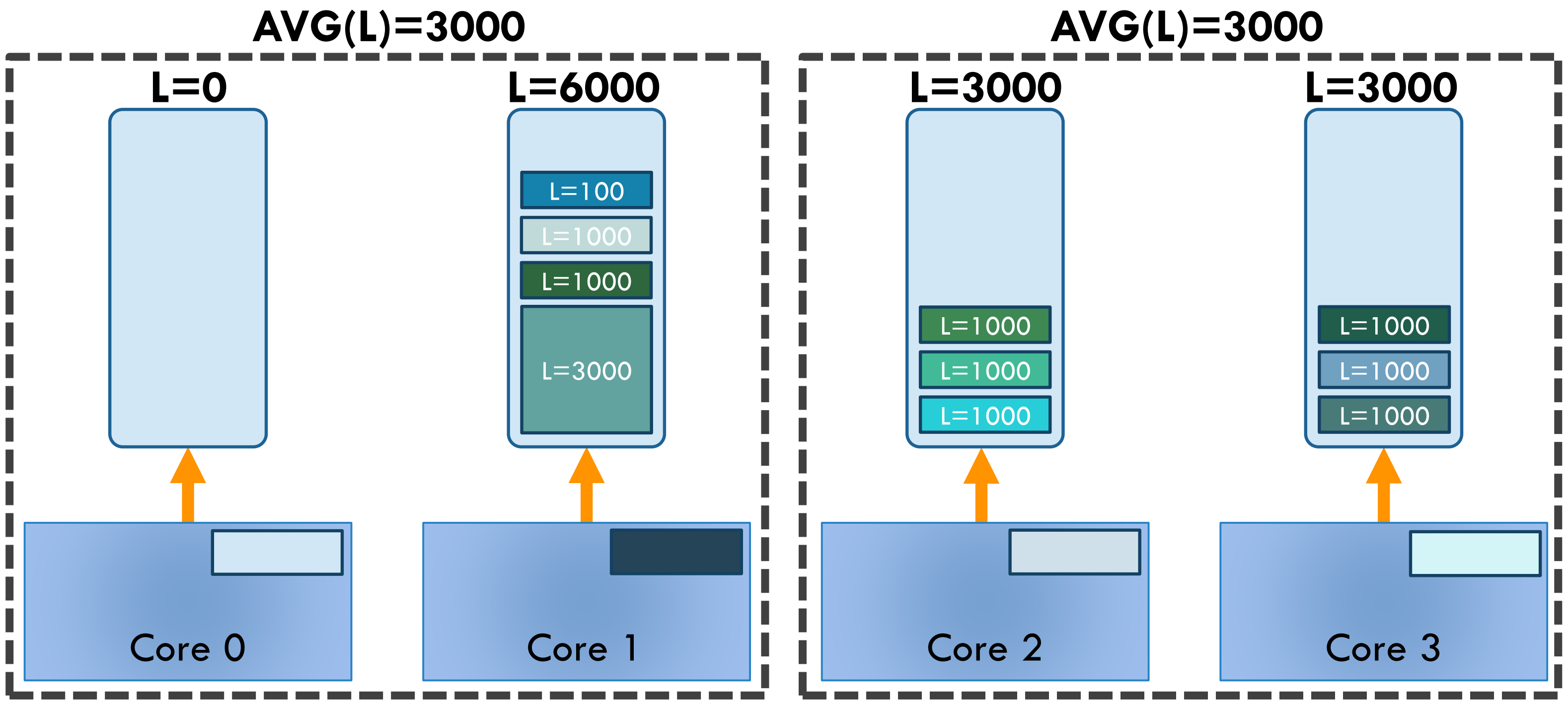

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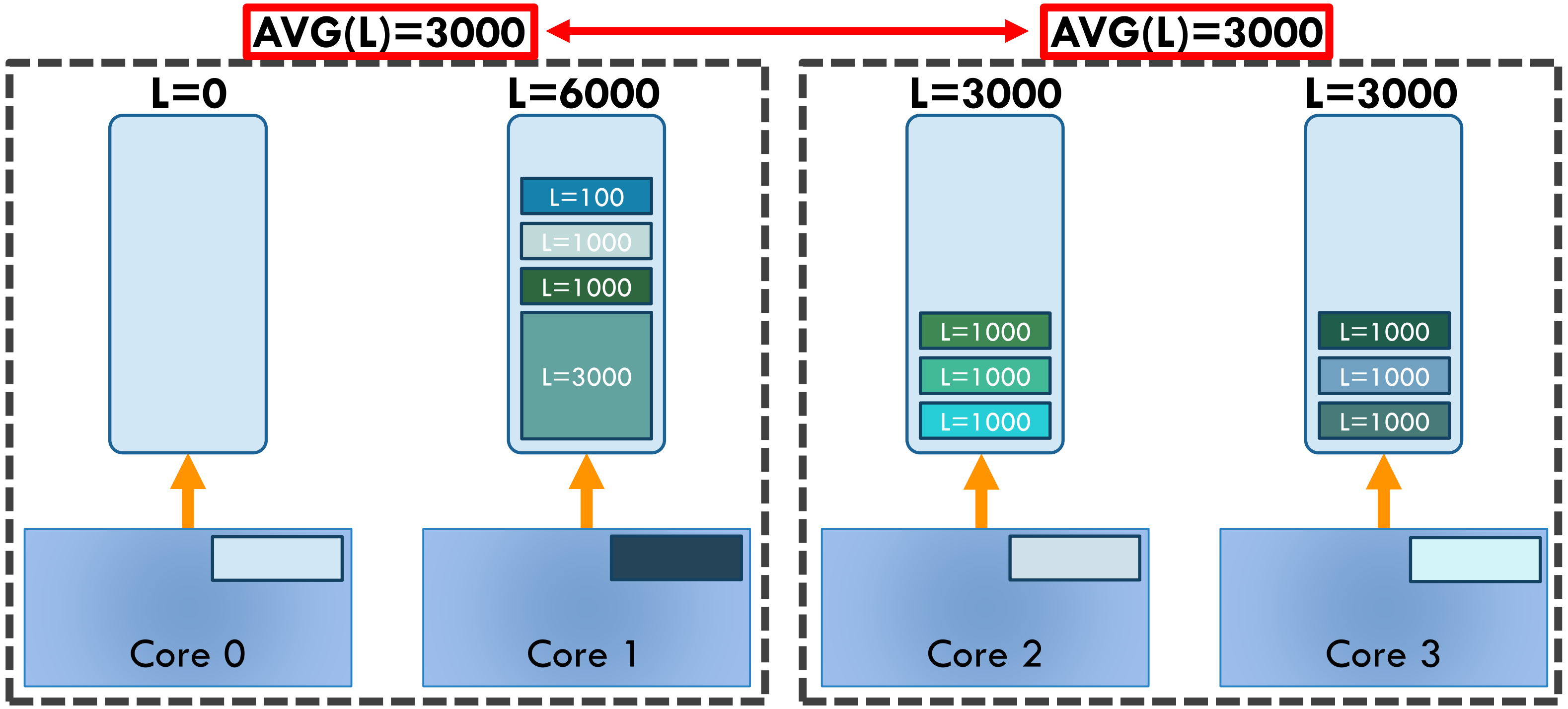

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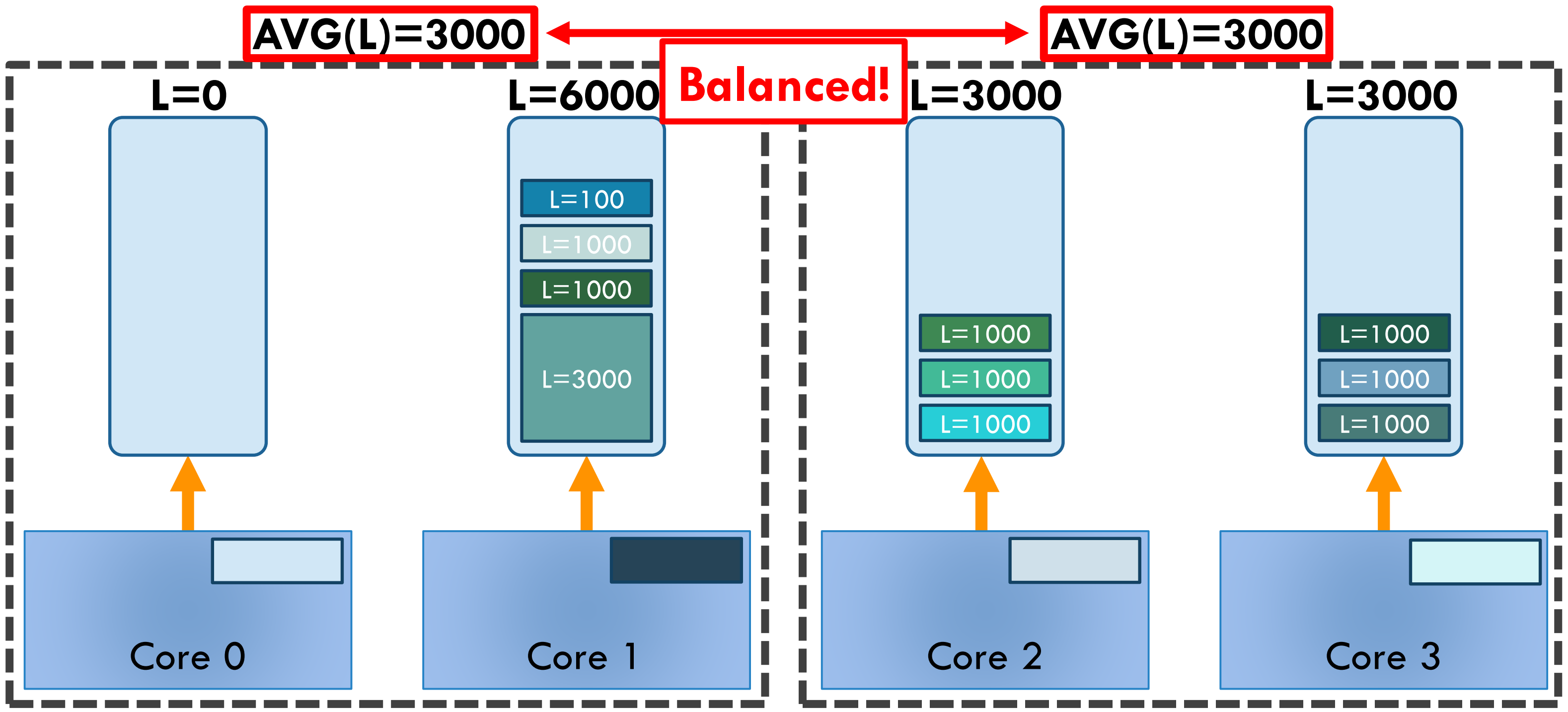

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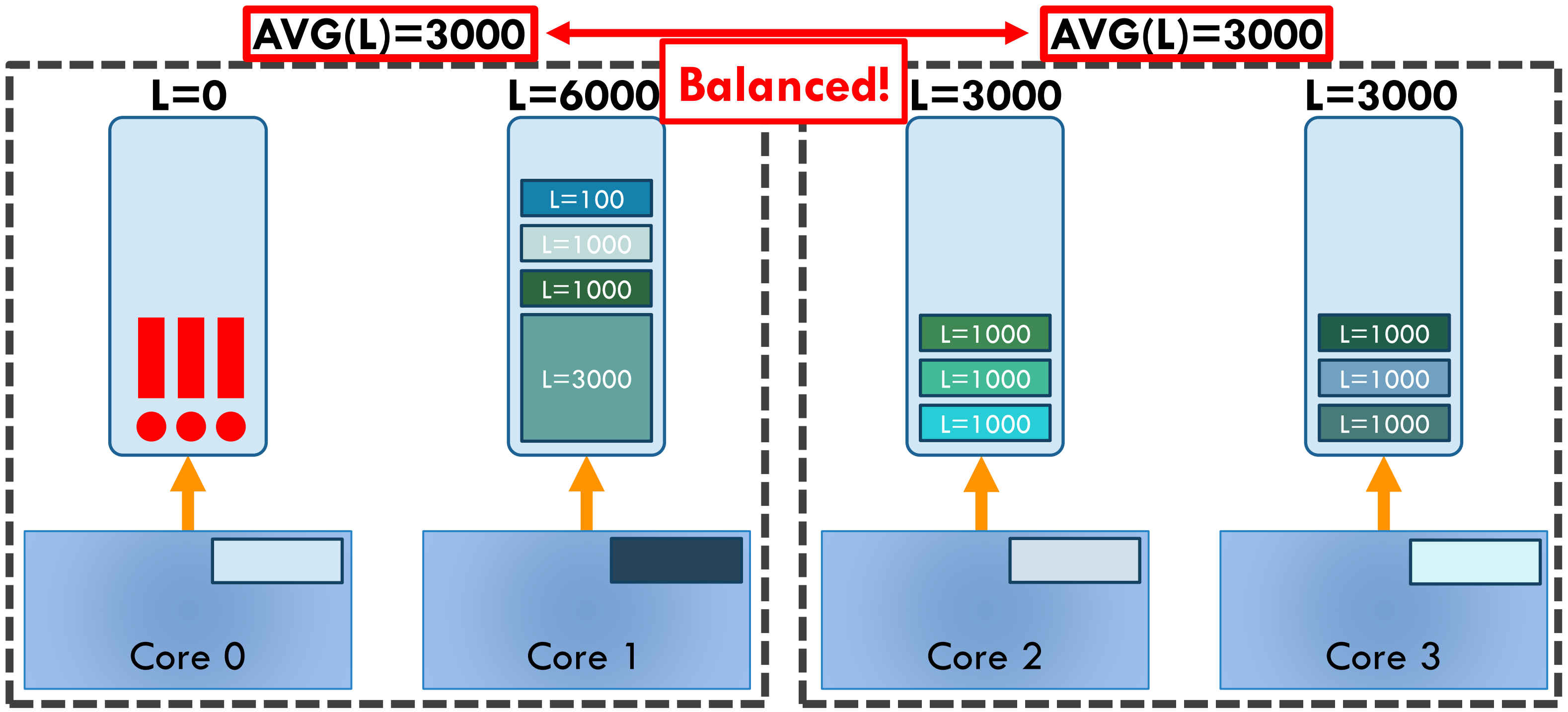

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  - Otherwise, easy to use more resources than other users by spawning many threads...

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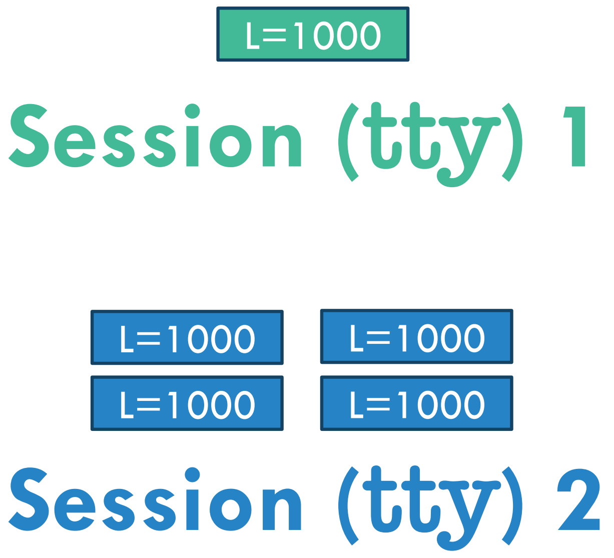

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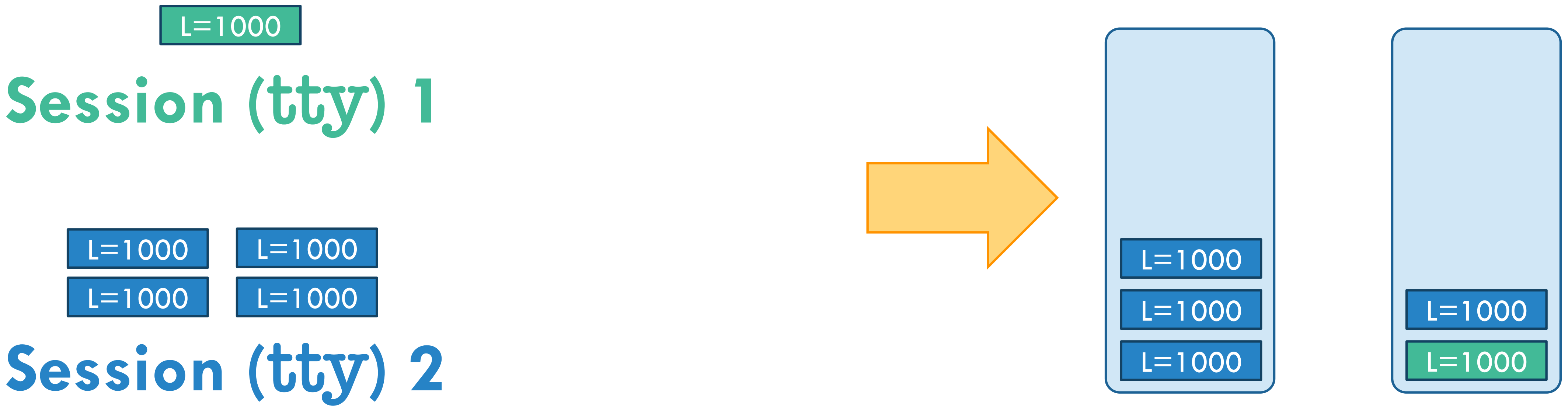

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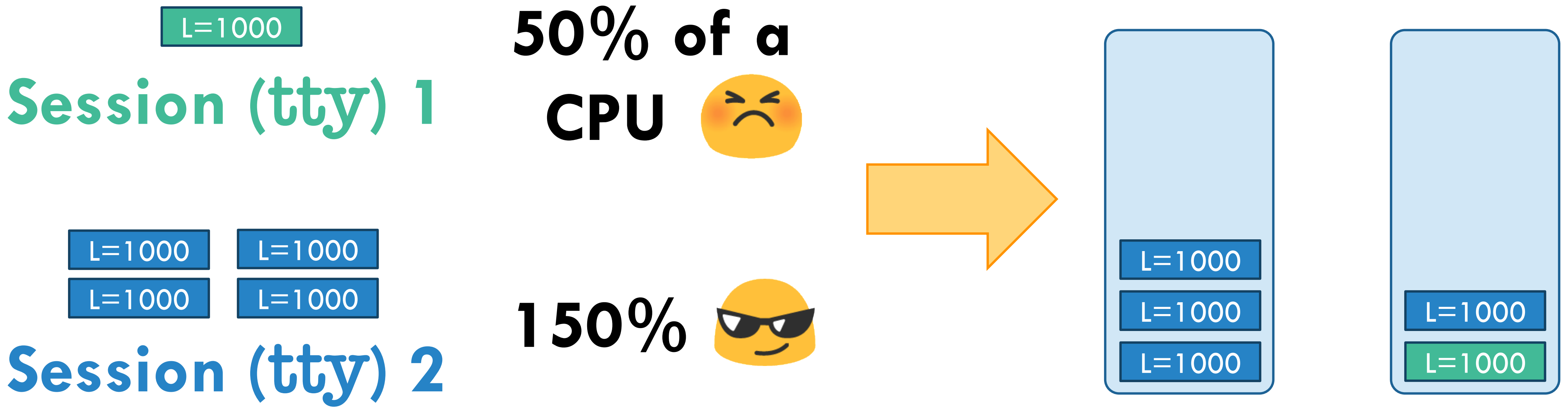

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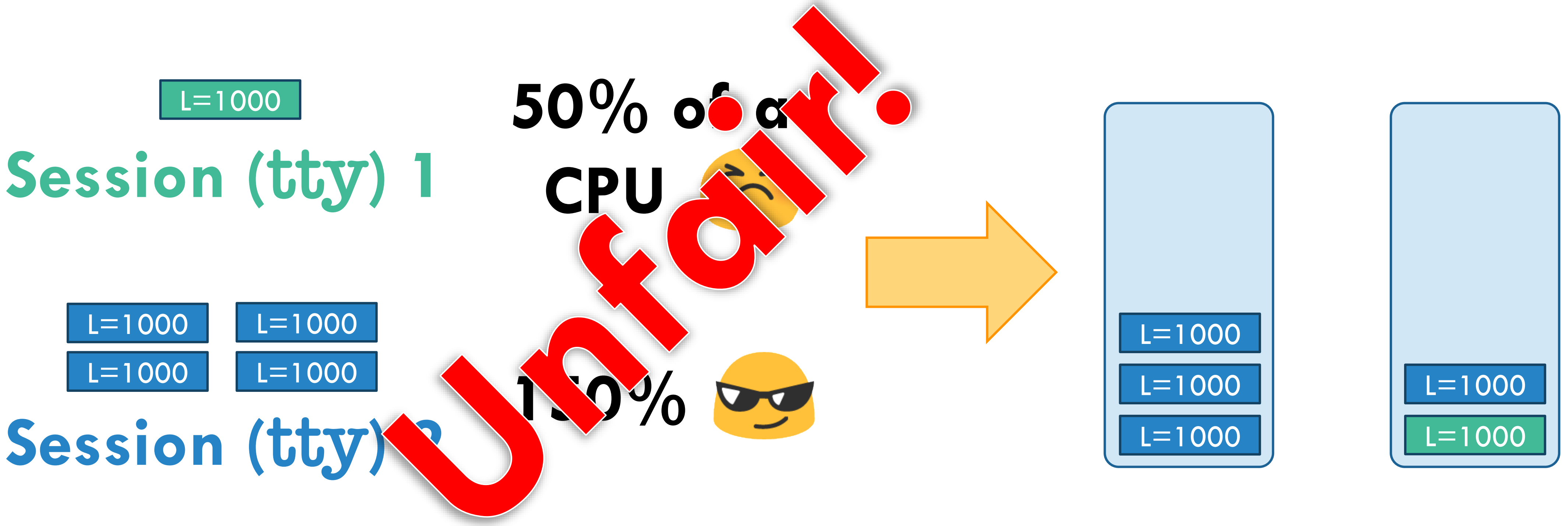

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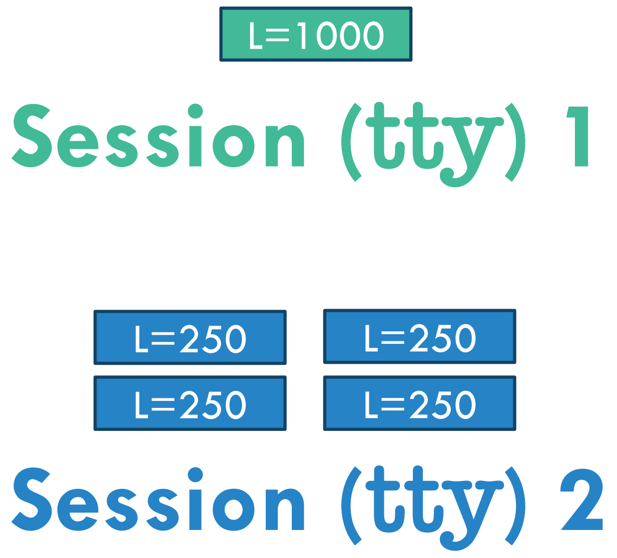

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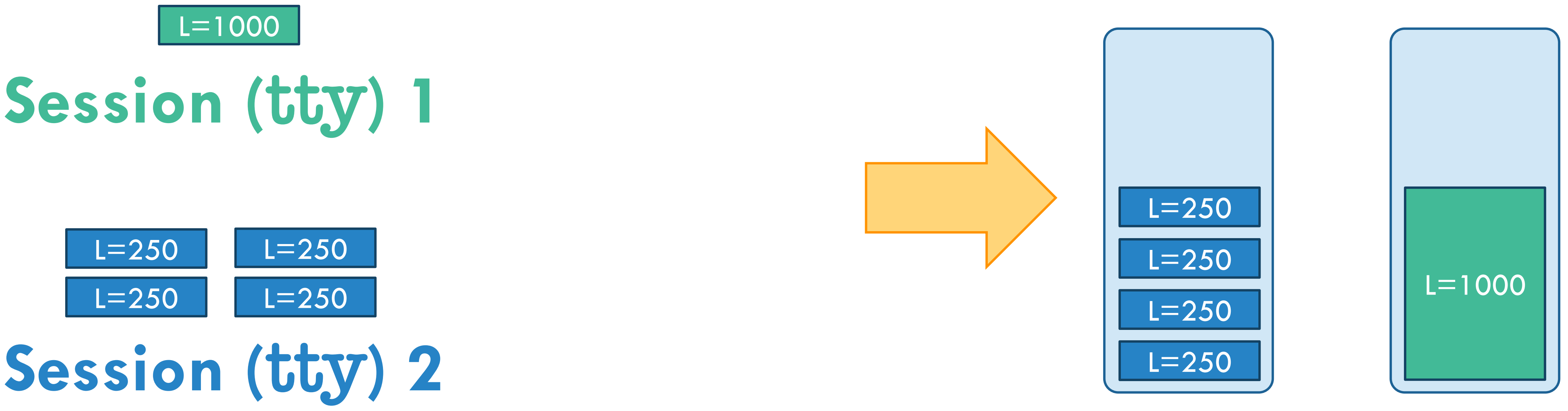

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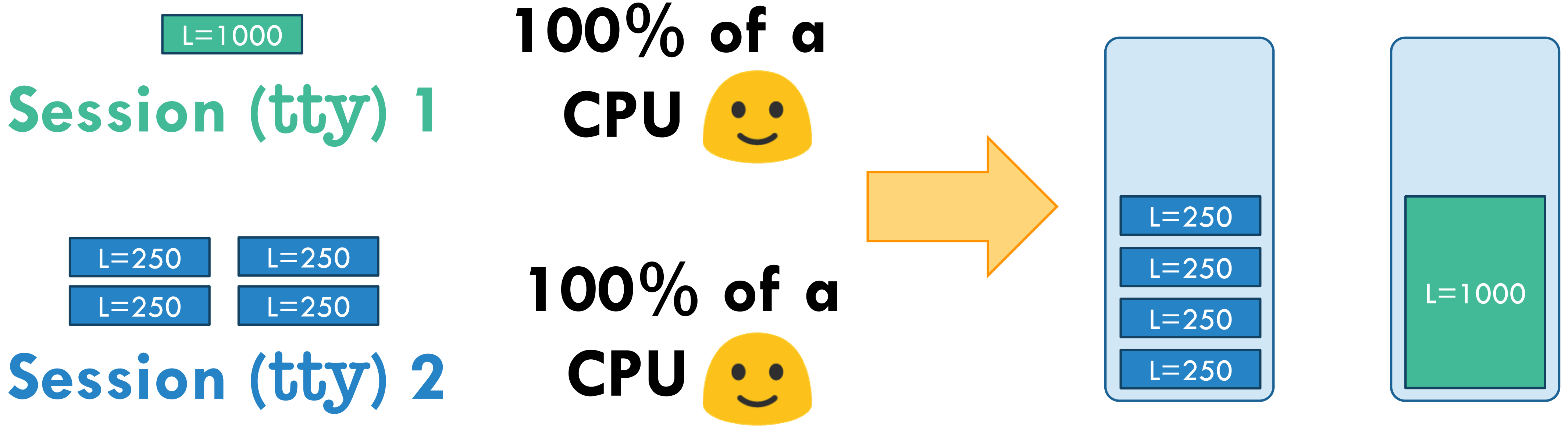

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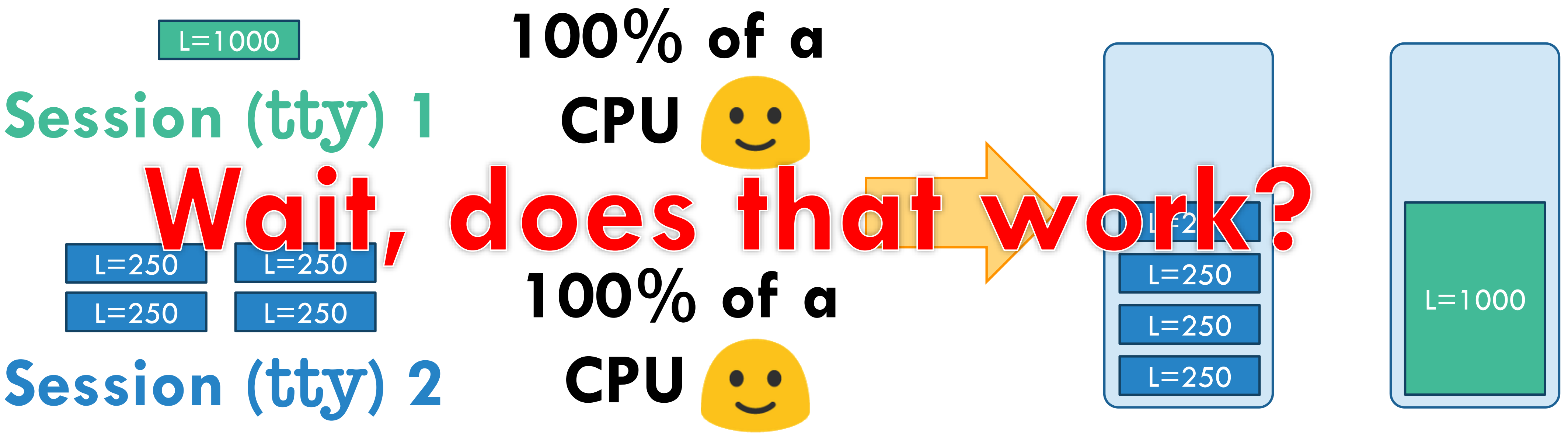
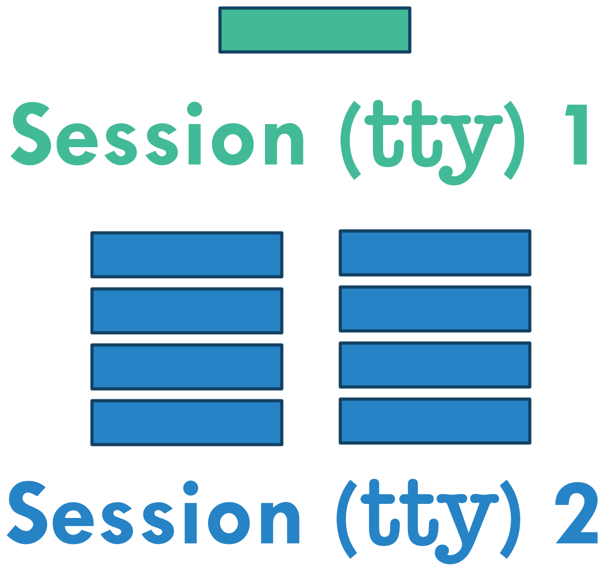


BUG 1/4: GROUP IMBALANCE



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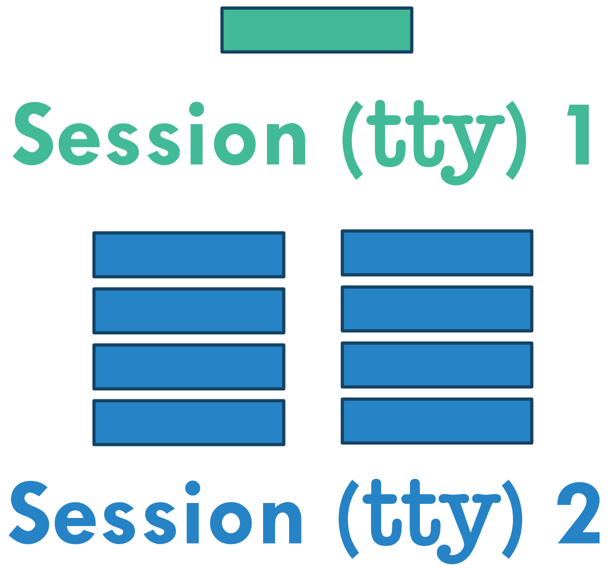
$$
\begin{aligned}
\text{Load(thread)} &= \%\text{cpu} \times \text{weight} \;/\; \#\text{threads} \\
&= 100 \times 10 \;/\; 1 \\
&= 1000
\end{aligned}
$$



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&= 125
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$$

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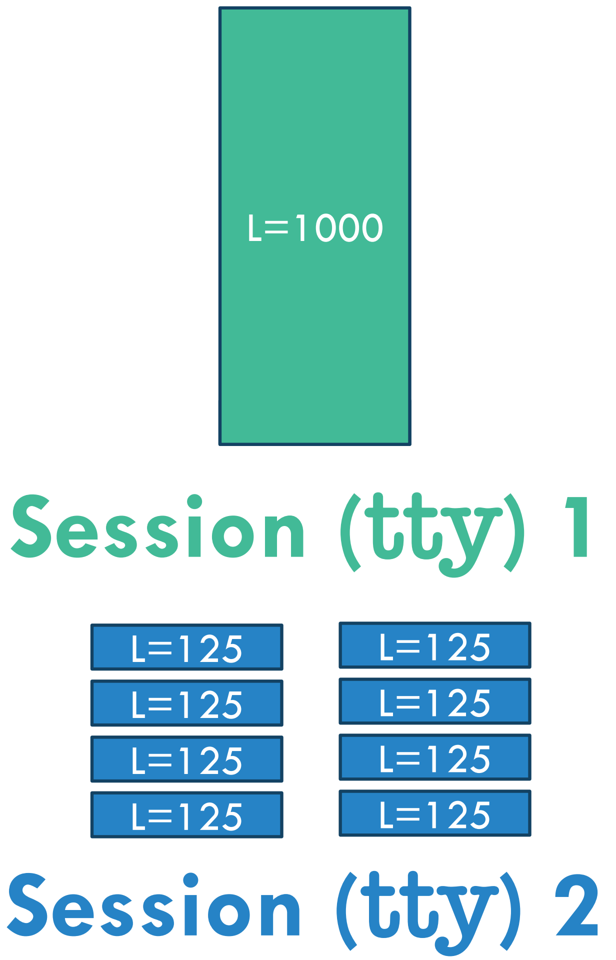
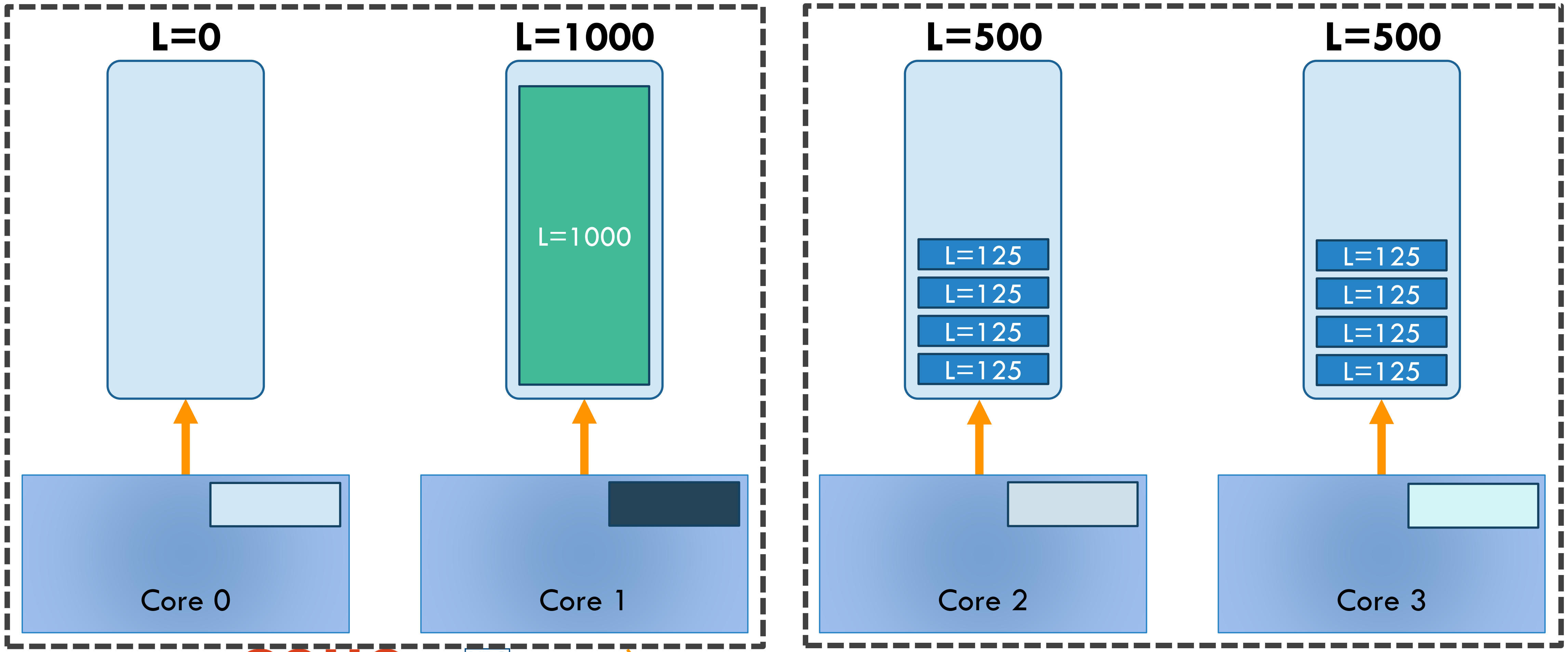


Load(thread) = %cpu × weight / #threads
= 100 × 10 / 1
= 1000

Load(thread) = %cpu × weight / #threads
= 100 × 10 / 8
= 125

BUG 1/4: GROUP IMBALANCE



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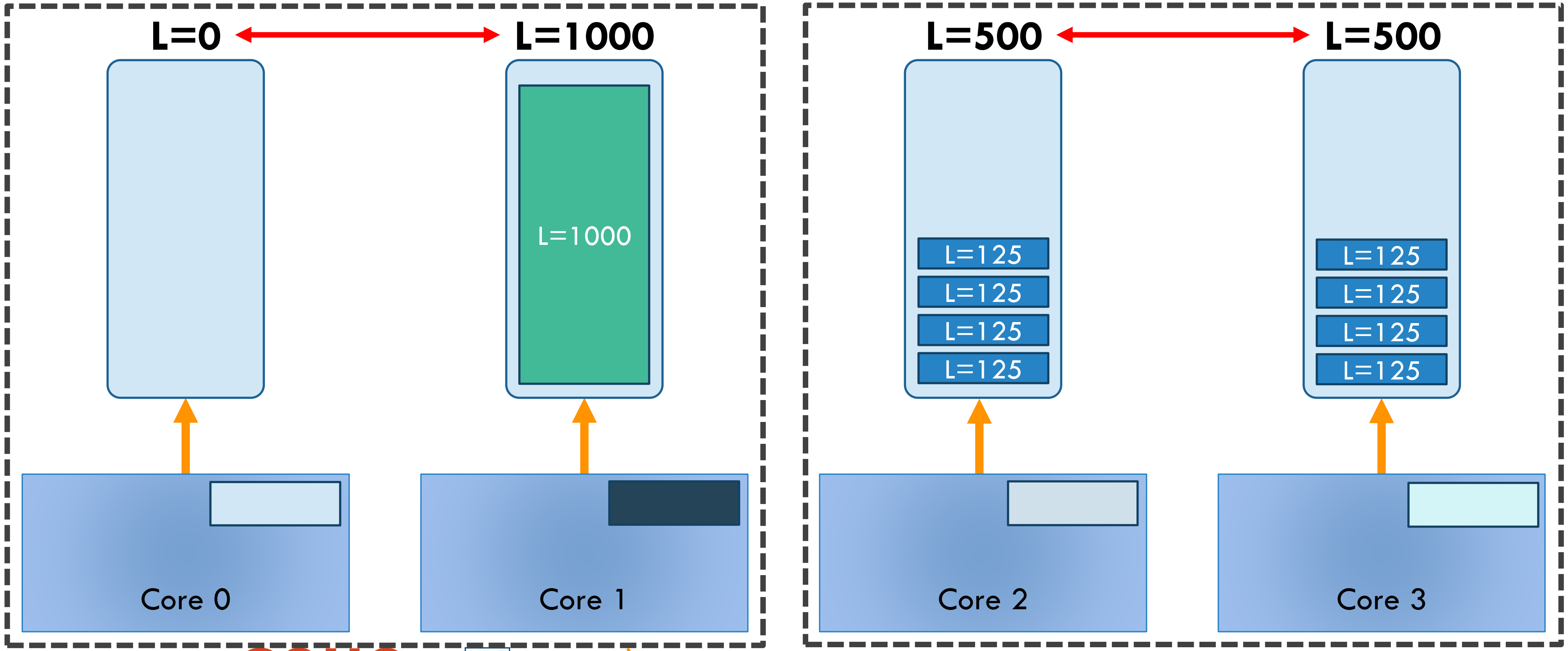

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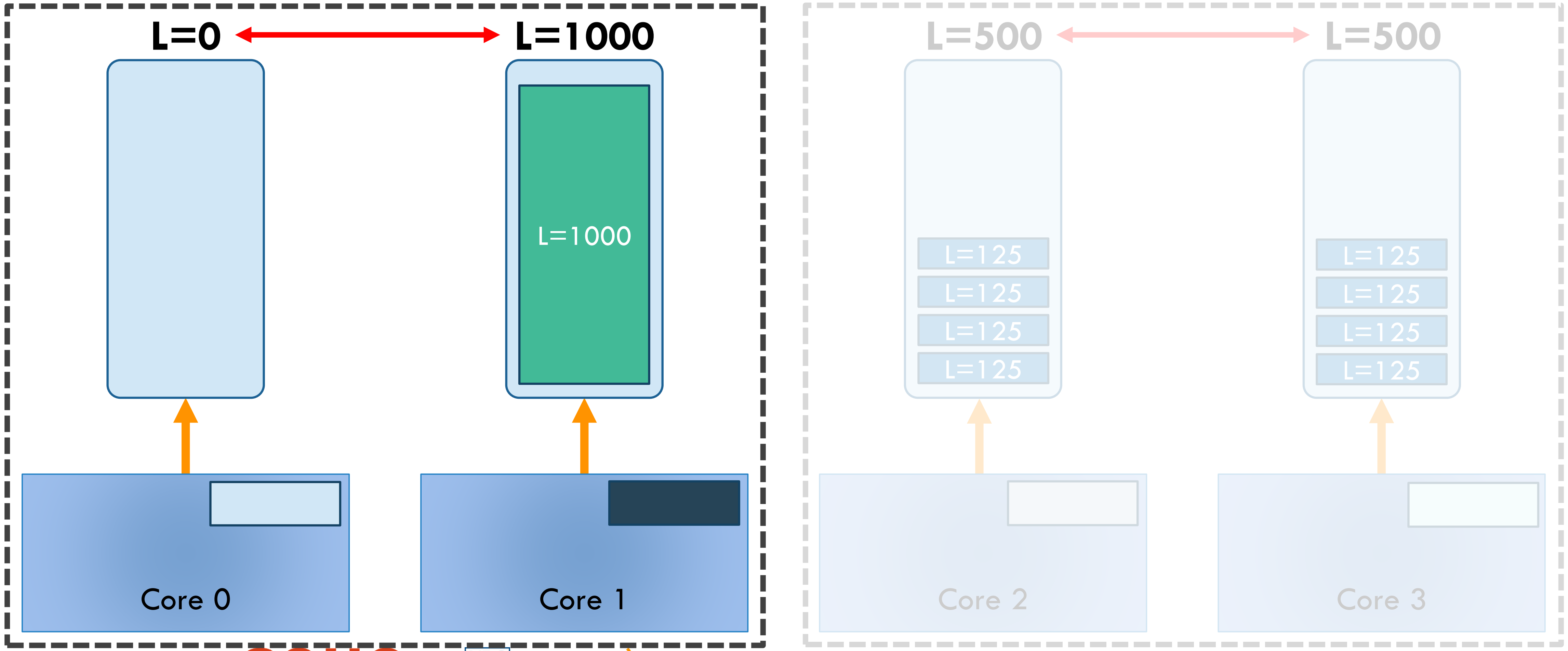

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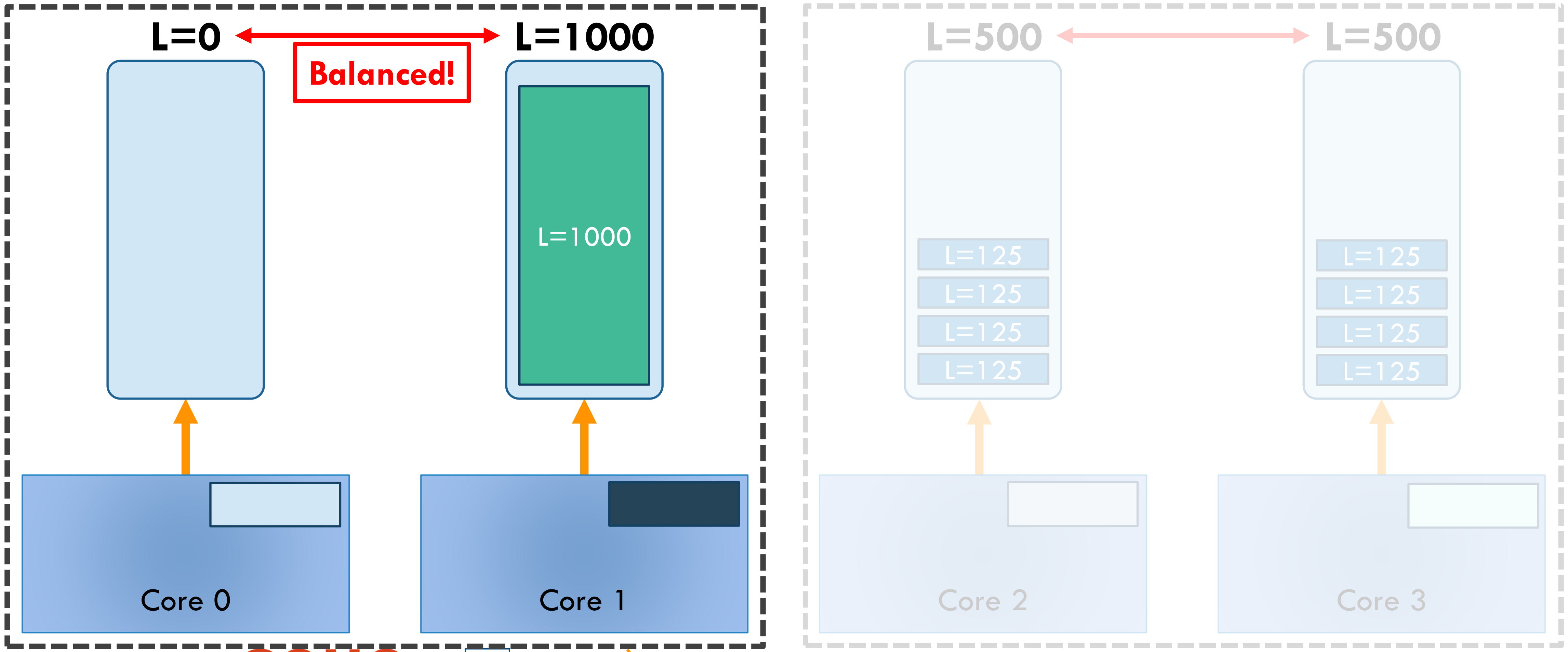

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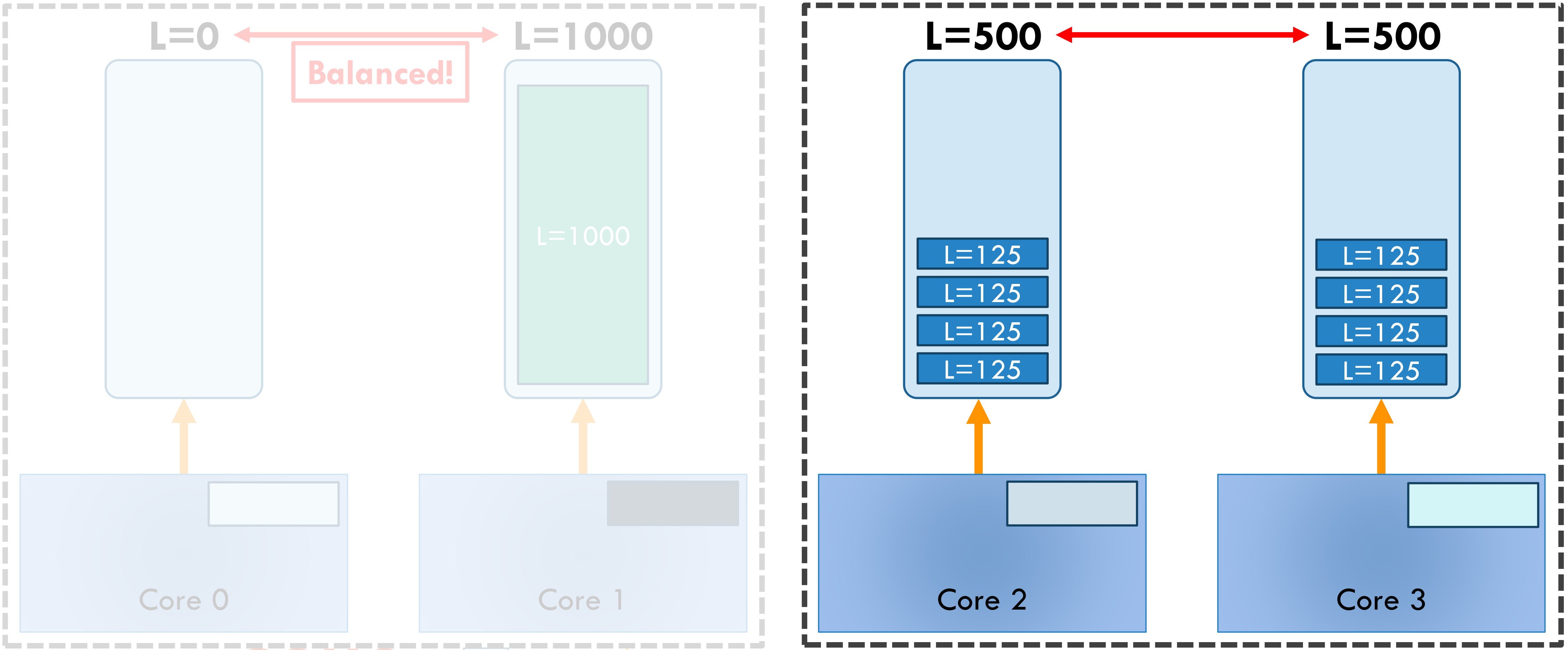

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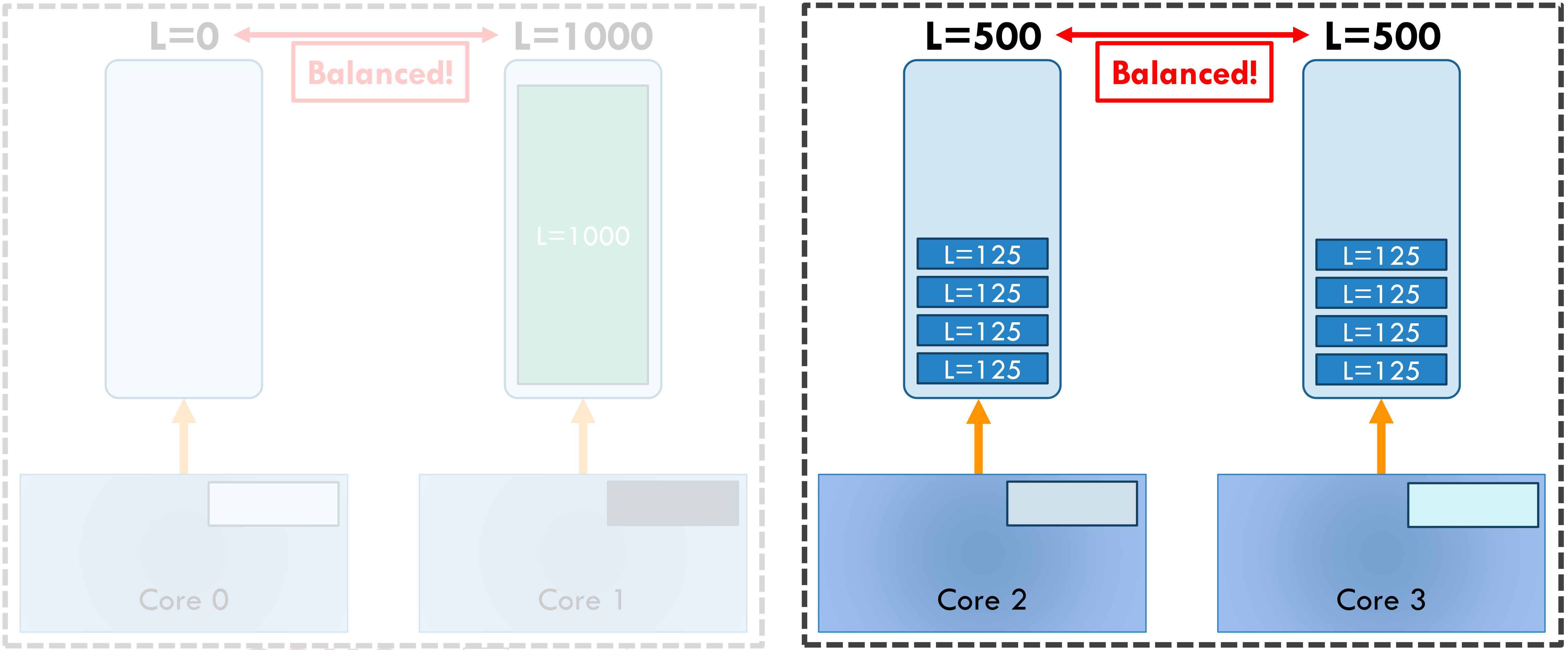

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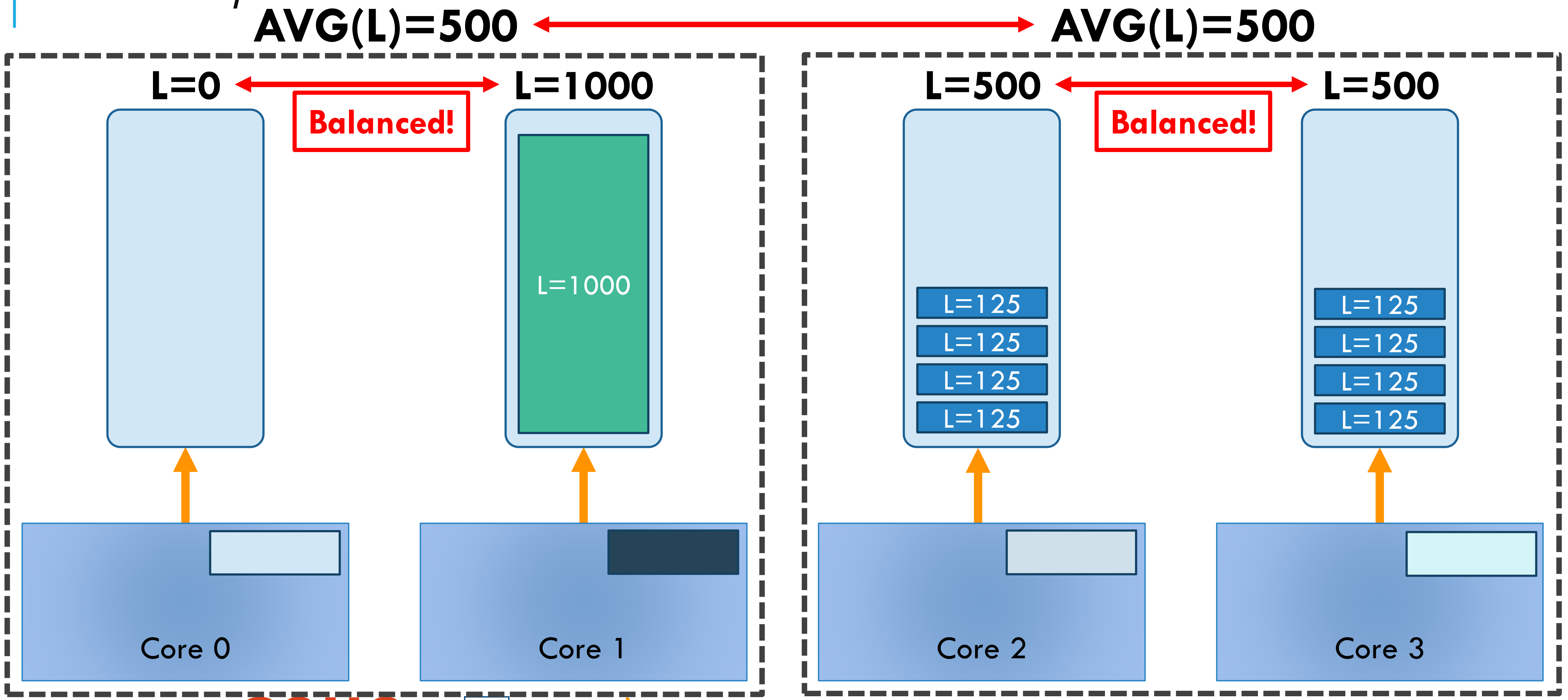

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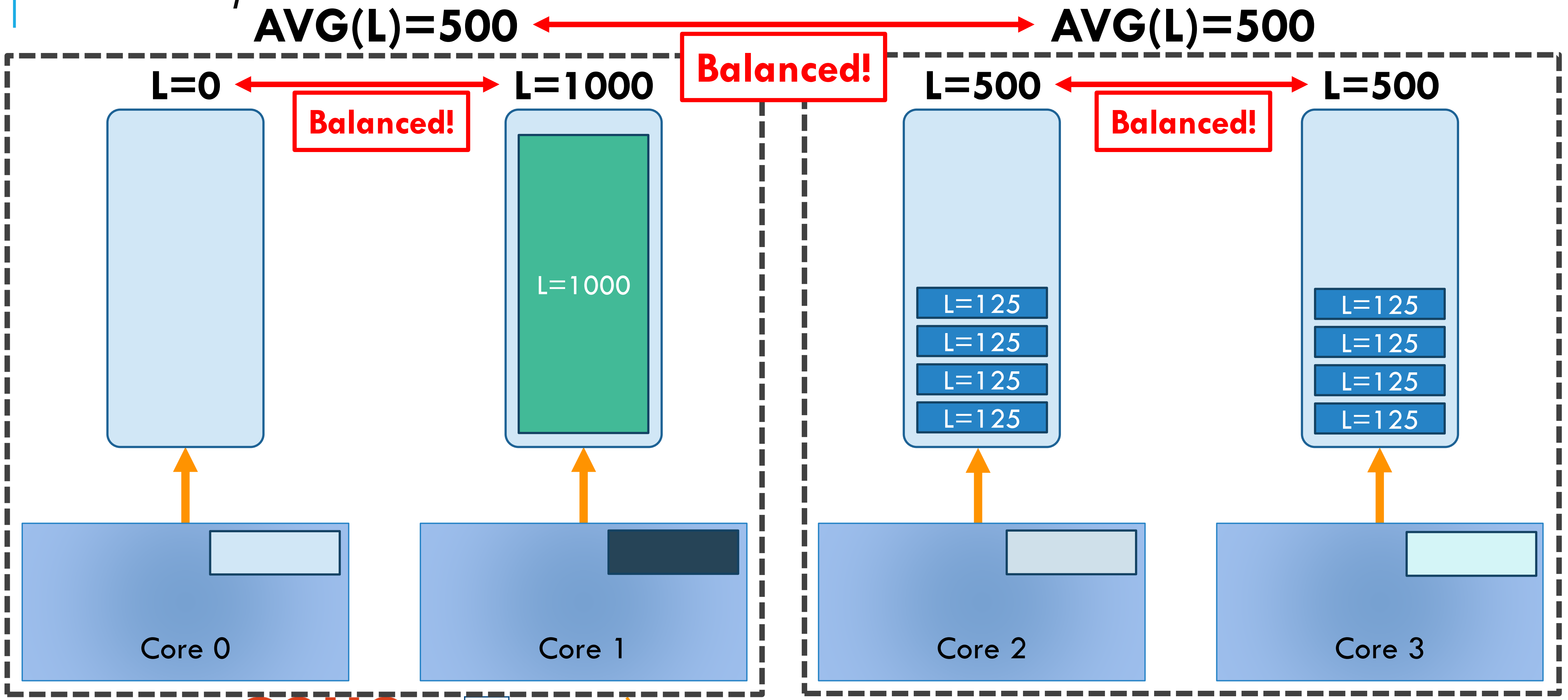

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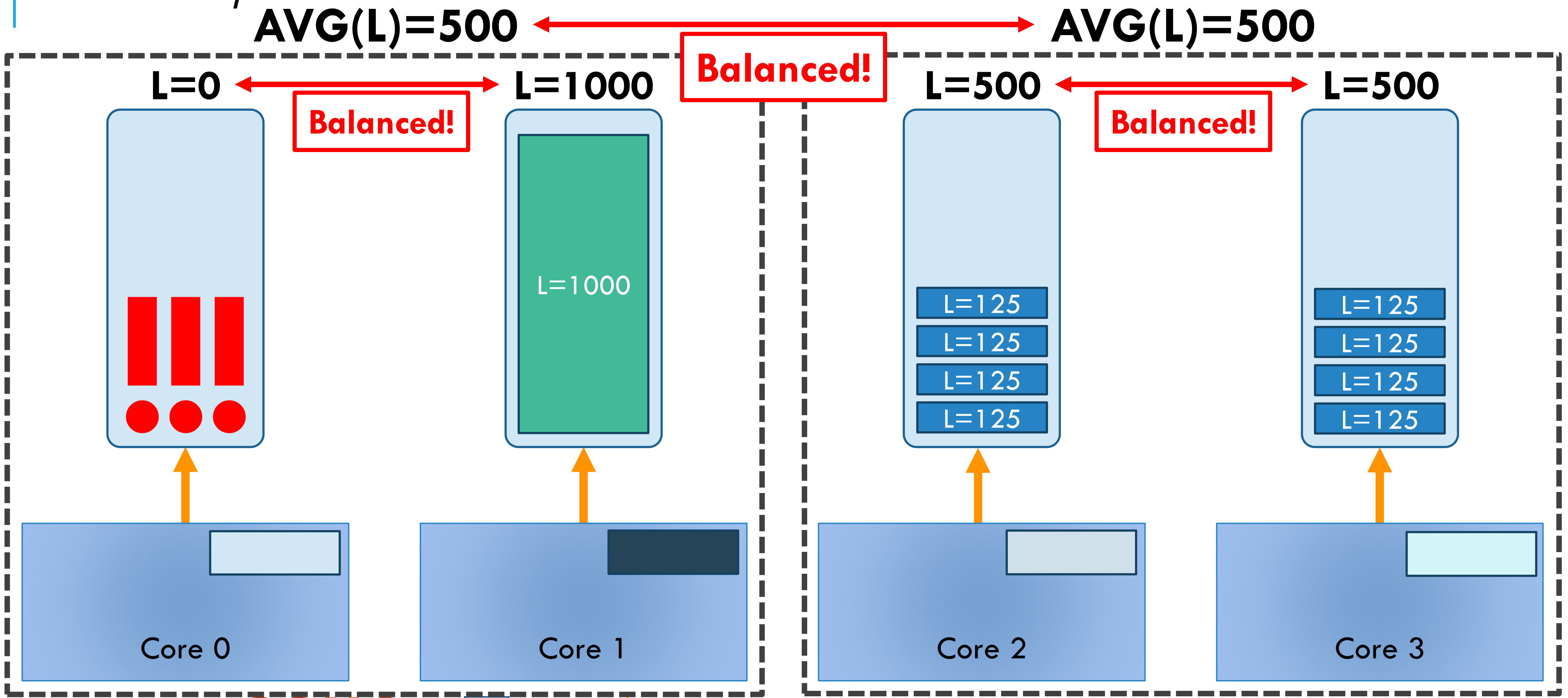

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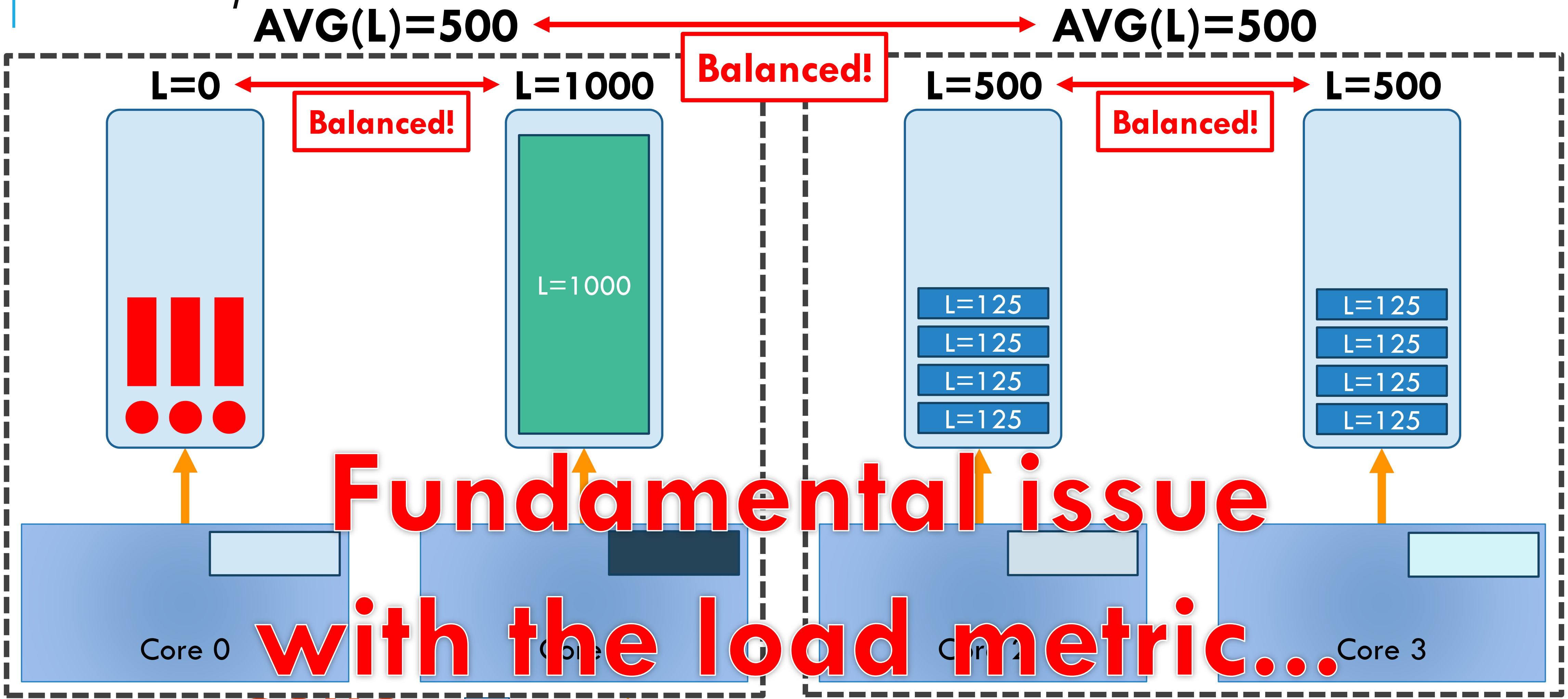

Fundamental issue with the load metric…

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  - First between pairs of cores (Bulldozer architecture, a bit like hyperthreading)
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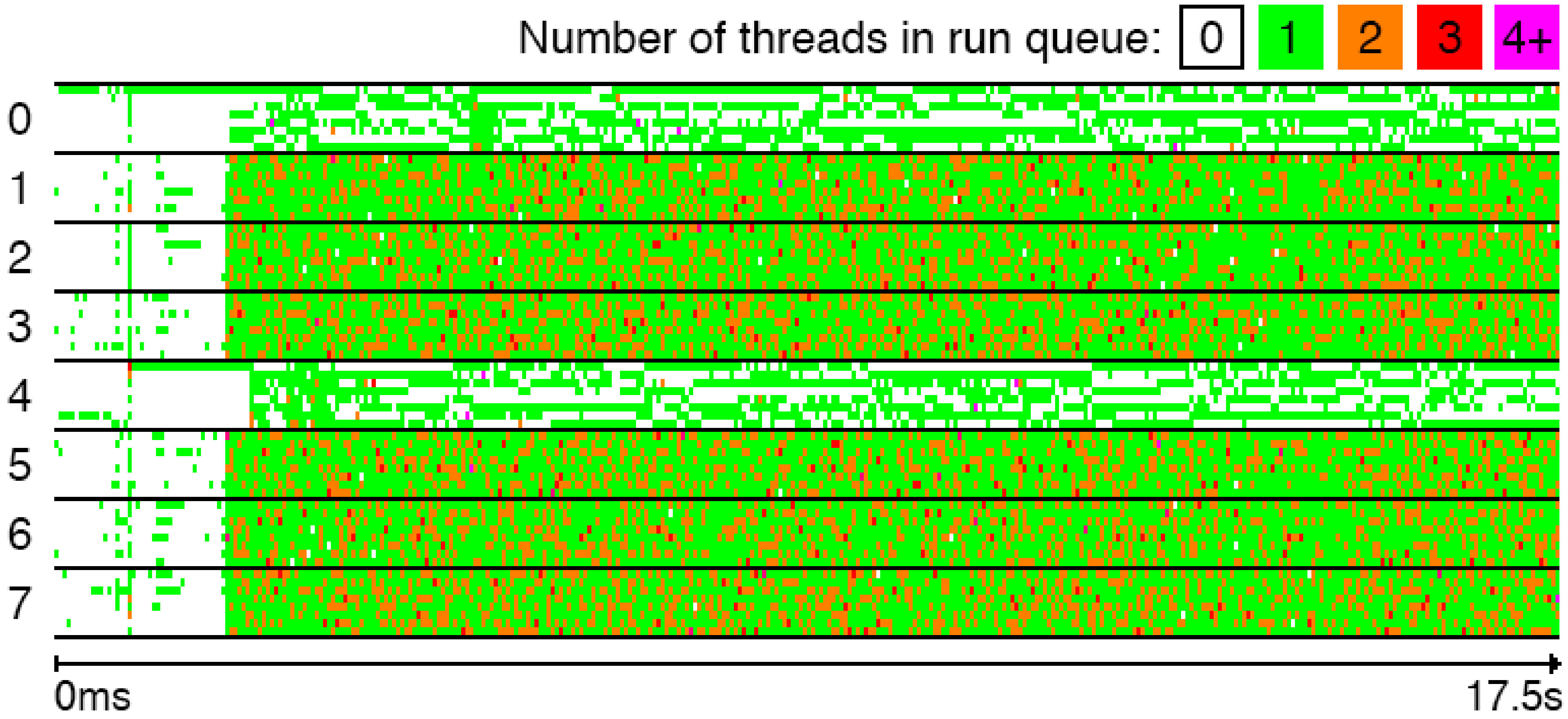

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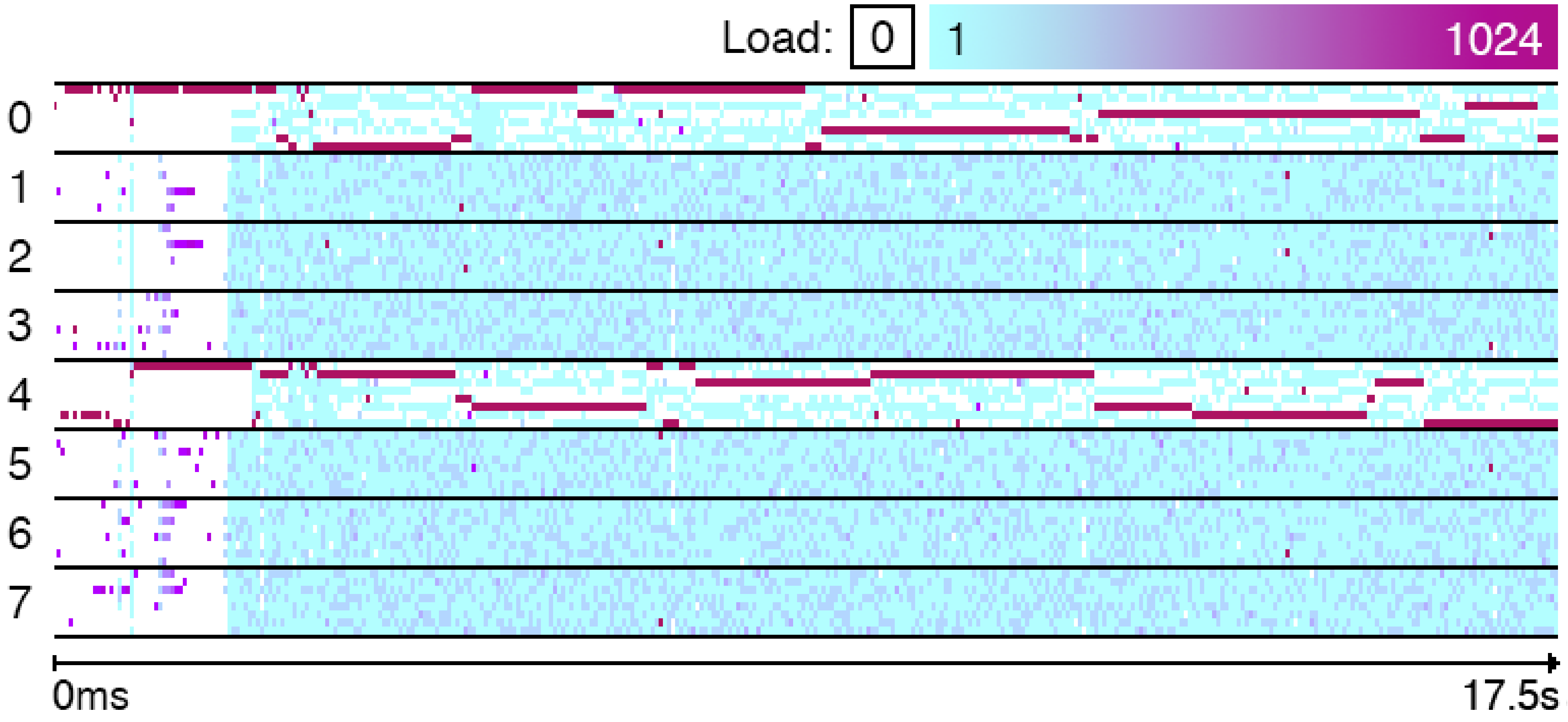

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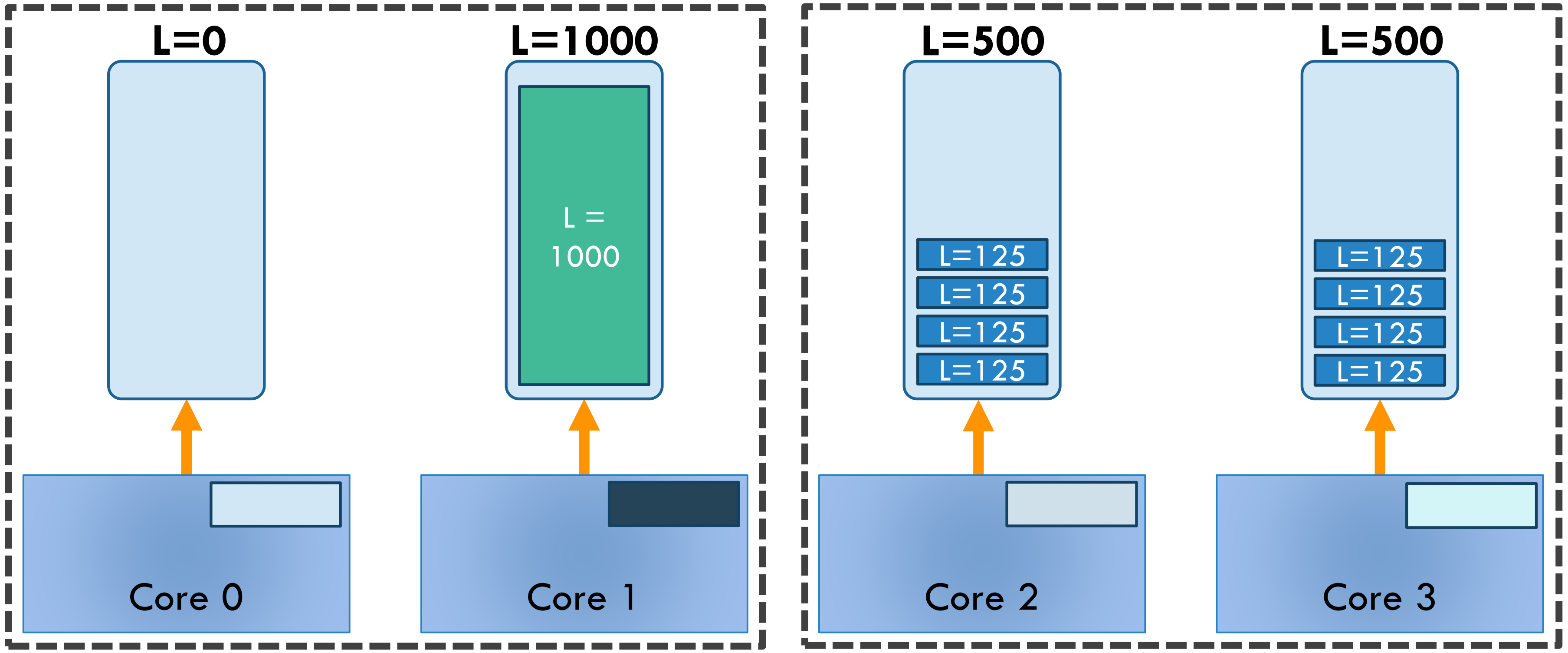

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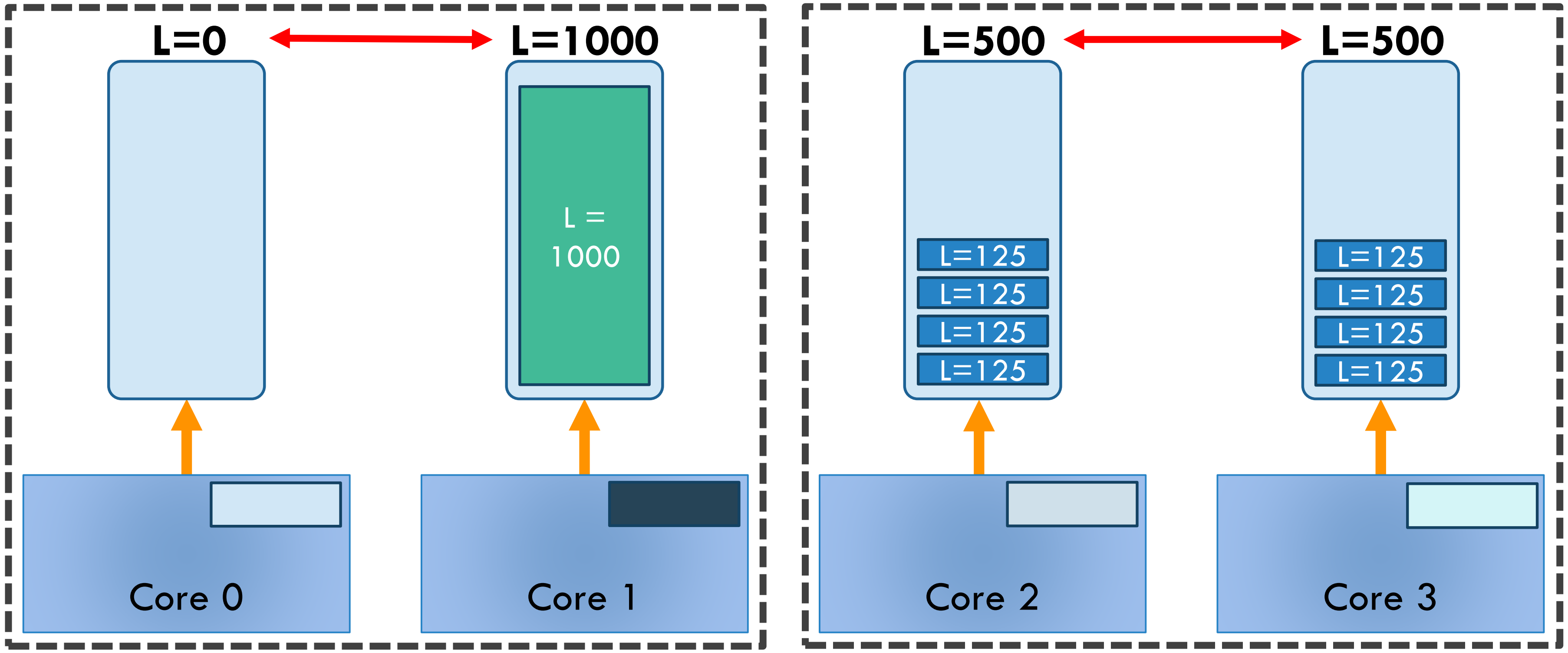

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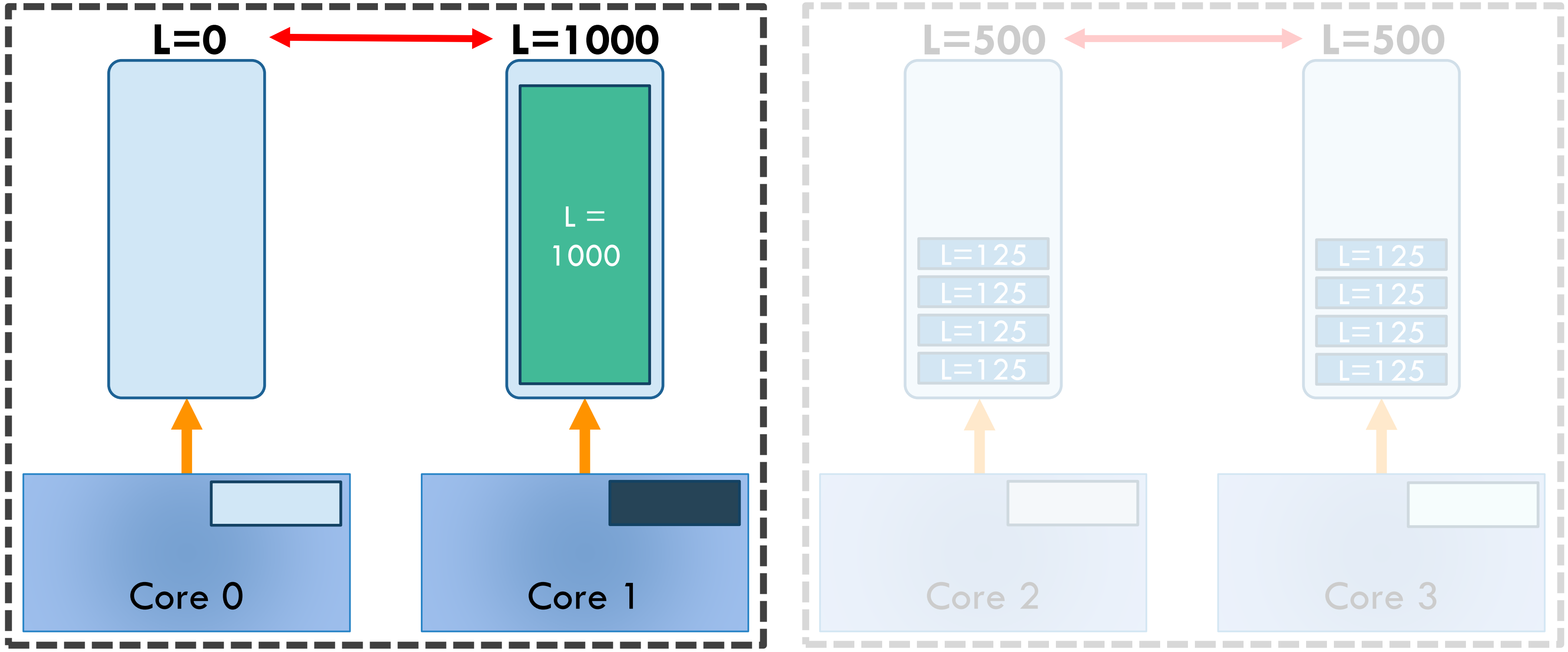

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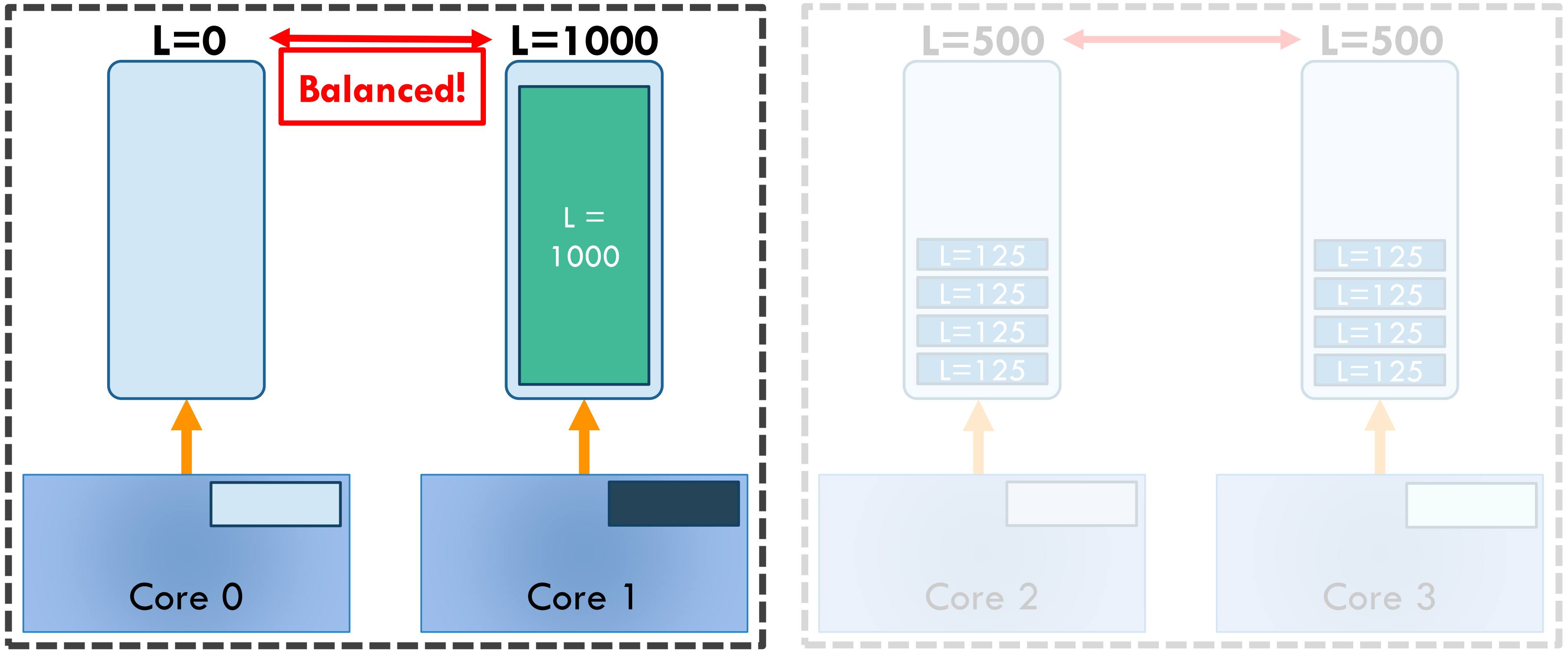

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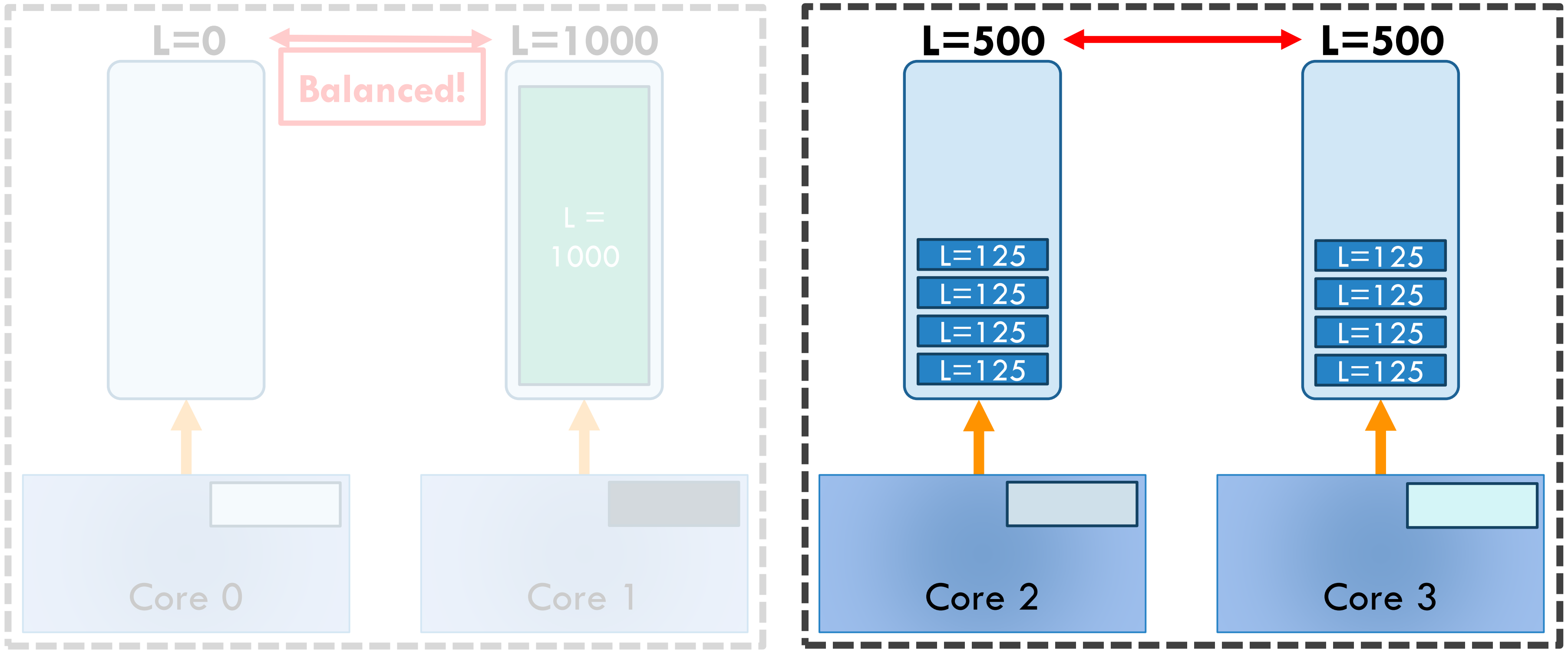

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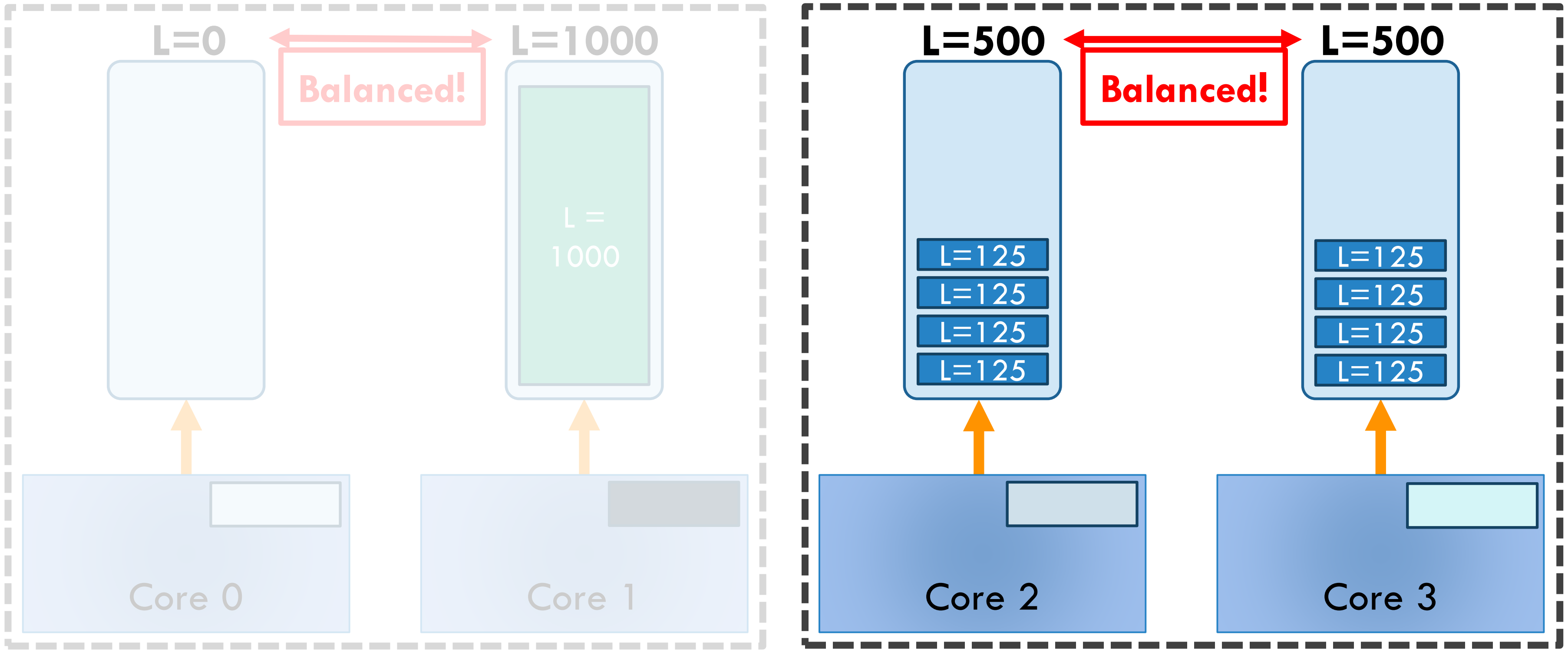

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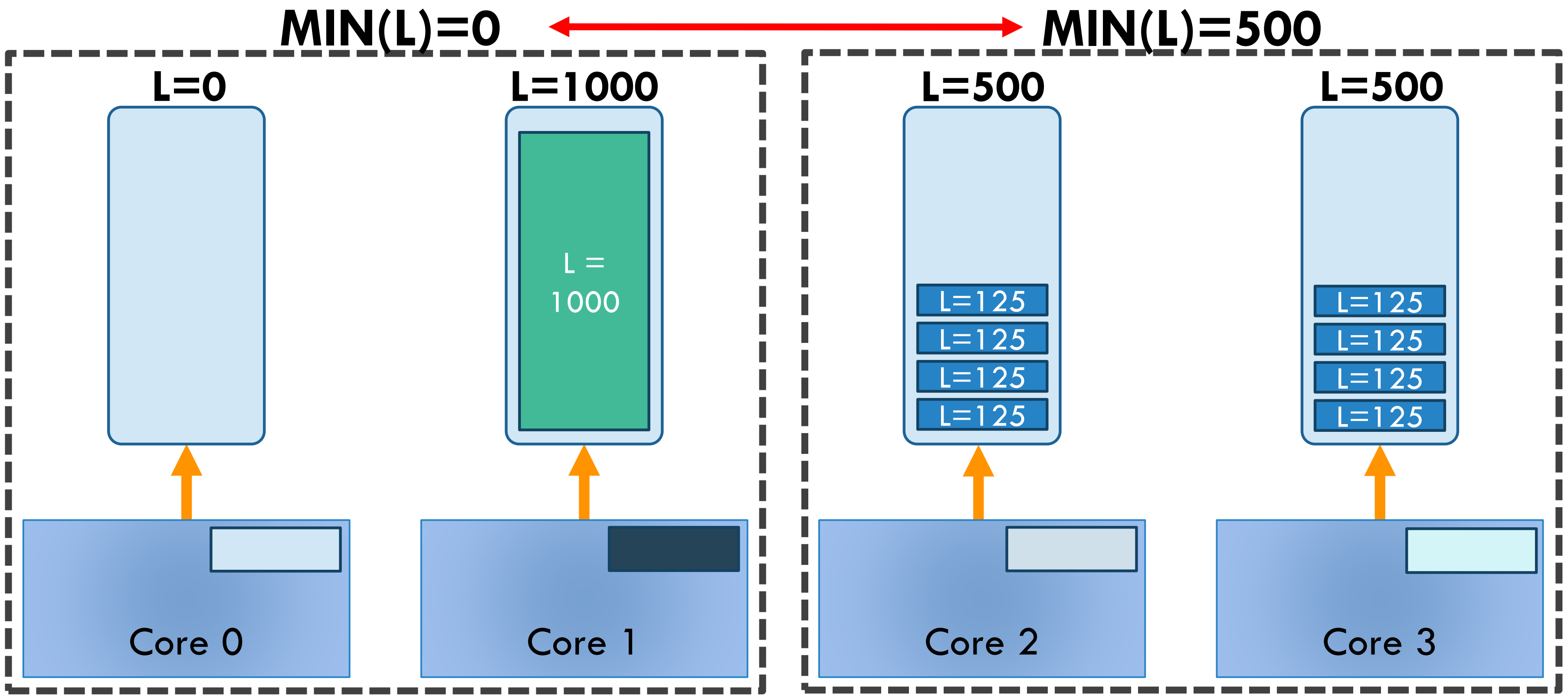

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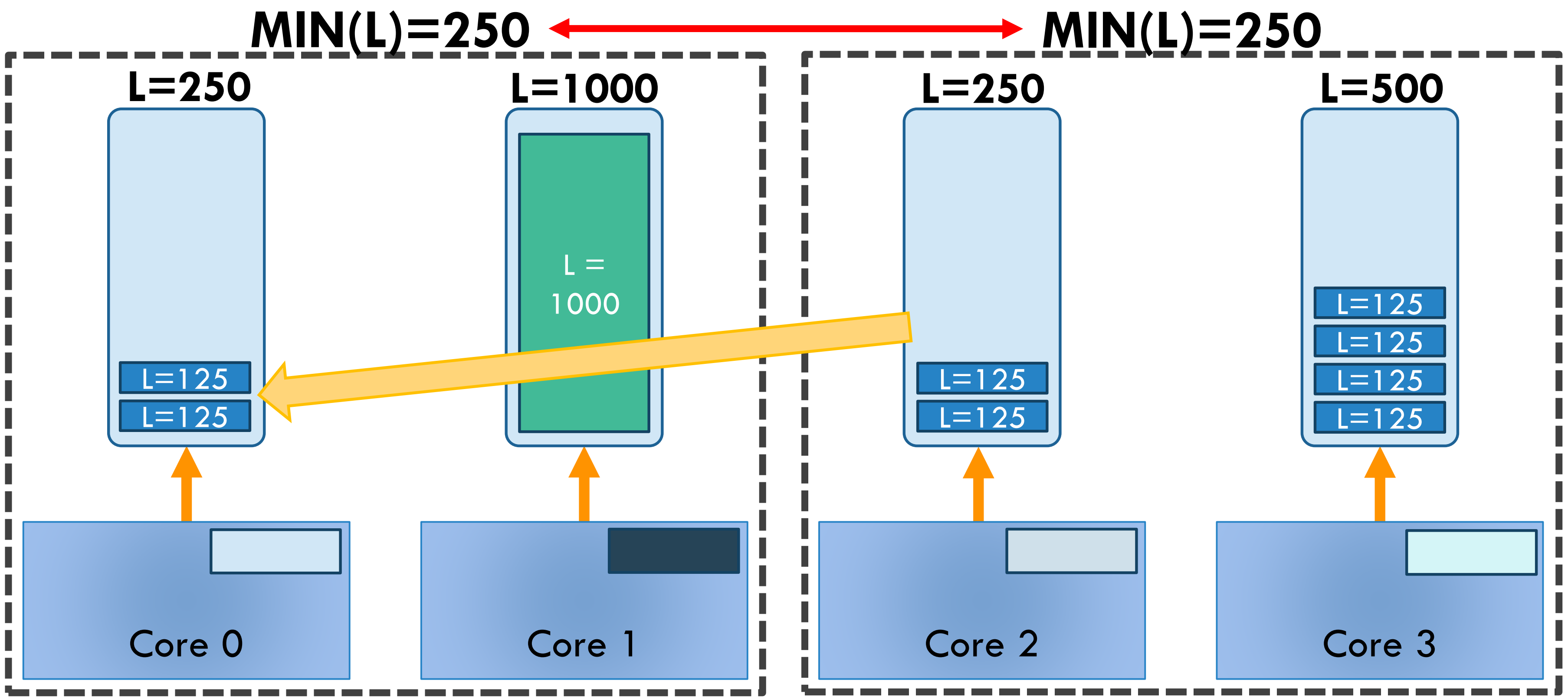

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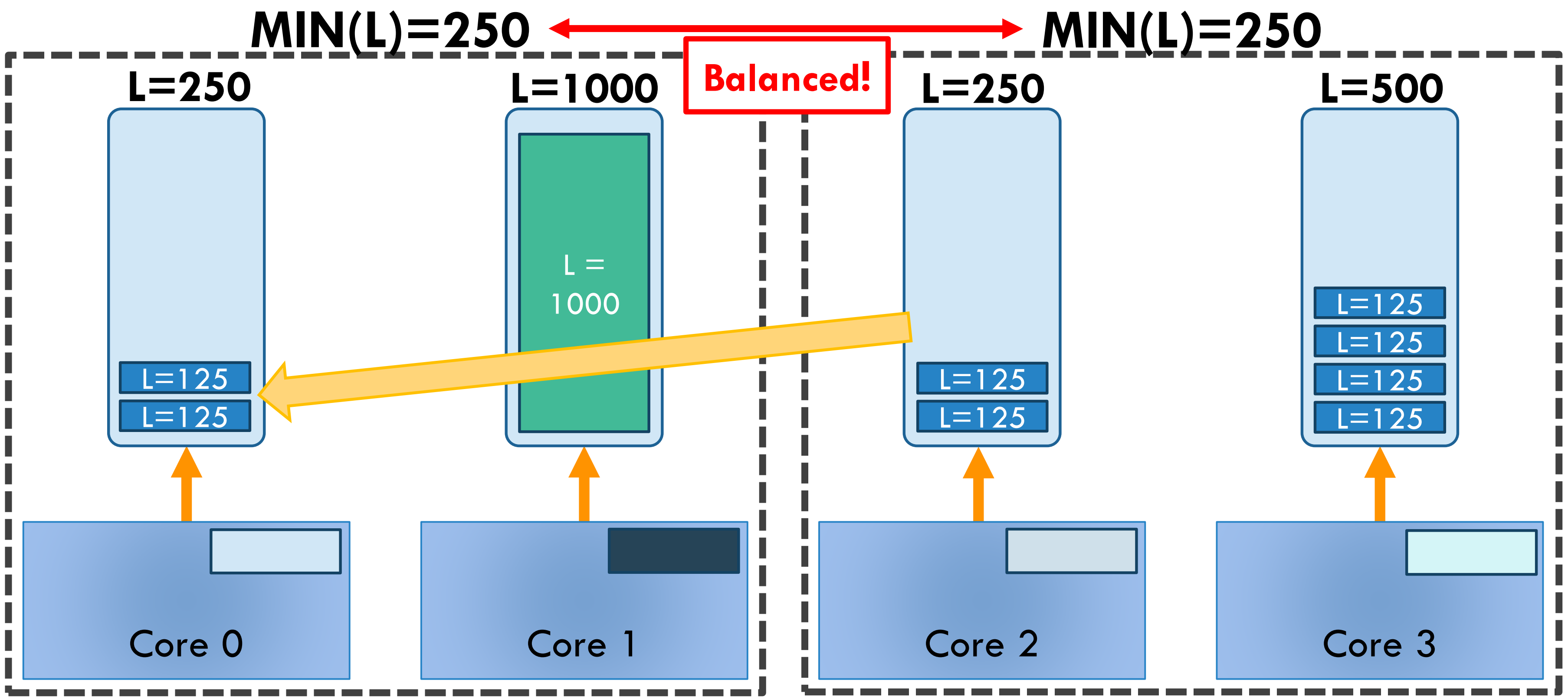

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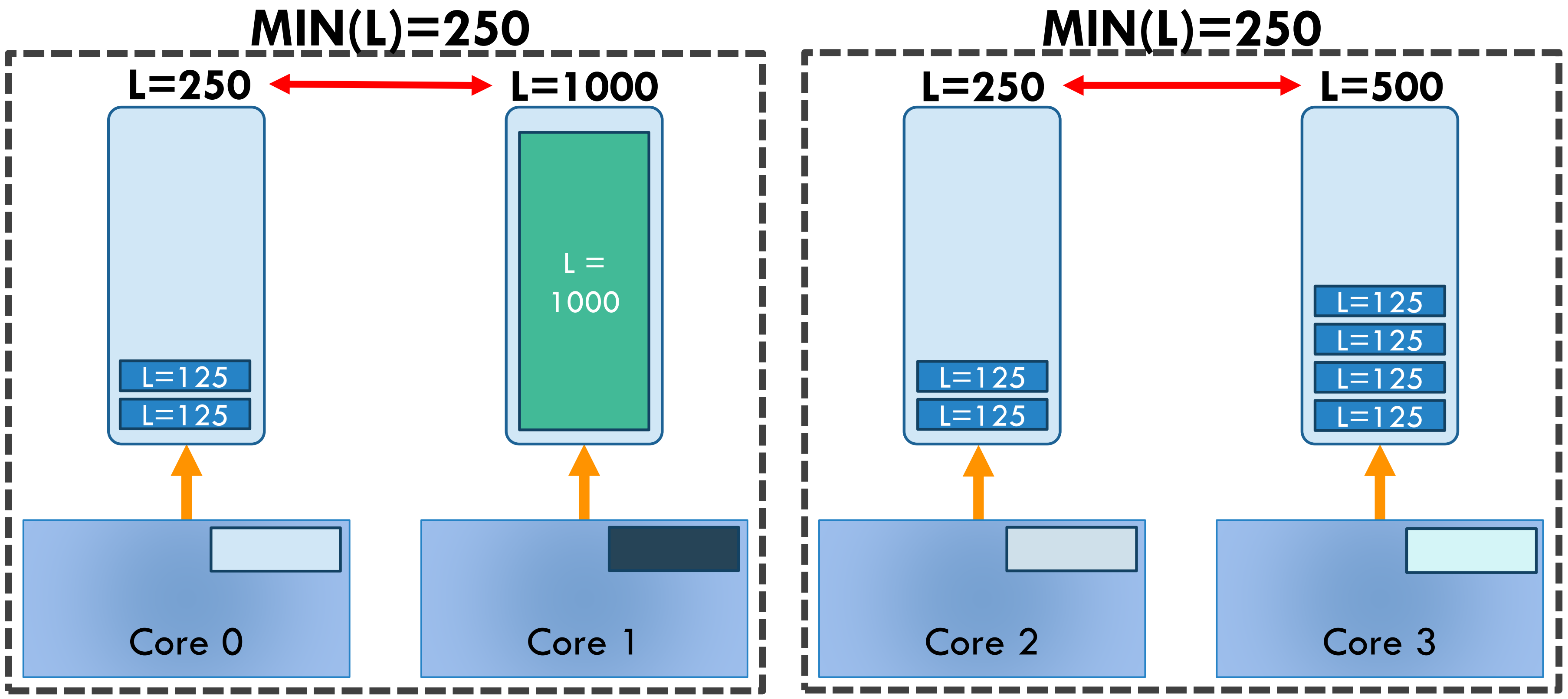

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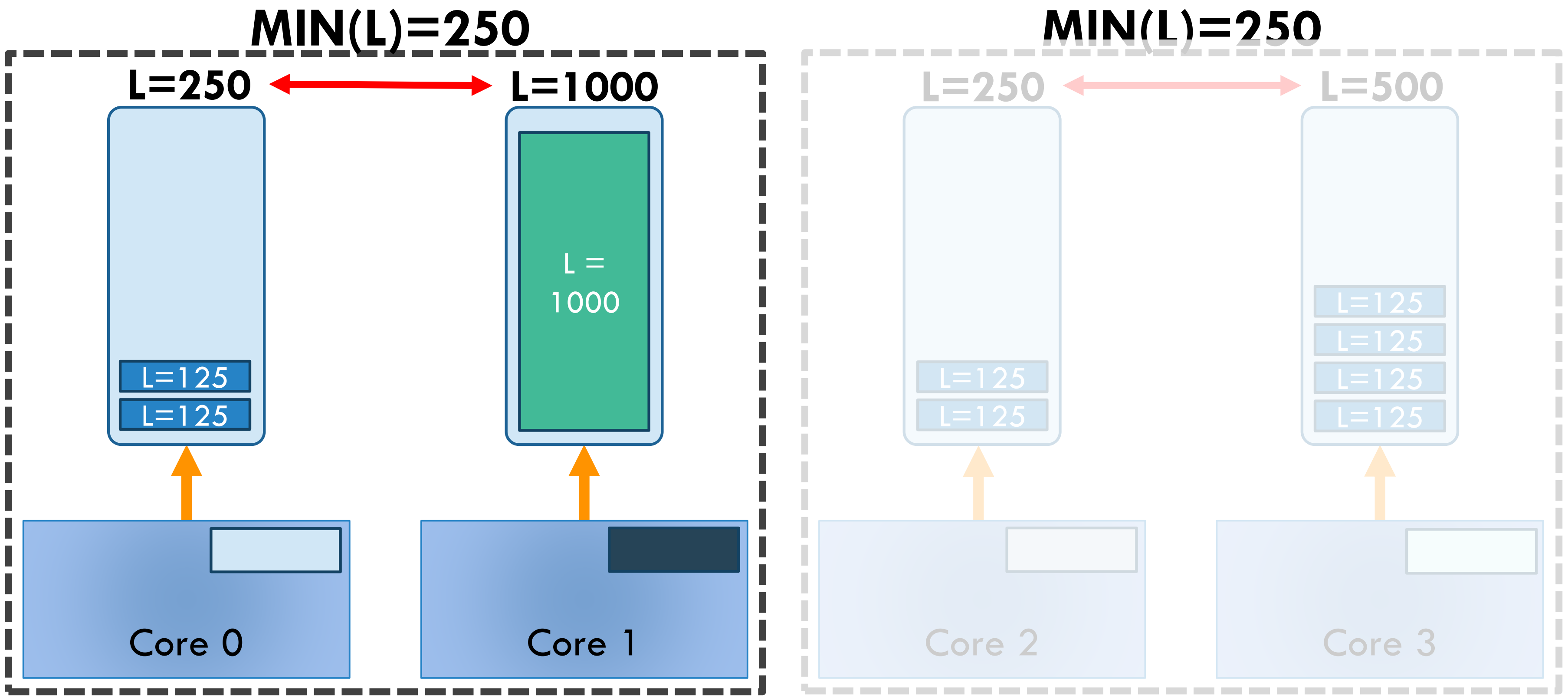

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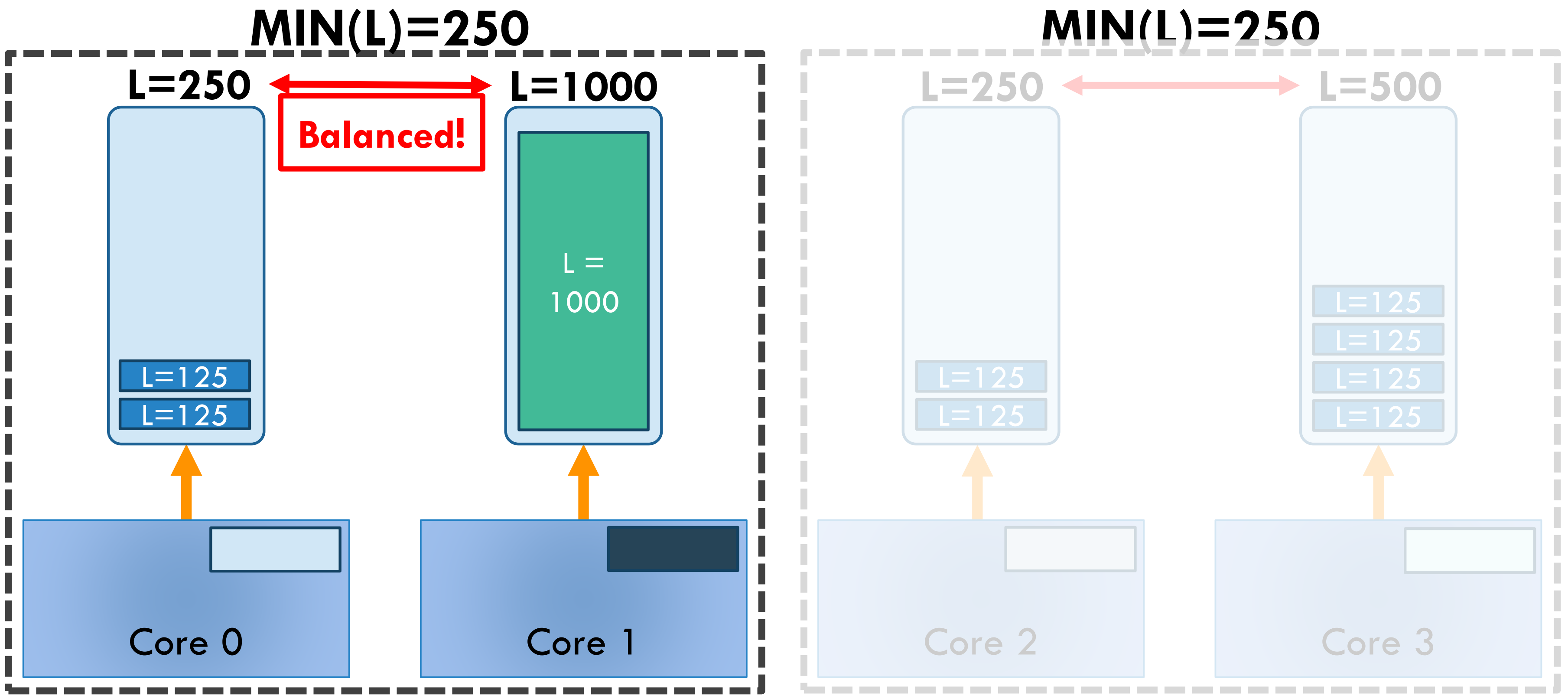

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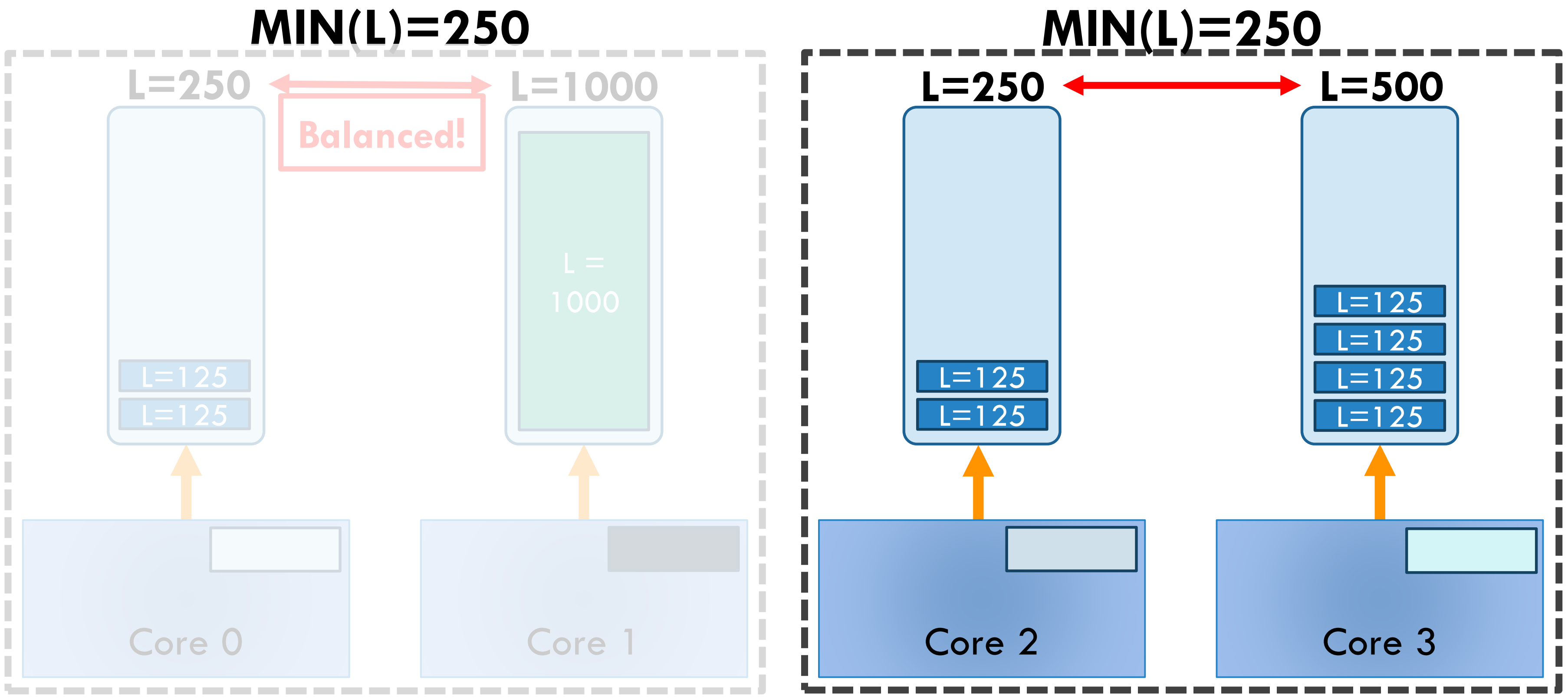

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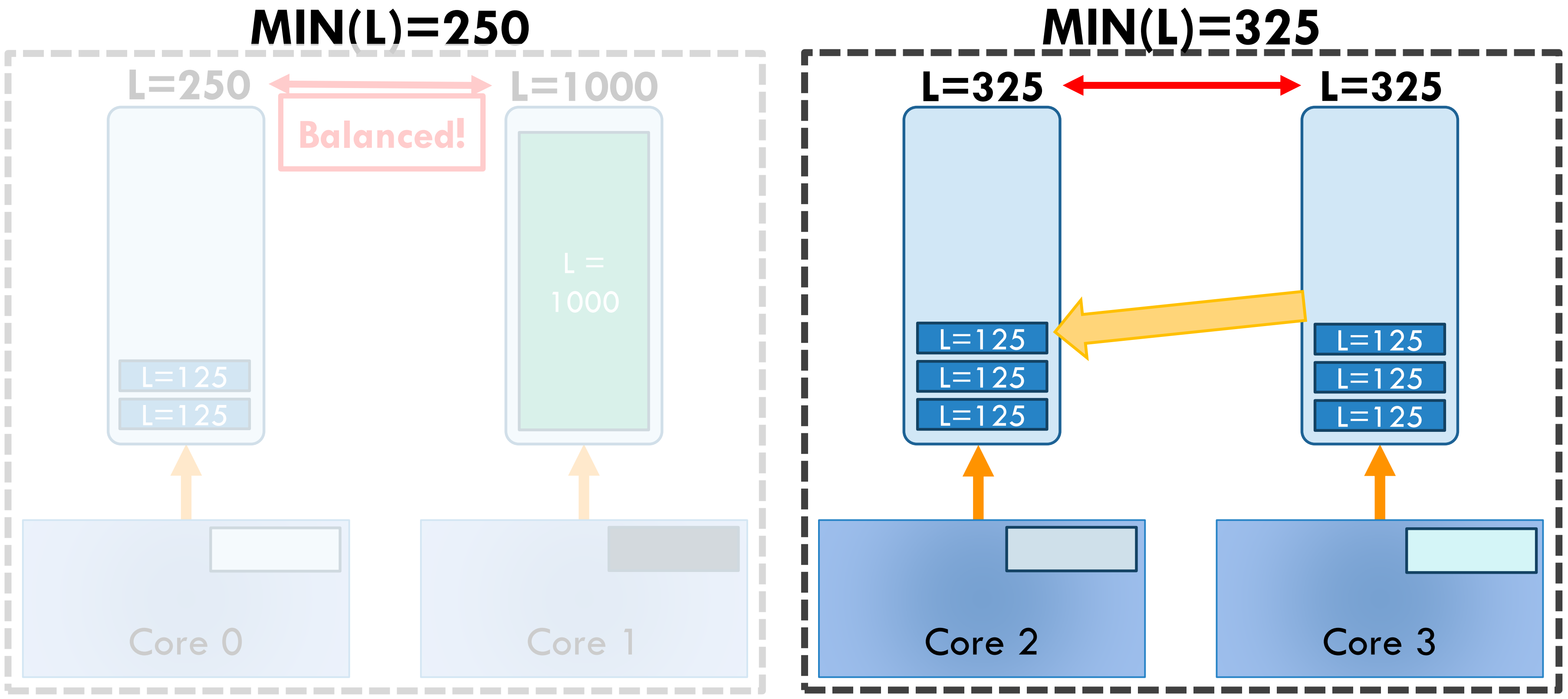

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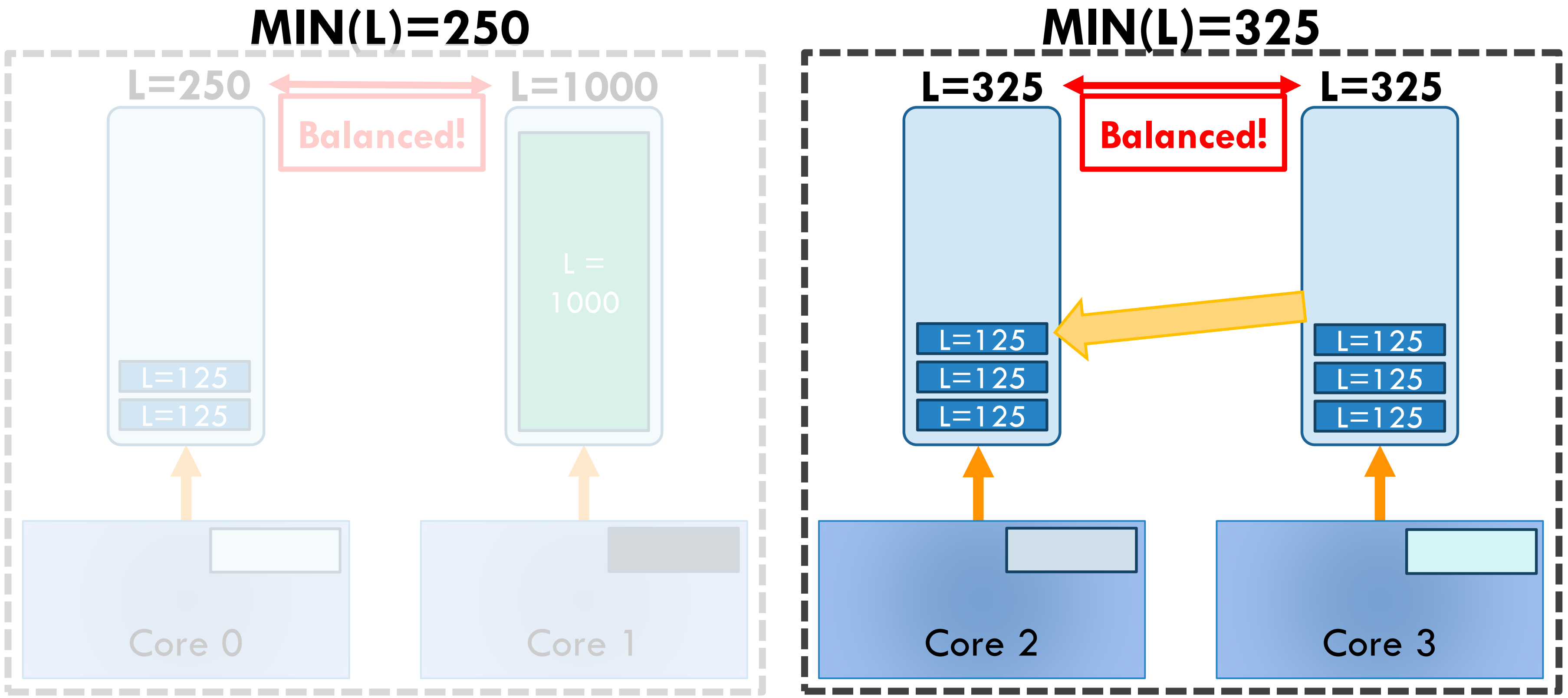

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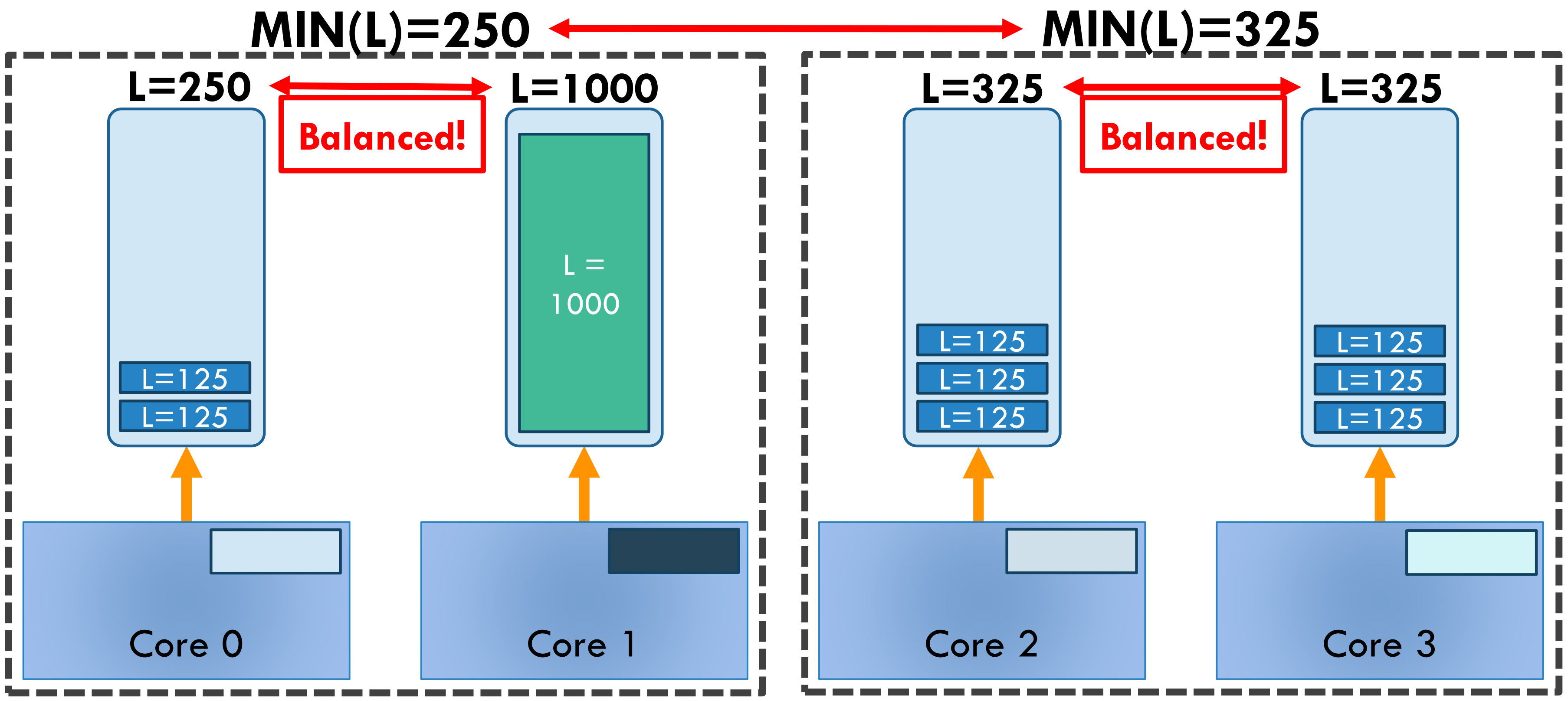

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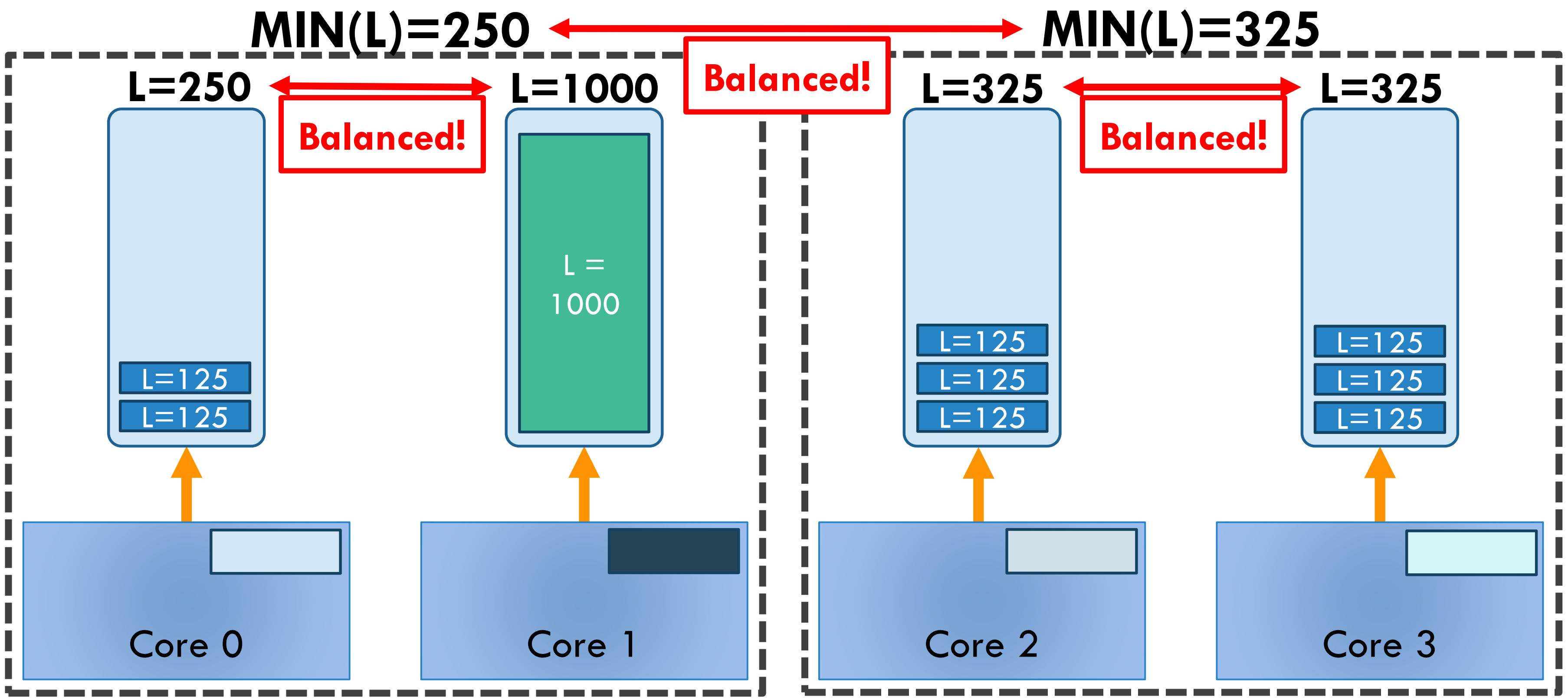

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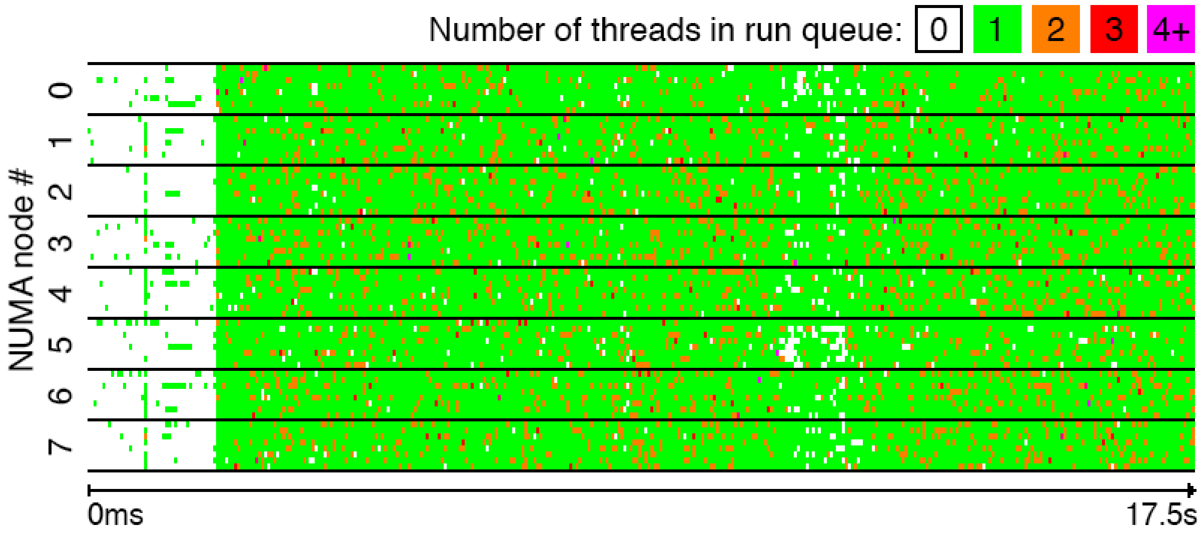

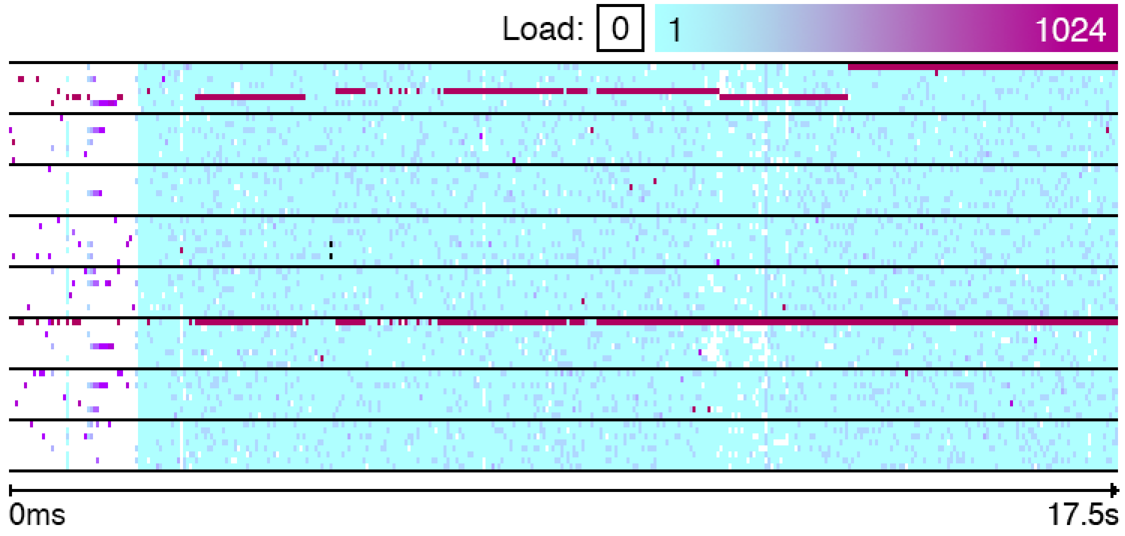

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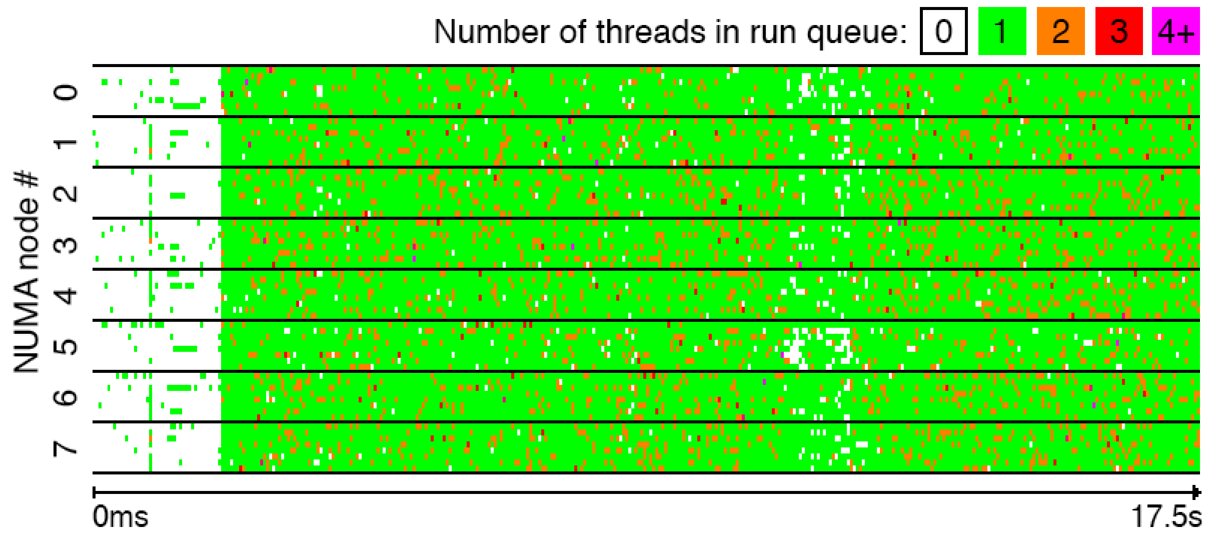

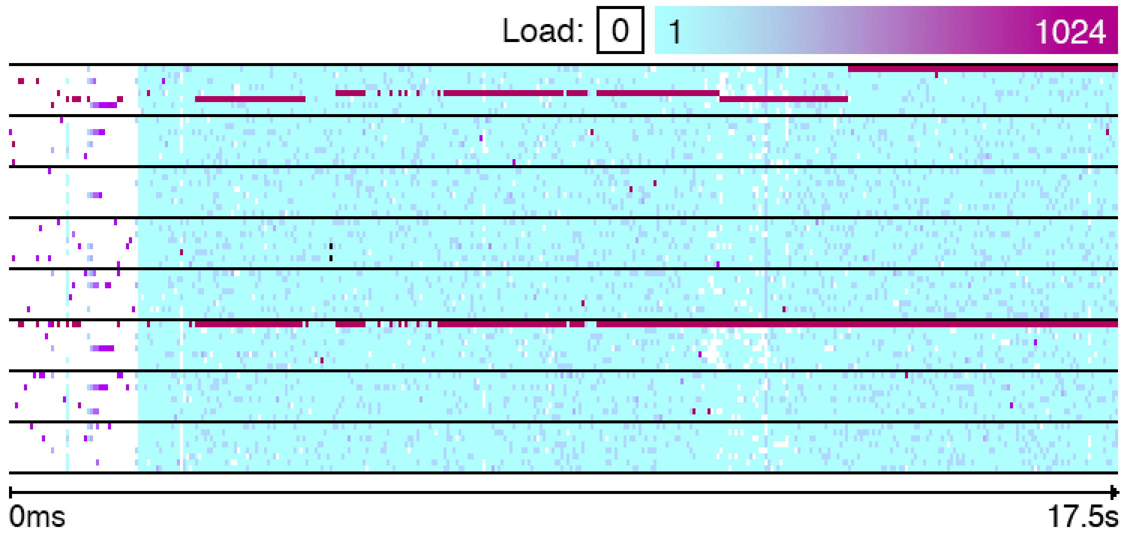

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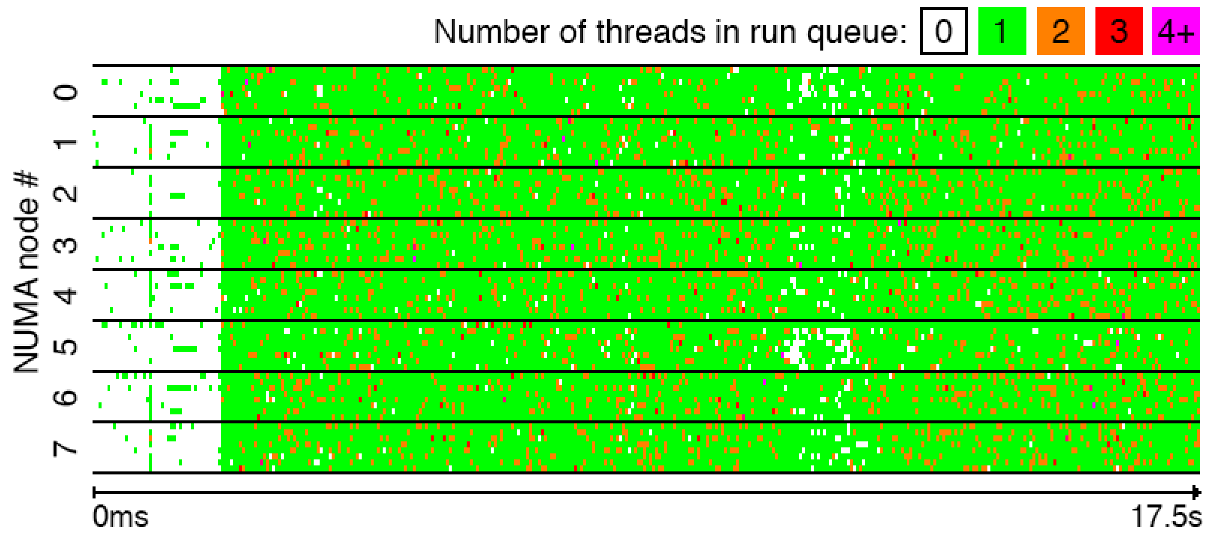

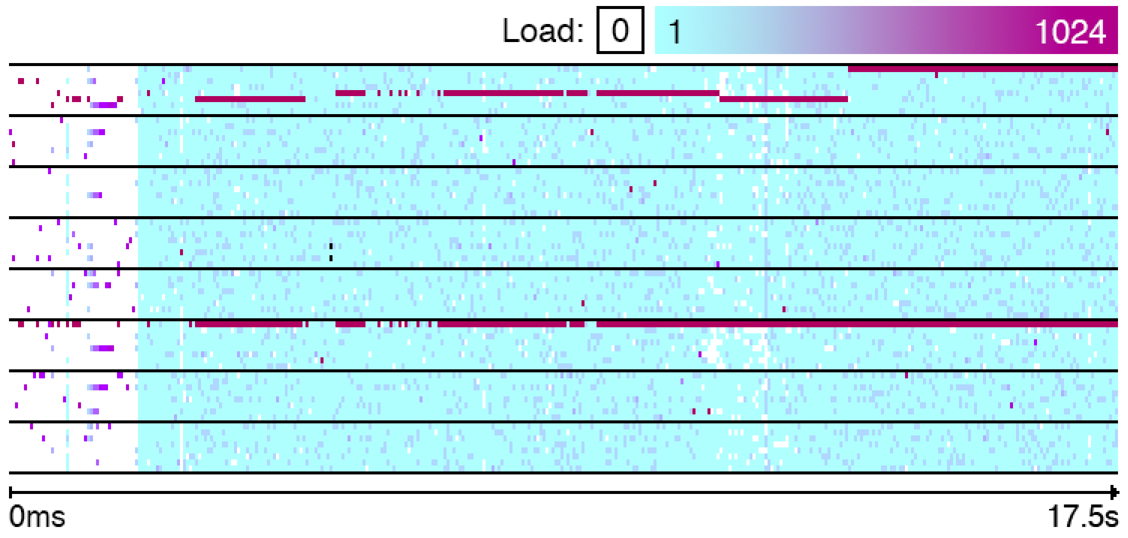

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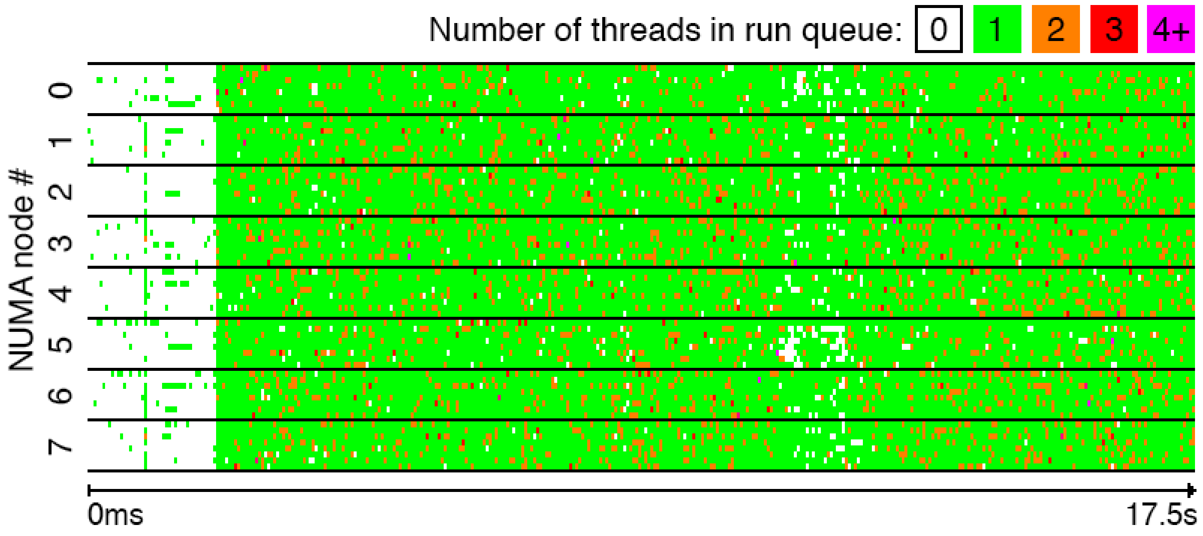

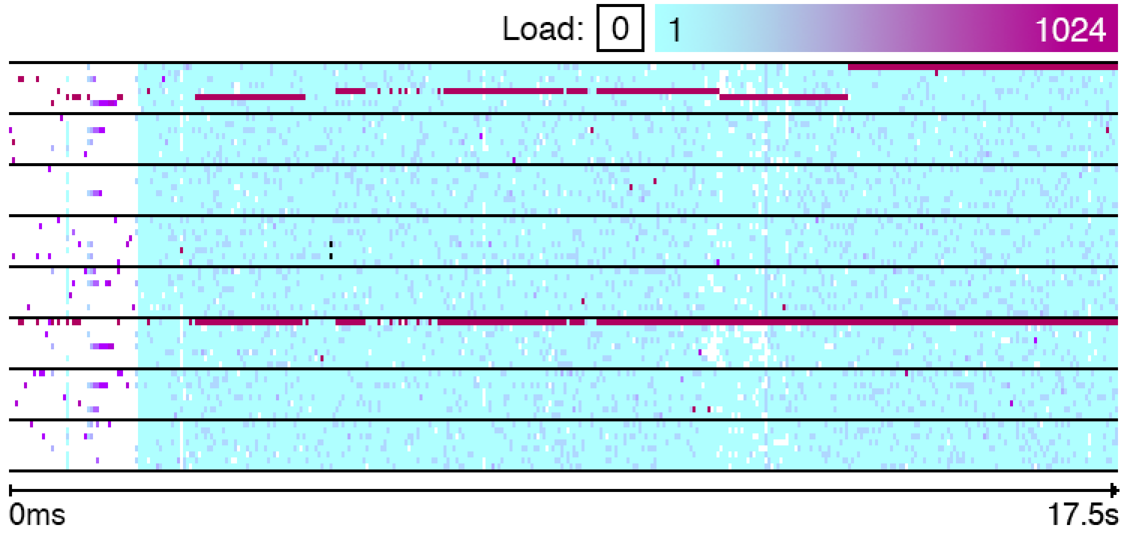

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  - *May cause lots of unnecessary rebalancing. Revamping load calculations needed?*

BUG 2/4: SCHEDULING GROUP CONSTRUCTION

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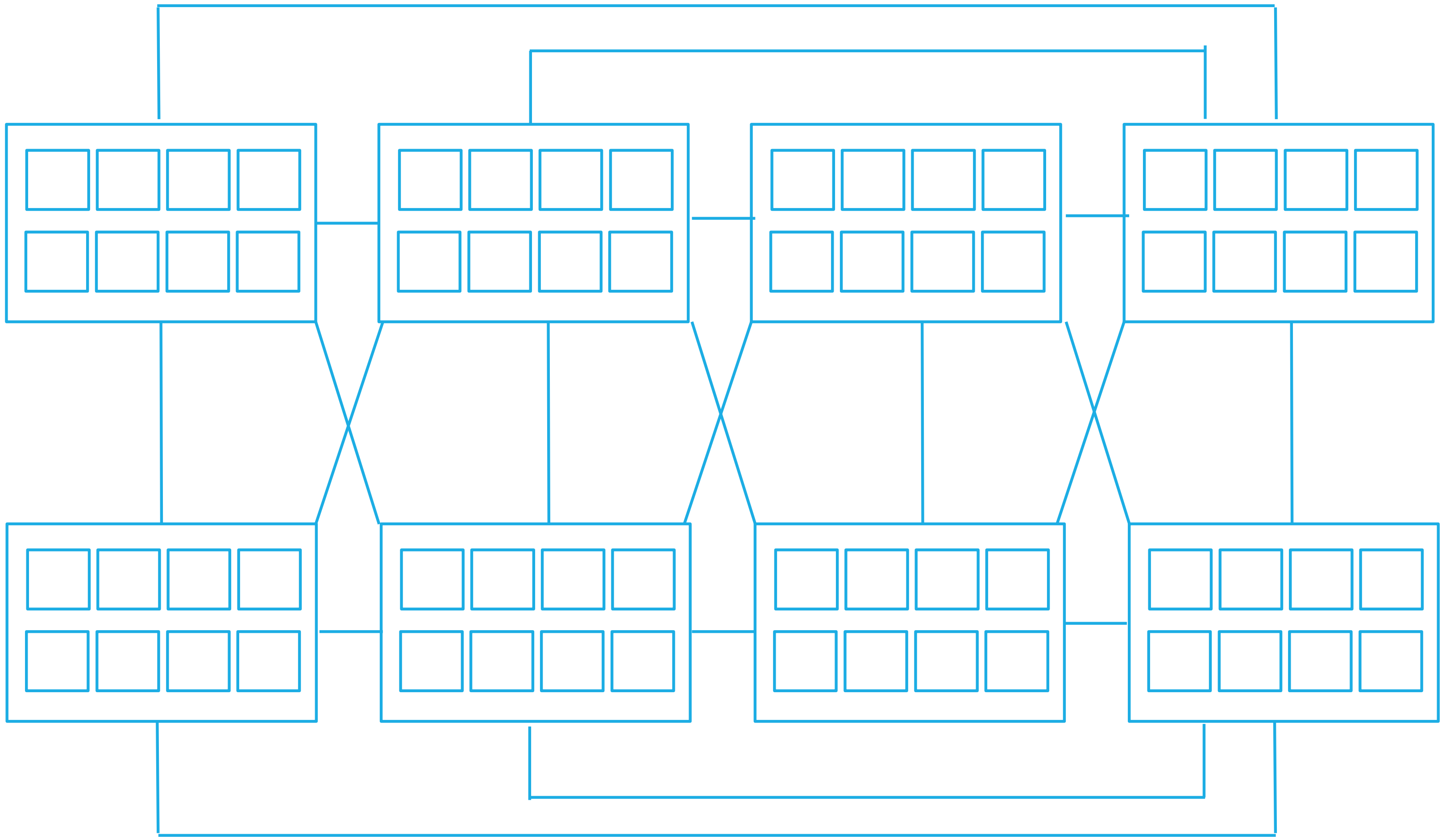
  - At level 4, the whole machine (s.d.) contains group of directly connected CPUs (s.g.)

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Bulldozer 64-core:
Eight CPUs, with
8 cores each,
non-complete interconnect graph!

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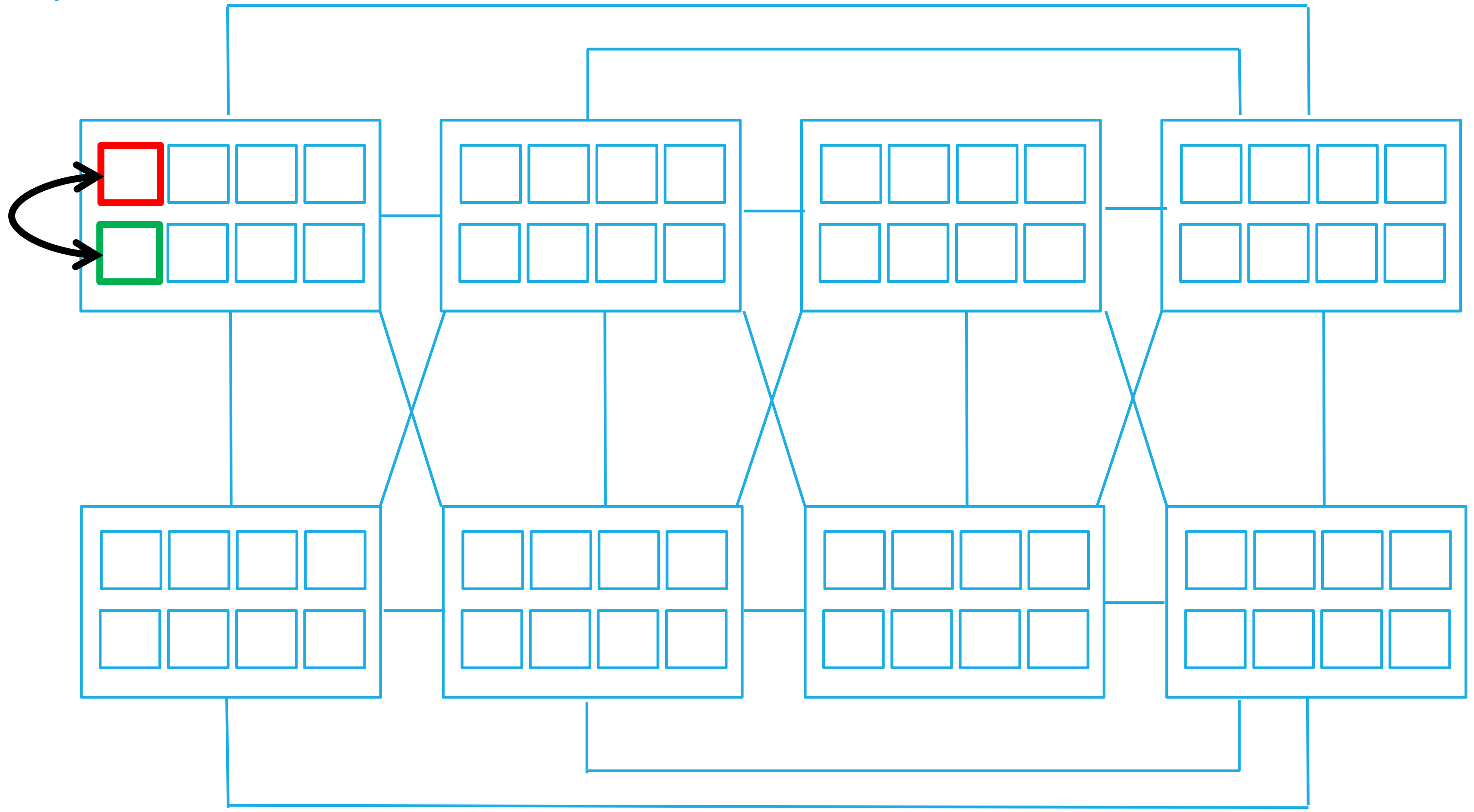
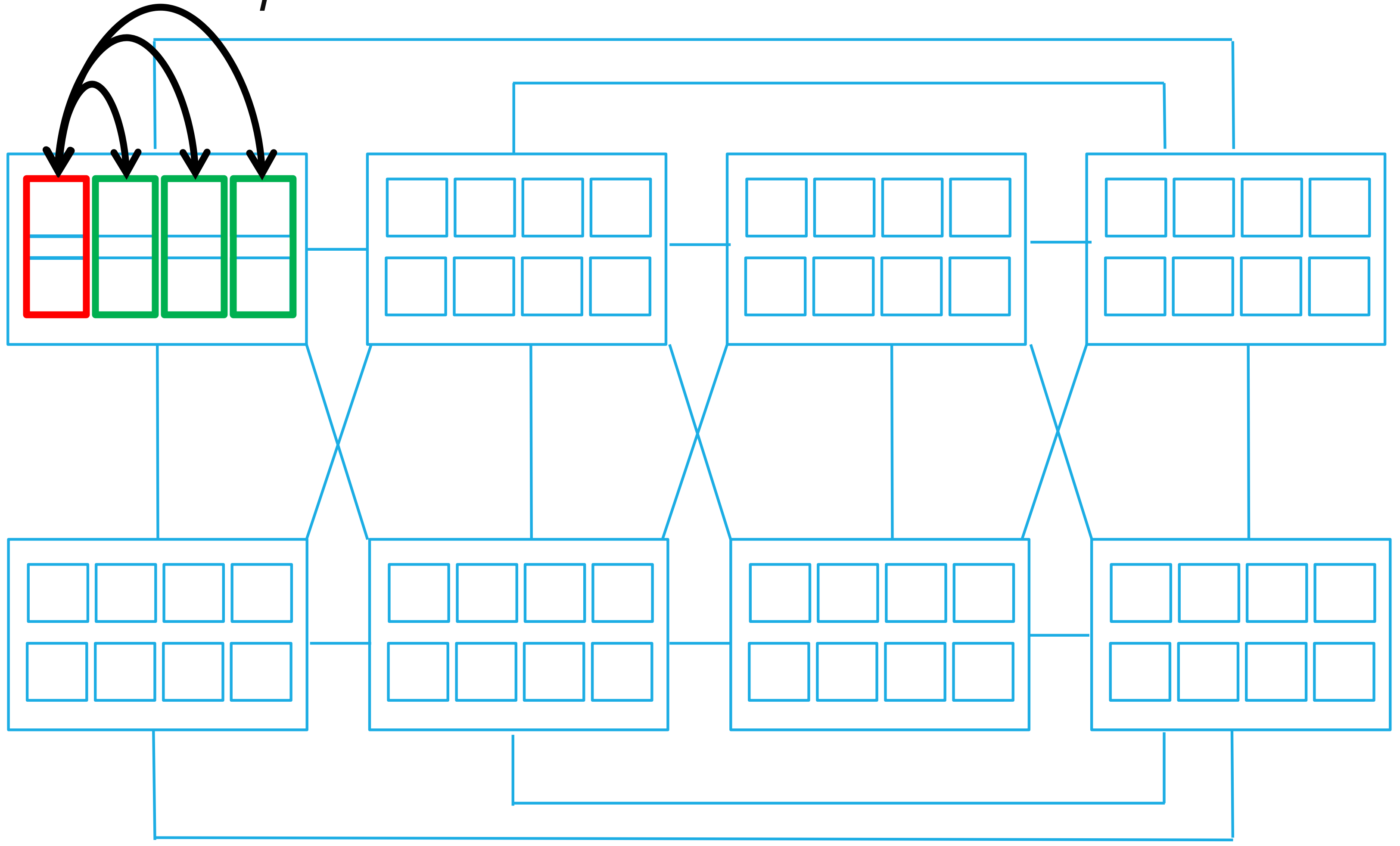


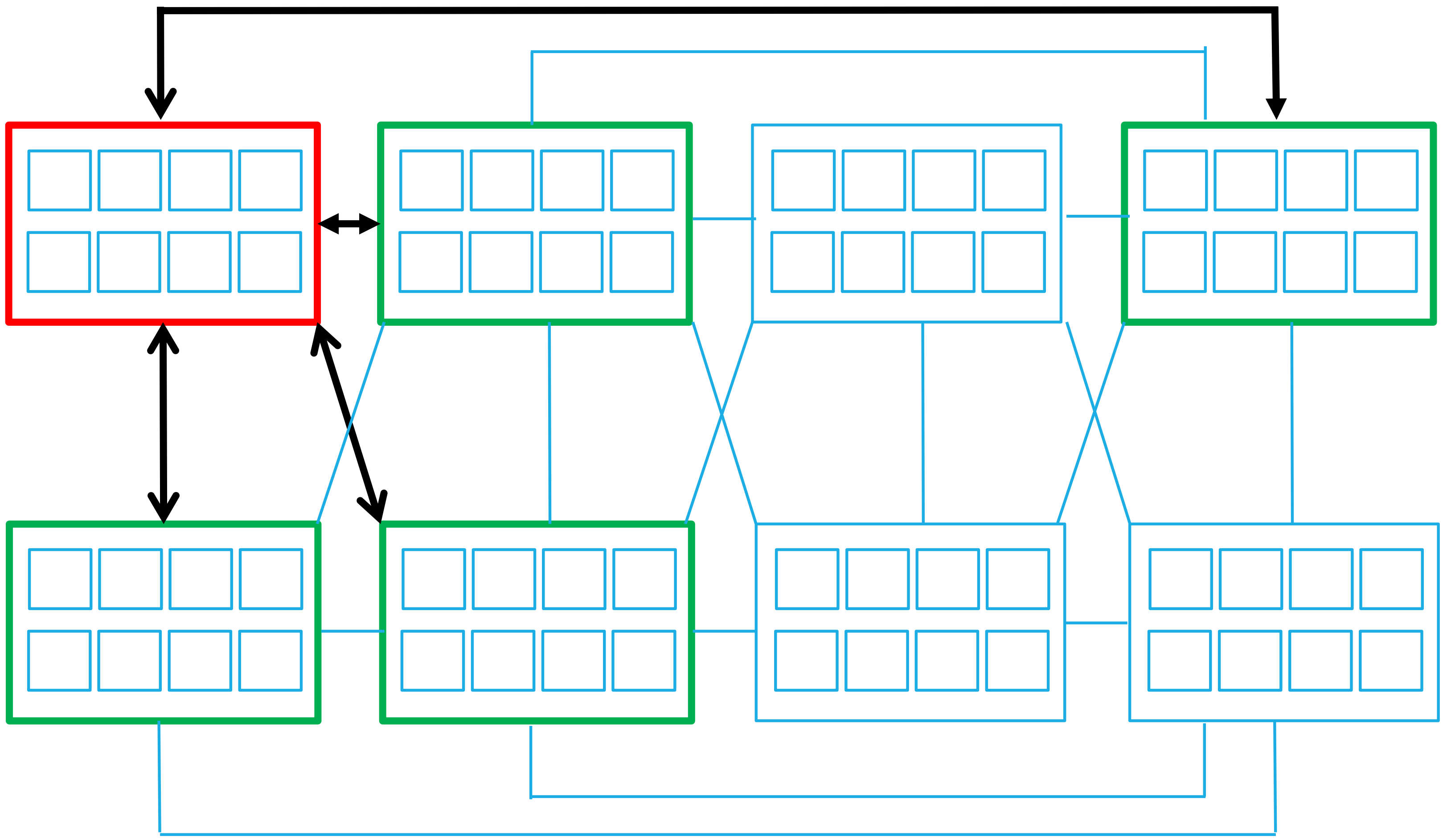
At the **first level**, the **first core** balances load with the other core **on the same pair** (because they share resources, high affinity)

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



At the **2nd level**, the **first pair** balances load with other pairs **on the same CPU**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



At the 3rd level, the **first CPU** balances load with **directly connected CPUS**

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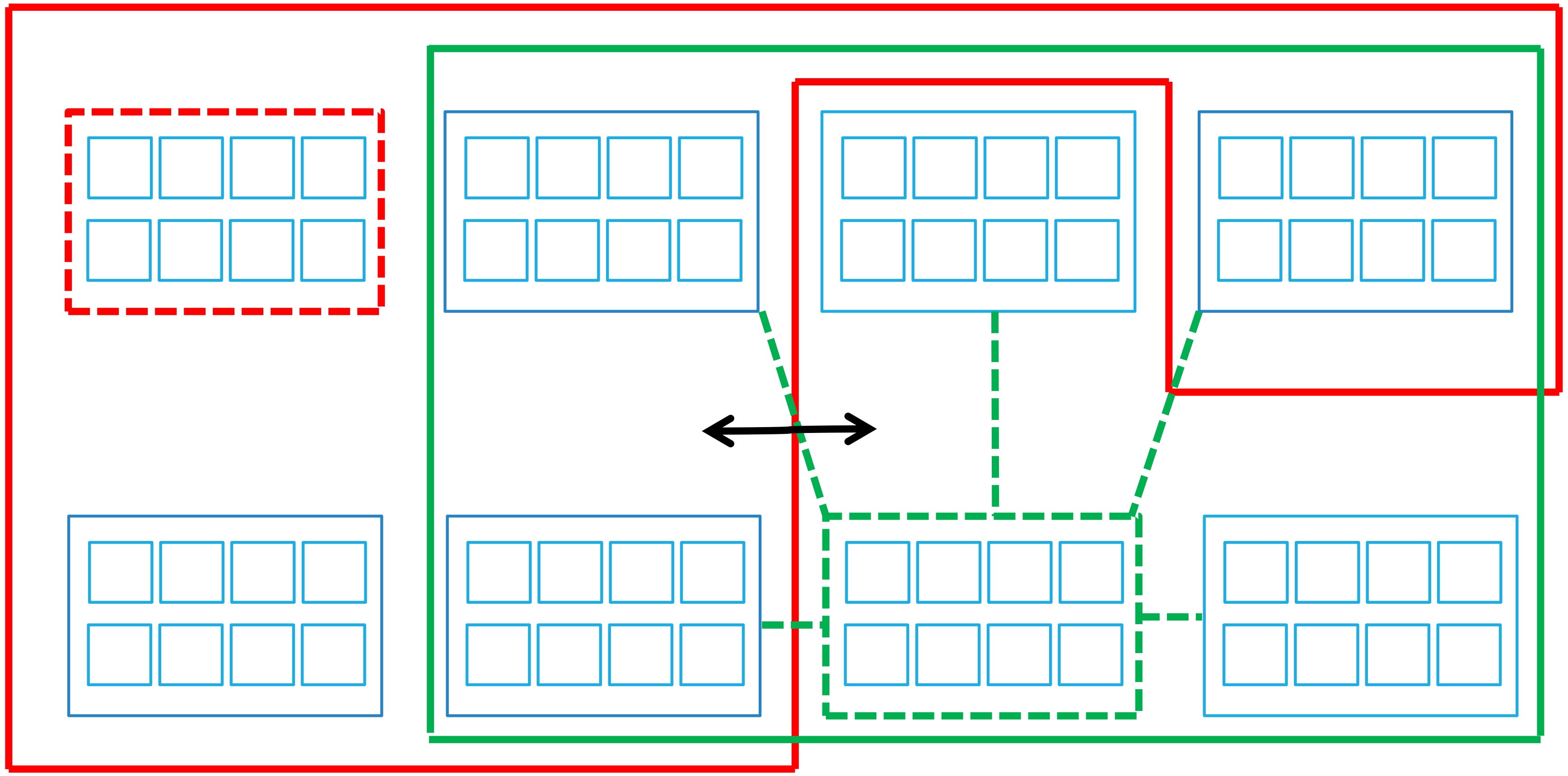
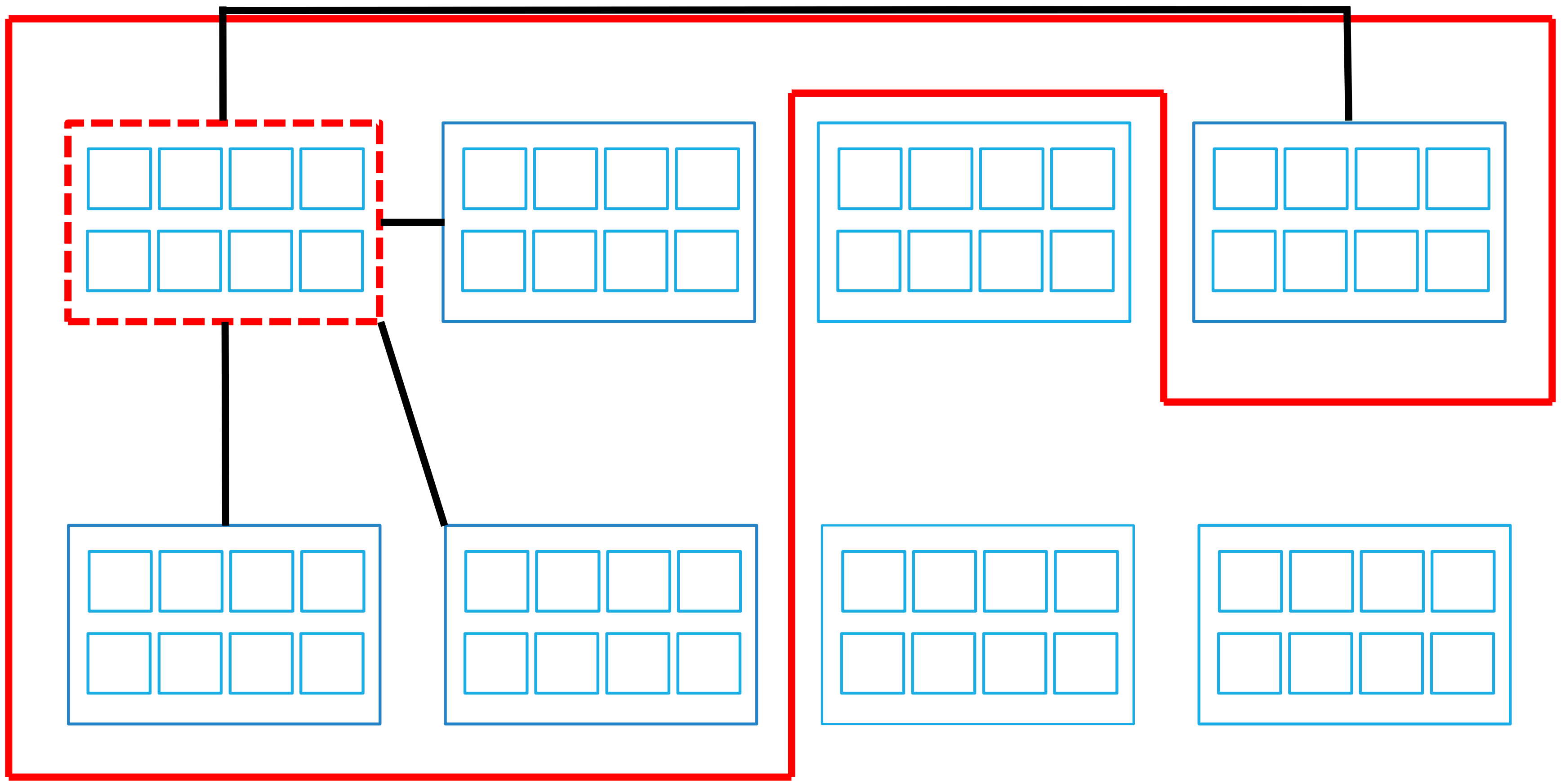


At the **4th level**, the **first group of directly connected CPUs** balances load with **the other groups of directly connected CPUs**

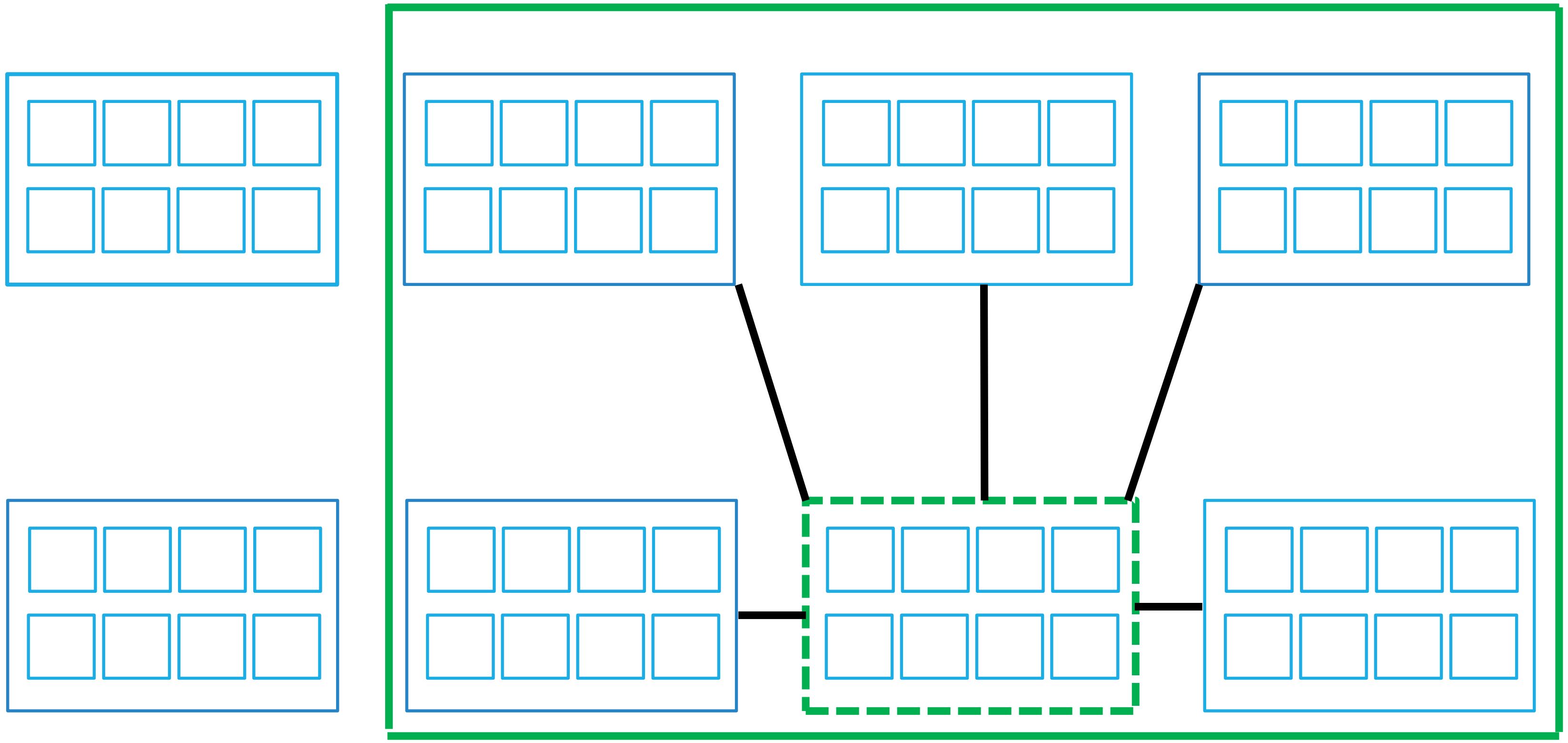
BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Groups of CPUs built by:

(1) picking first CPU and looking for all directly connected CPUs

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Groups of CPUs built by:

(2) picking first CPU not in a group and looking for all directly connected CPUs

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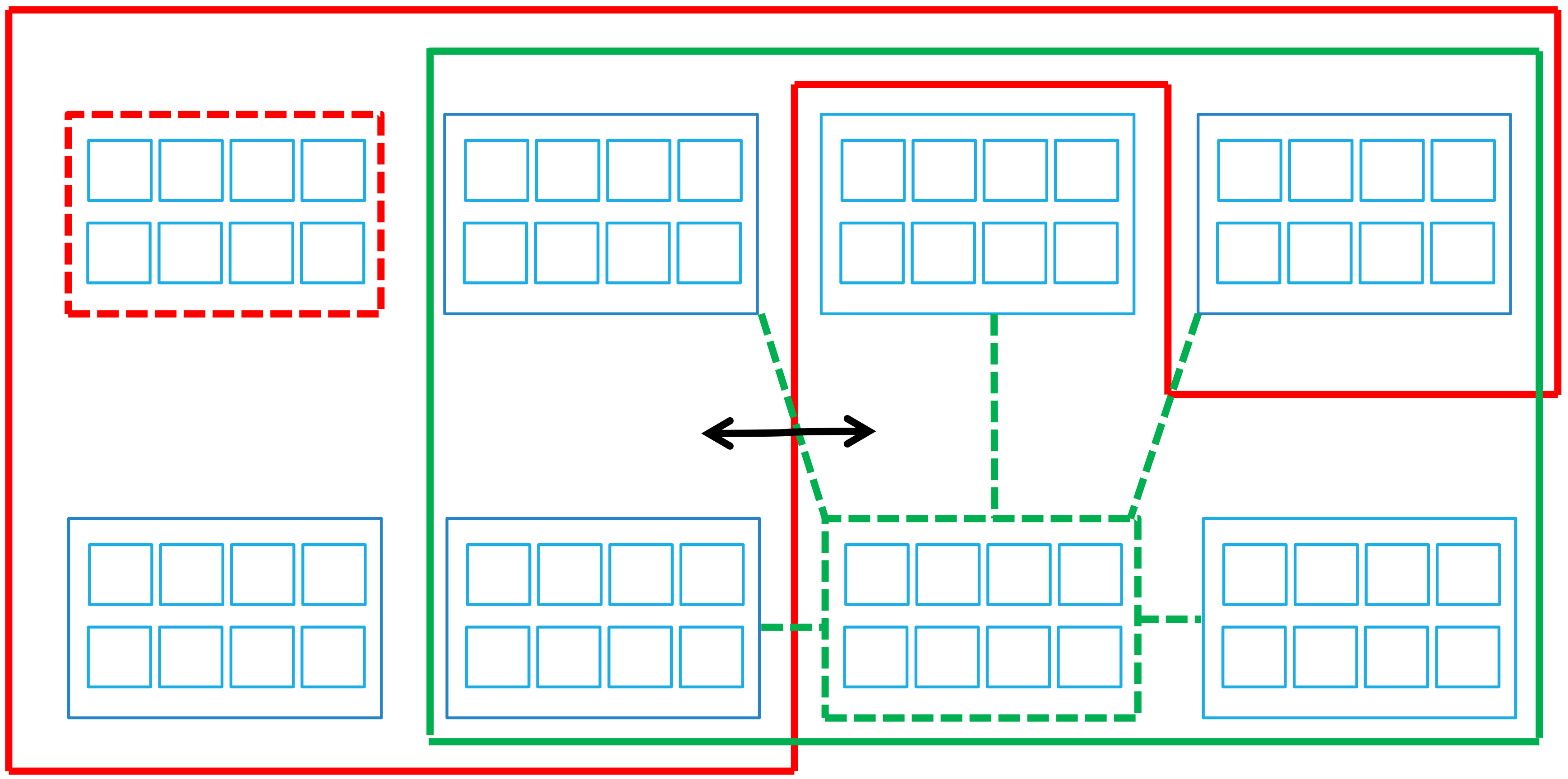
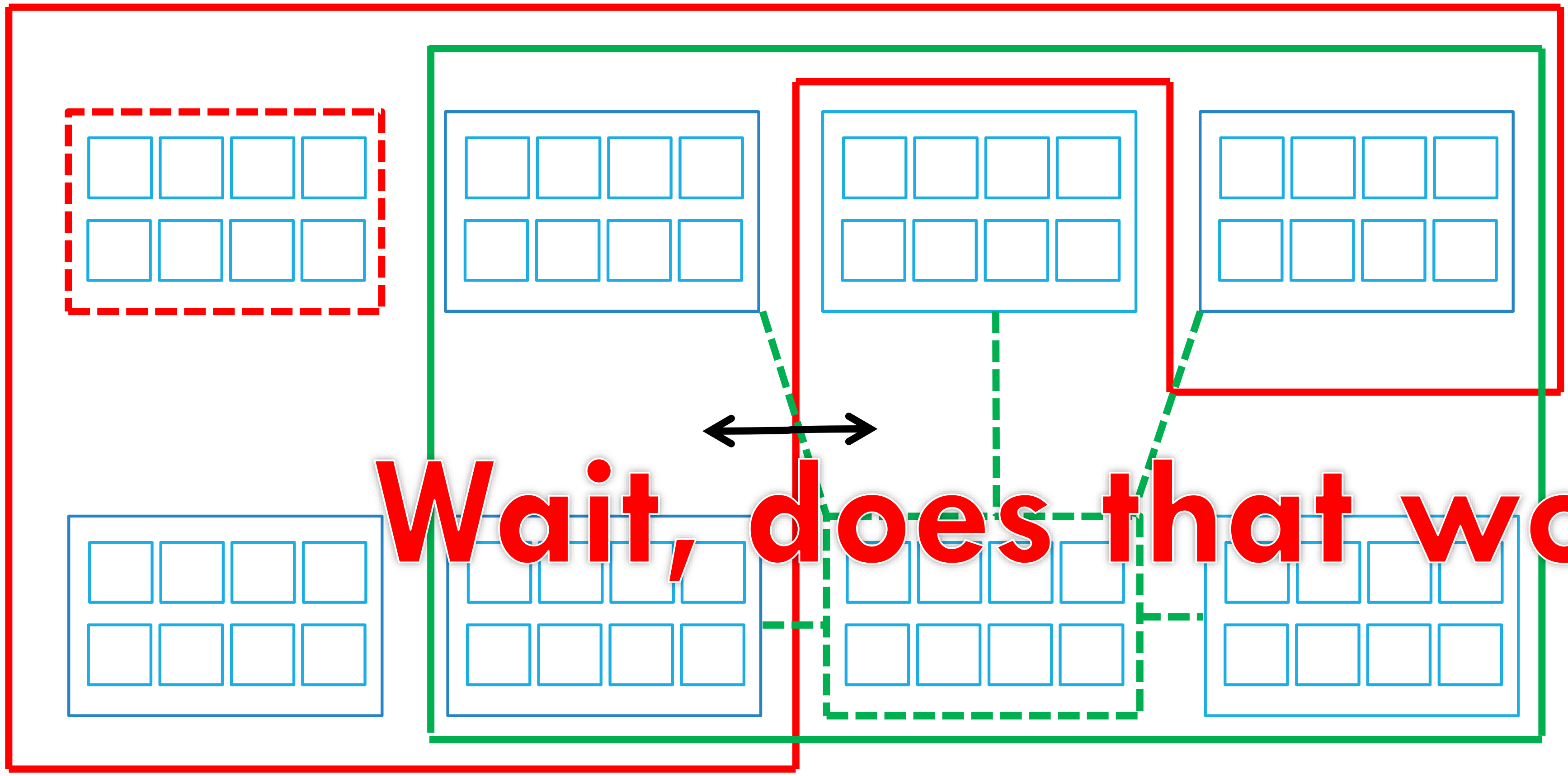


And then stop, **because all CPUs are in a group**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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Wait, does that work?

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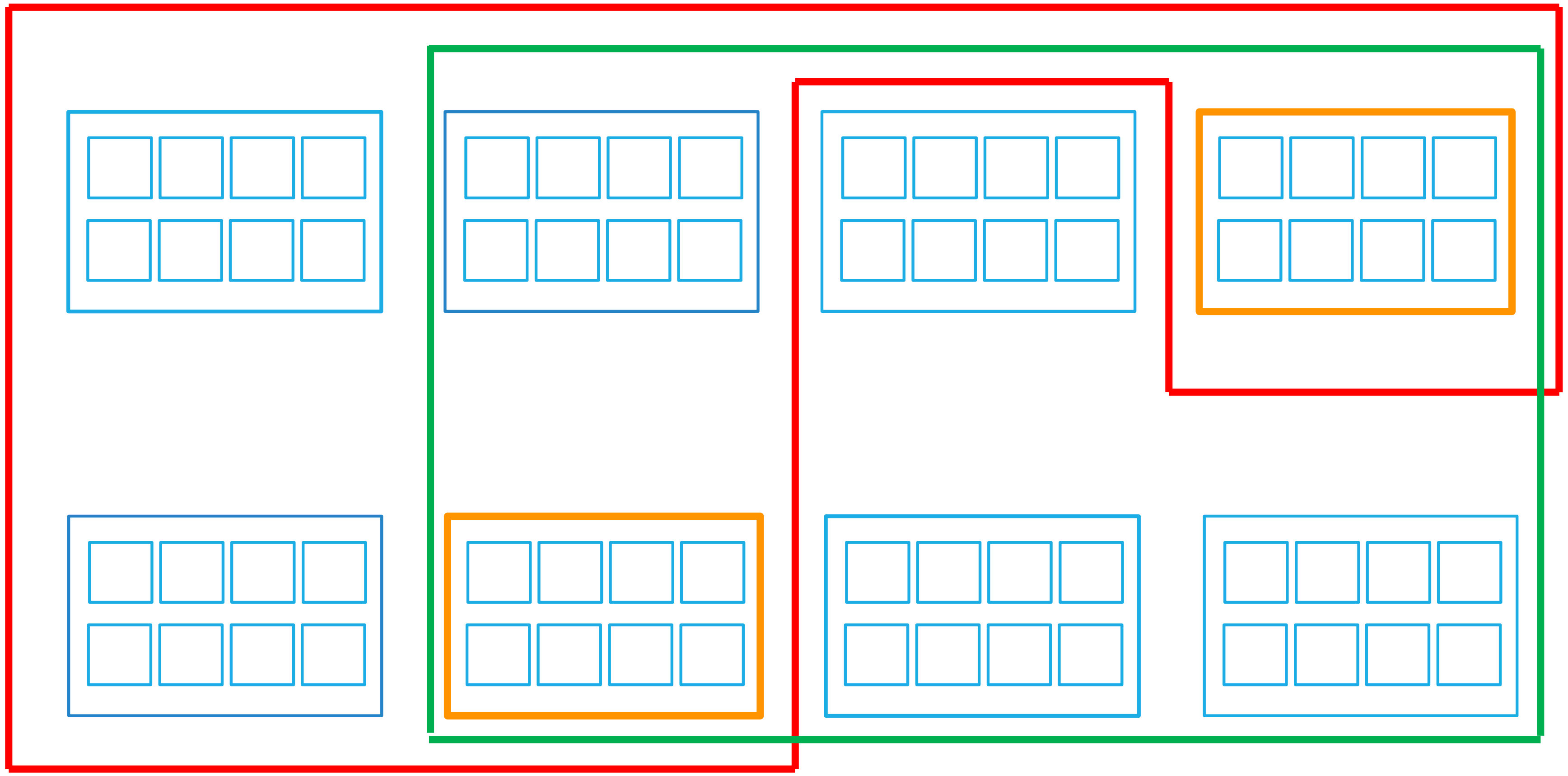
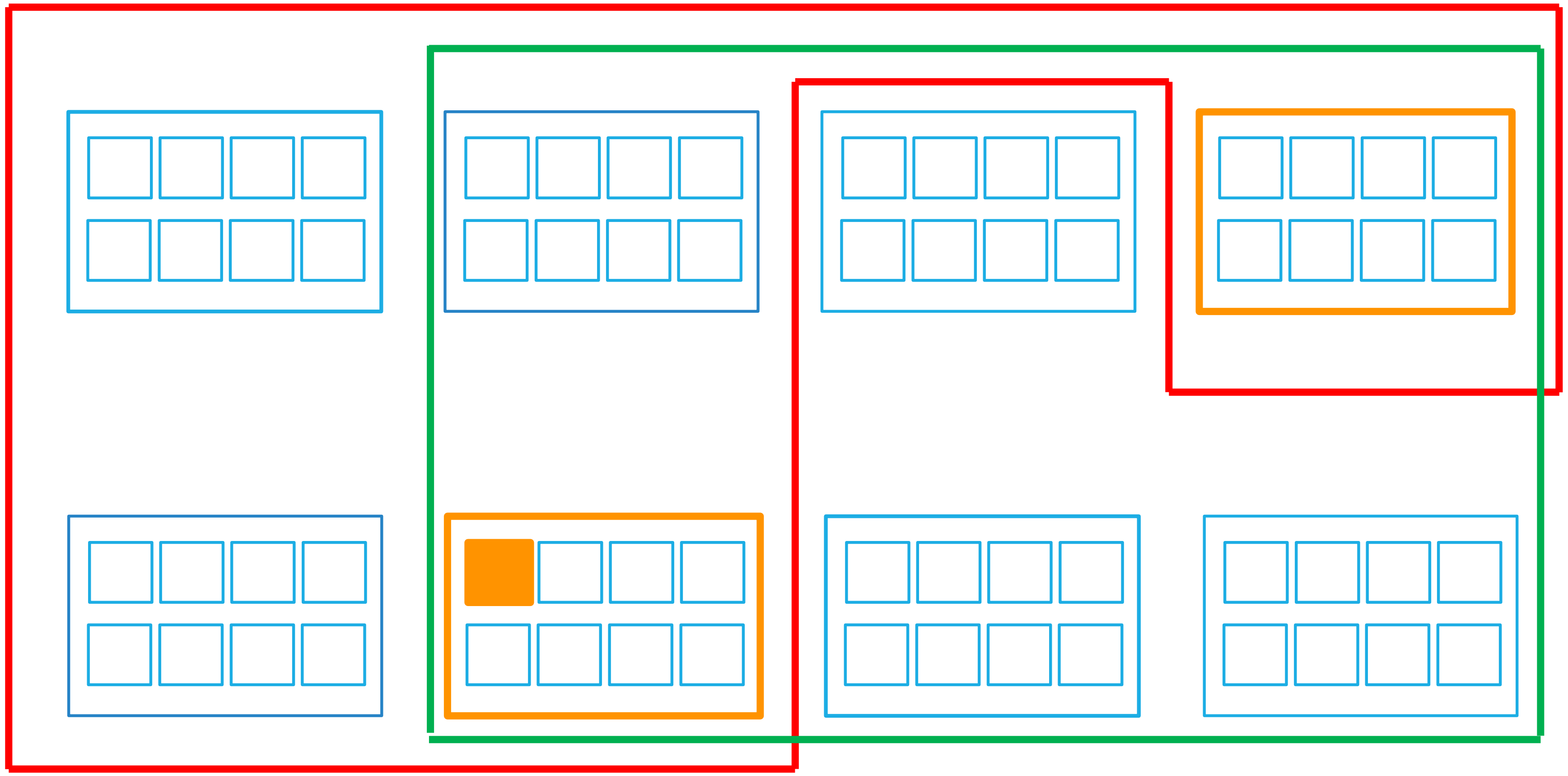


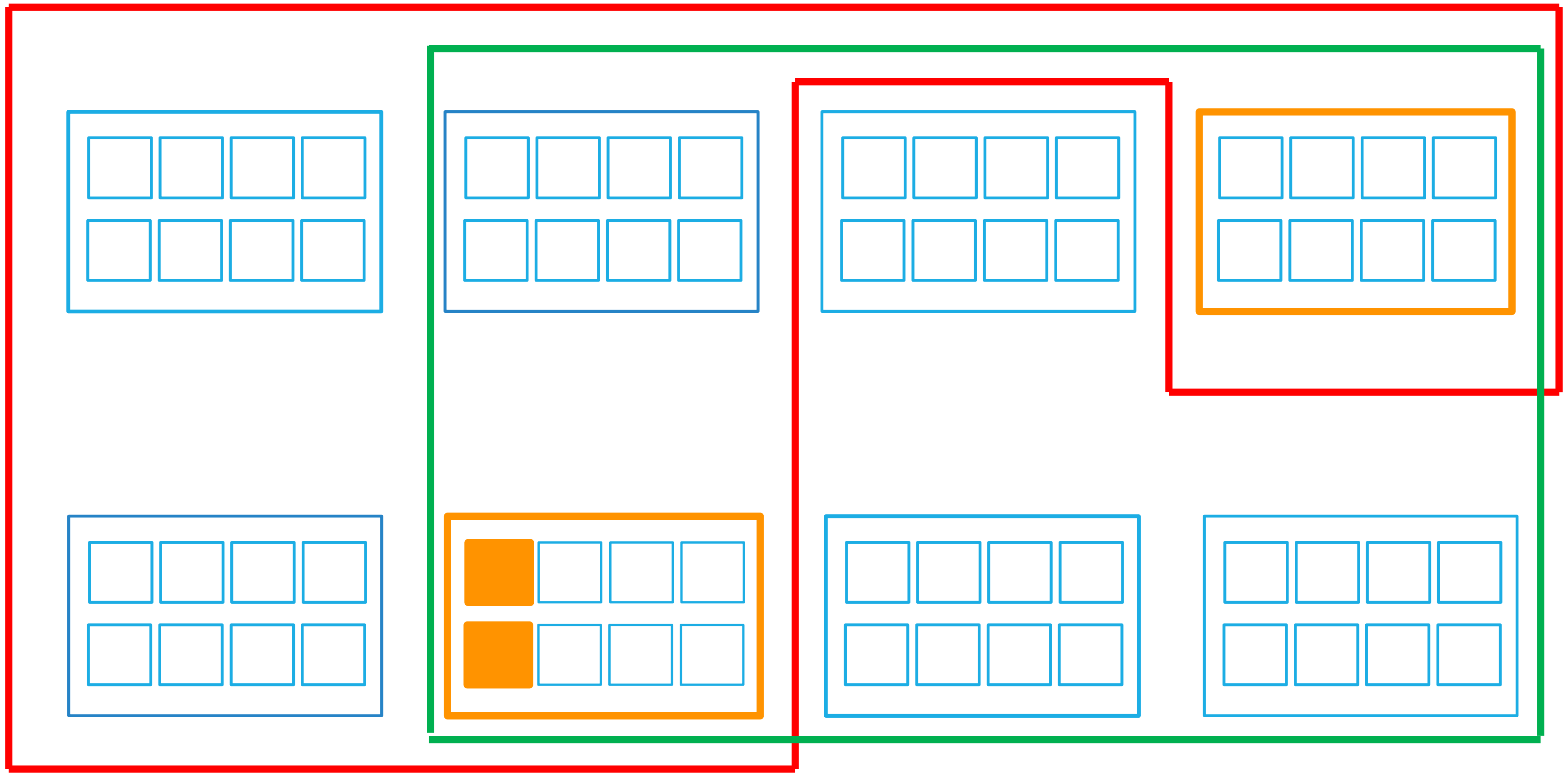
Suppose we taskset an application on **these two nodes,** two hops apart

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



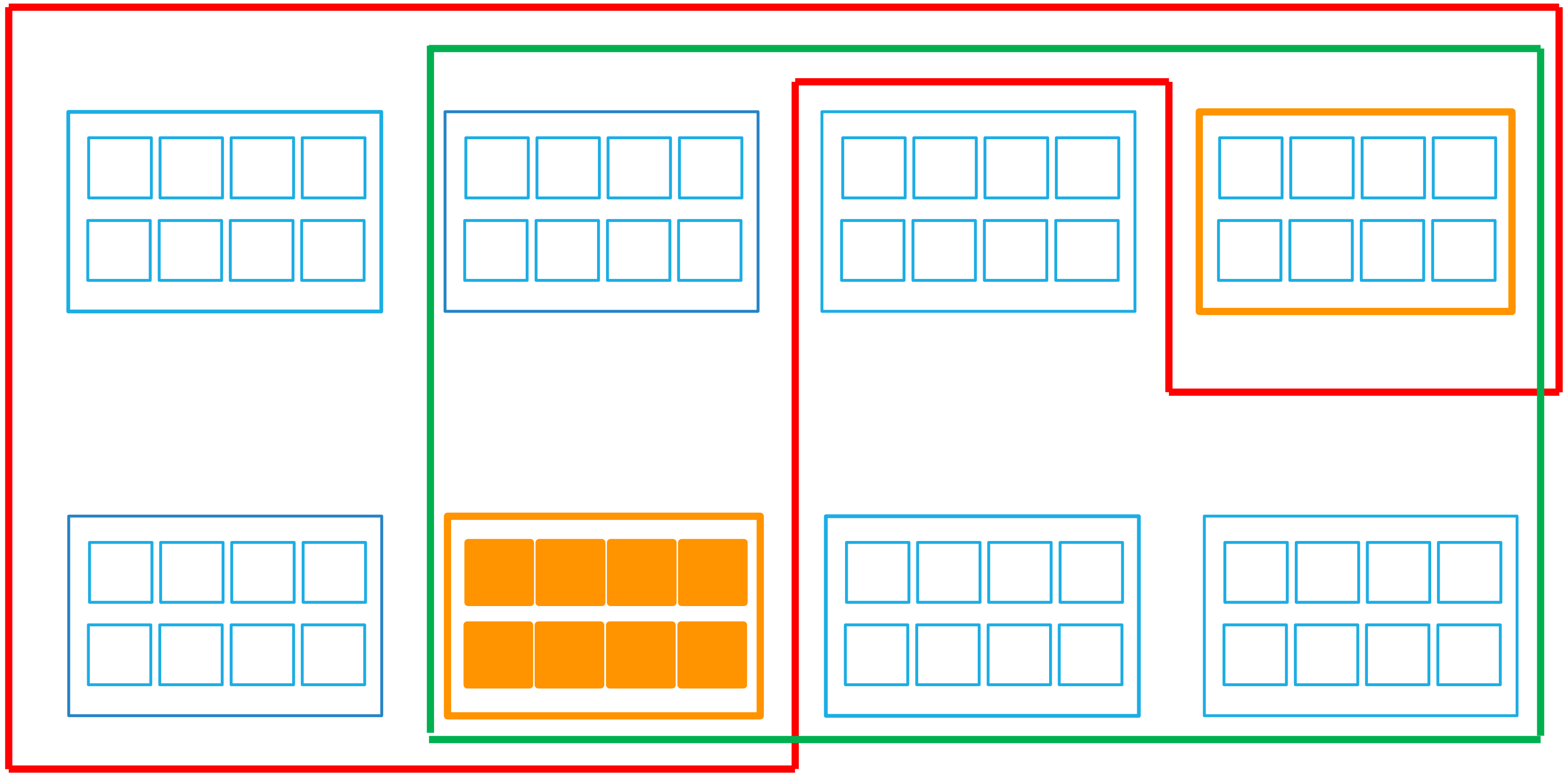
And threads are created **on this core**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Load gets correctly balanced **on the pair of cores**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Load gets correctly balanced **on the CPU** (8 threads)

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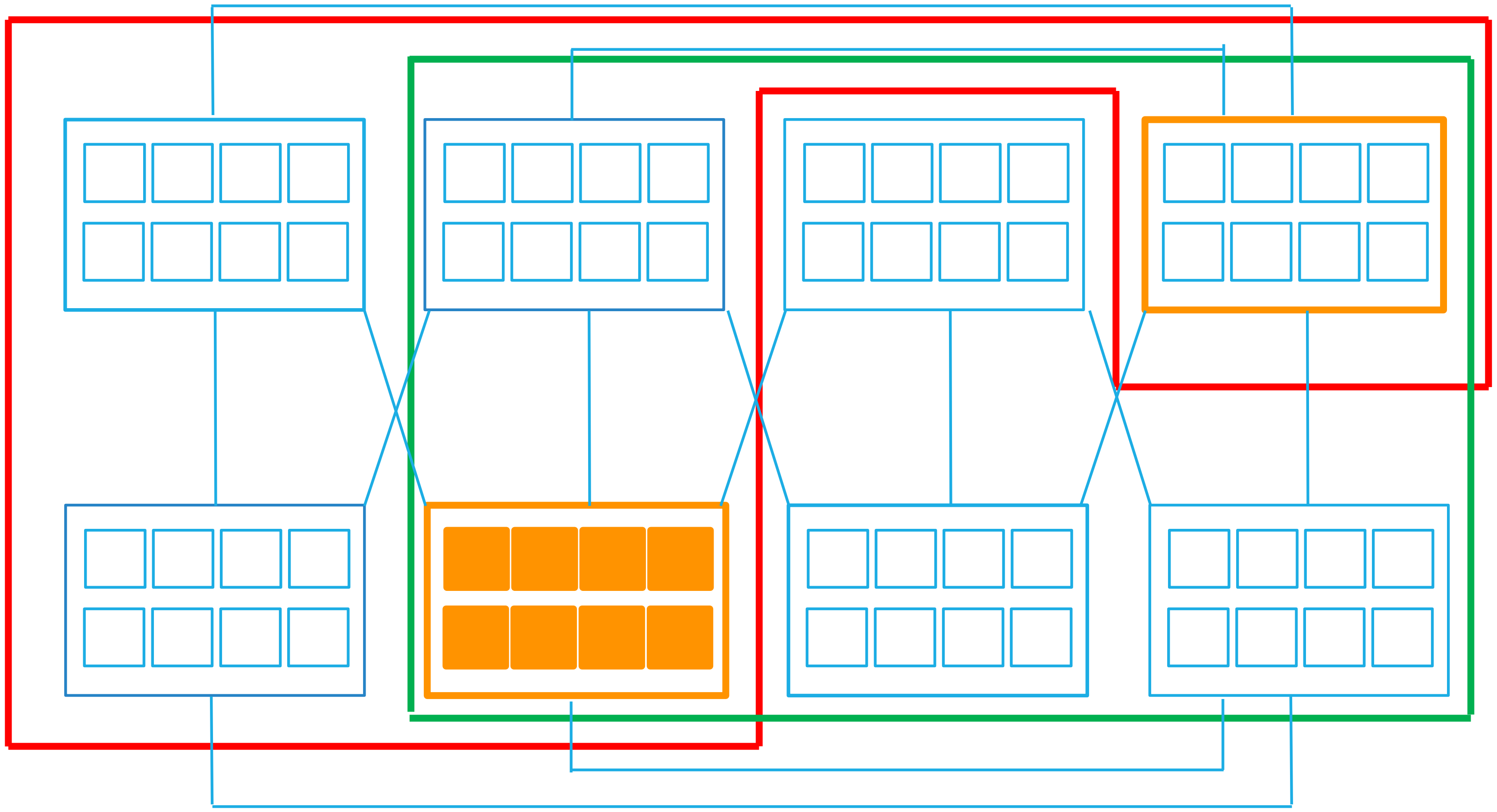

No stealing at level 3, because nodes not directly connected (1 hop apart)

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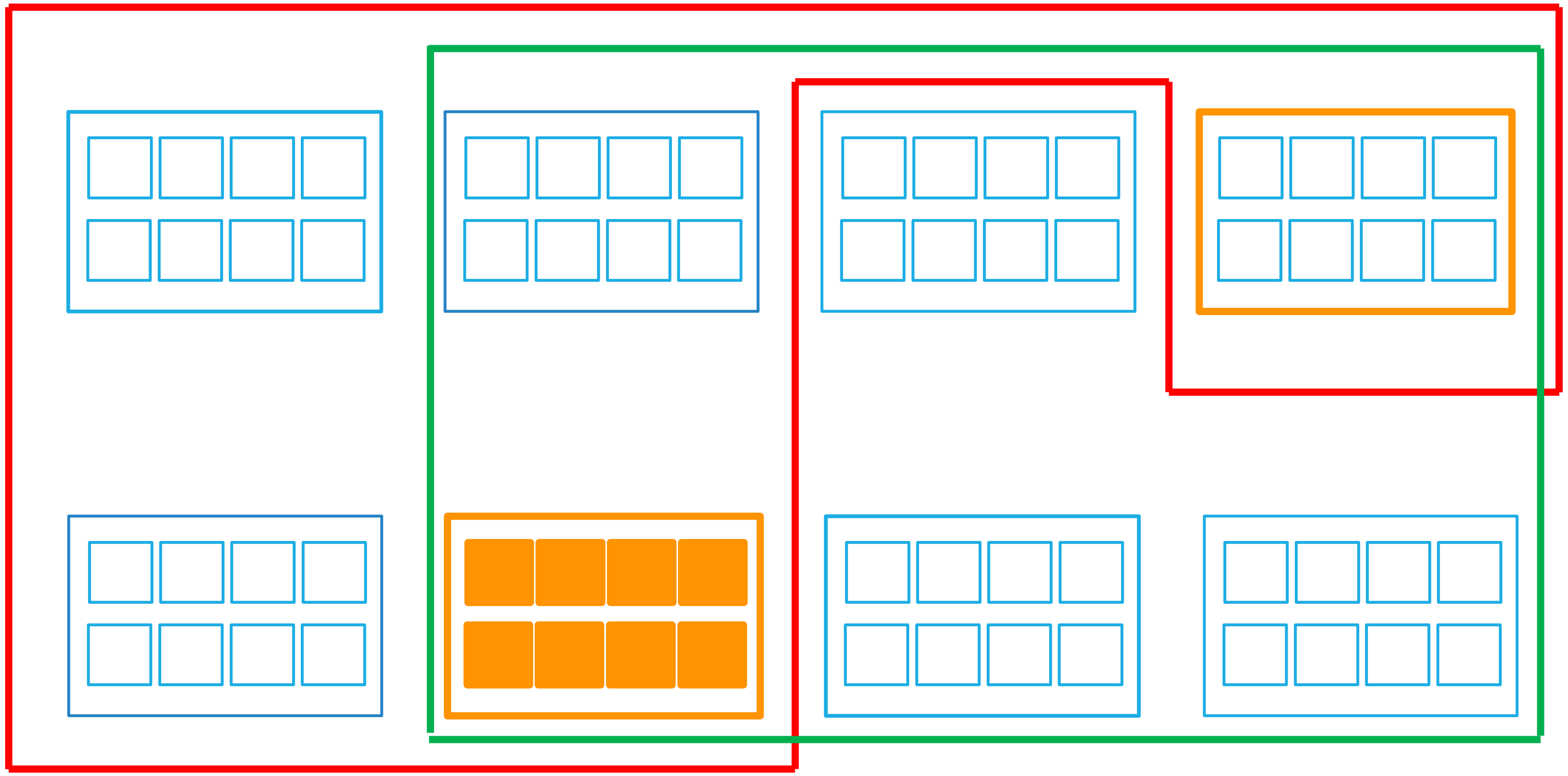

At level 4, stealing between the red and green groups…

Overloaded node in both groups!

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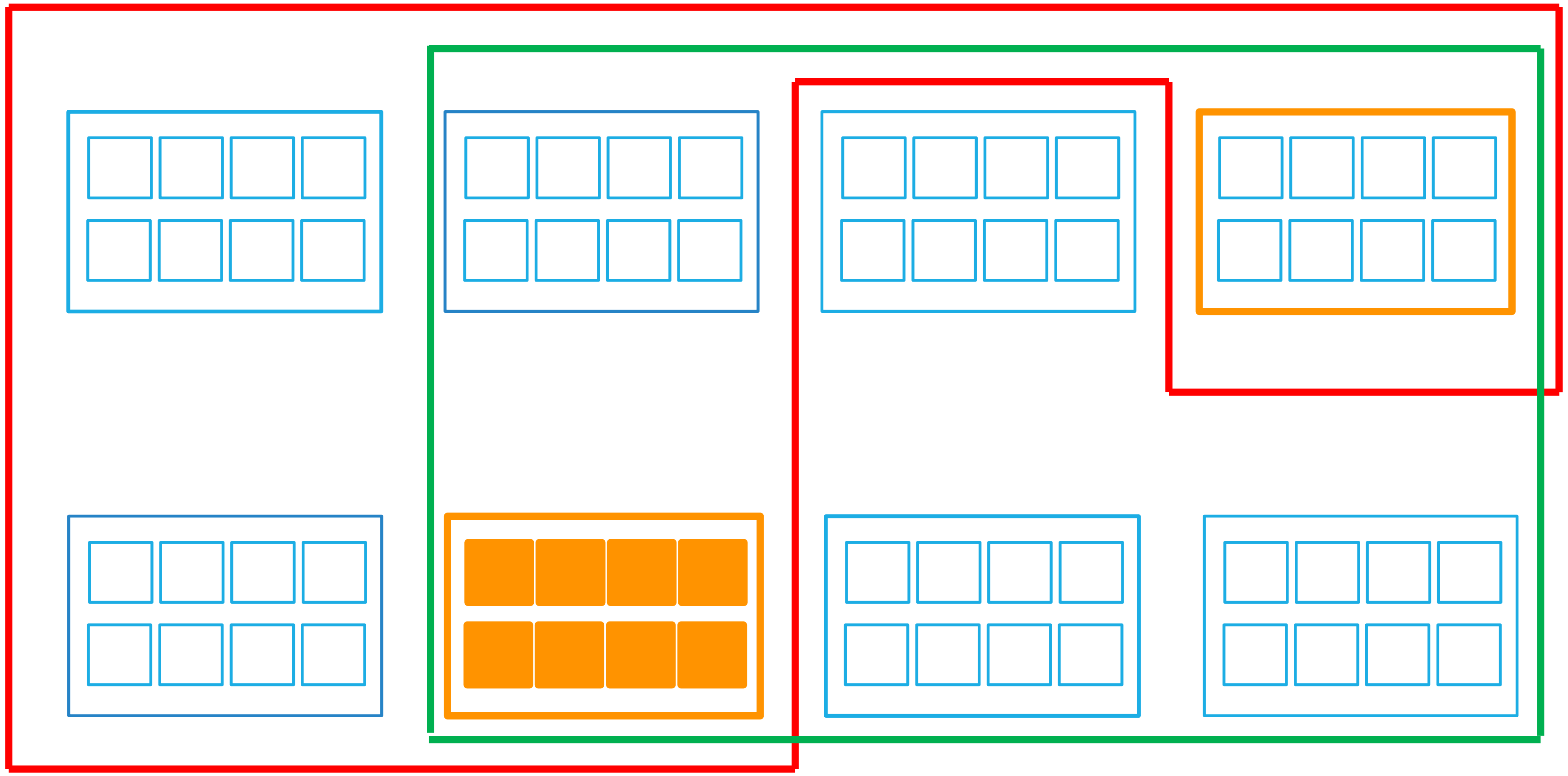

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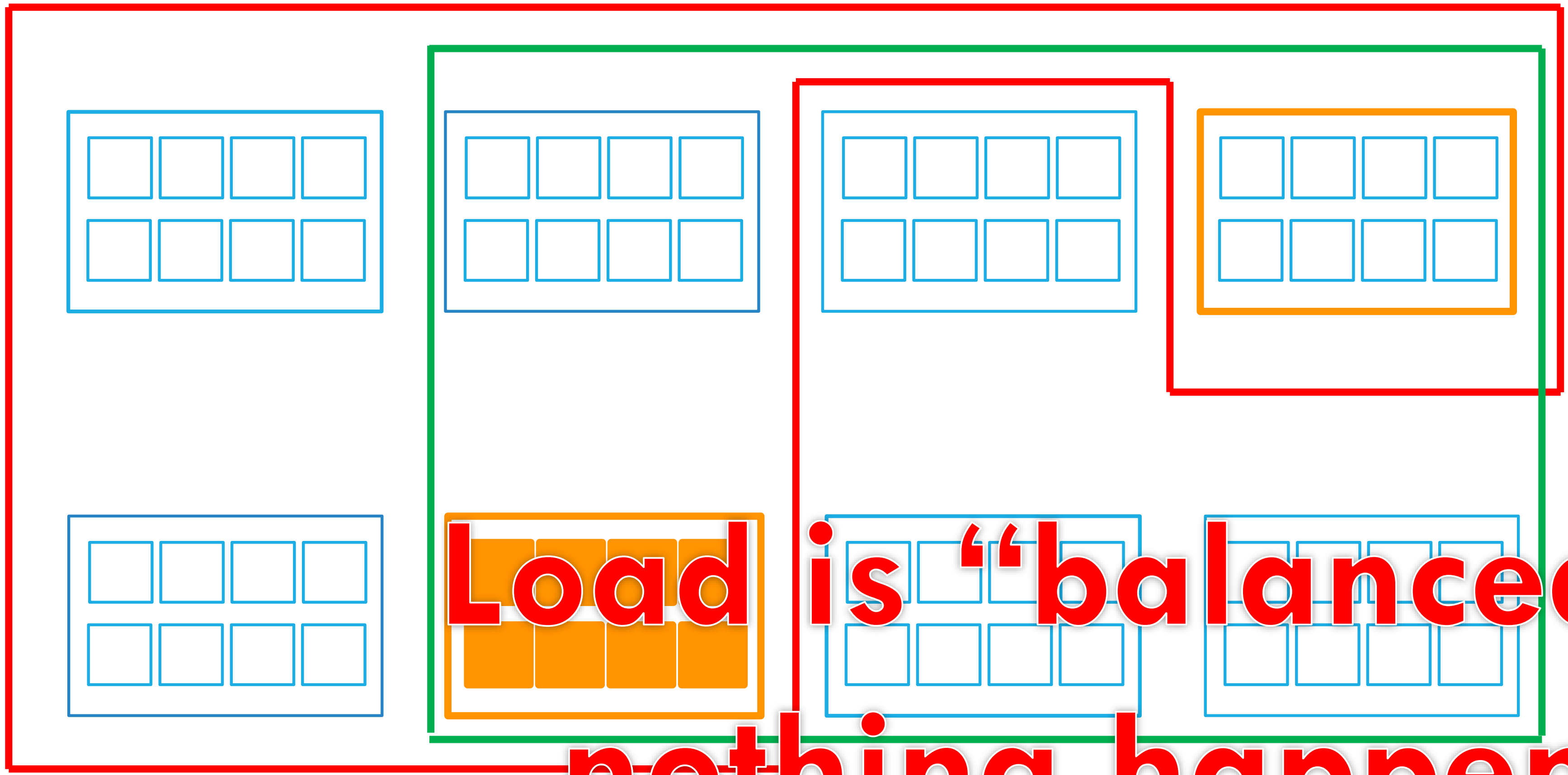

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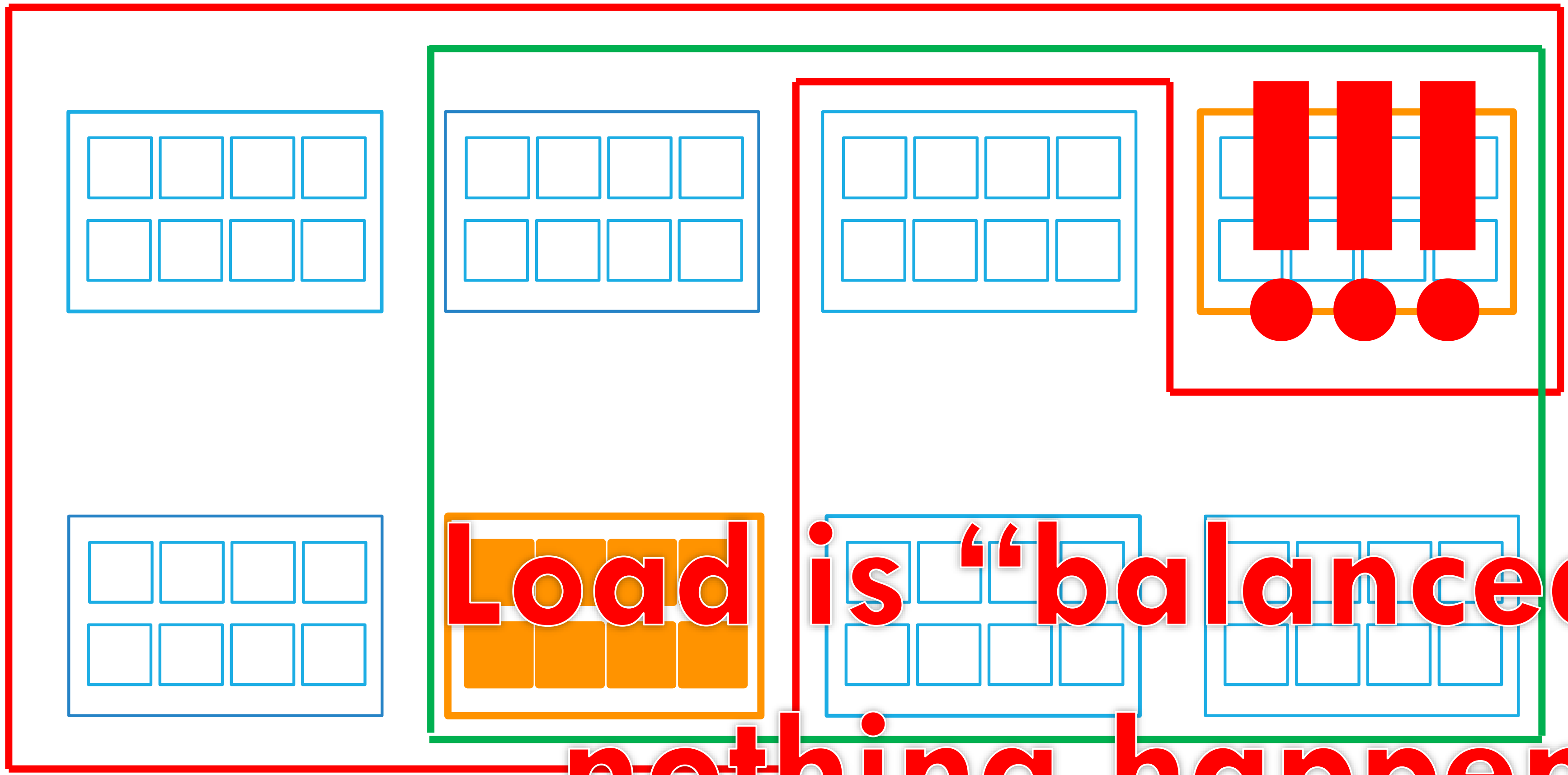

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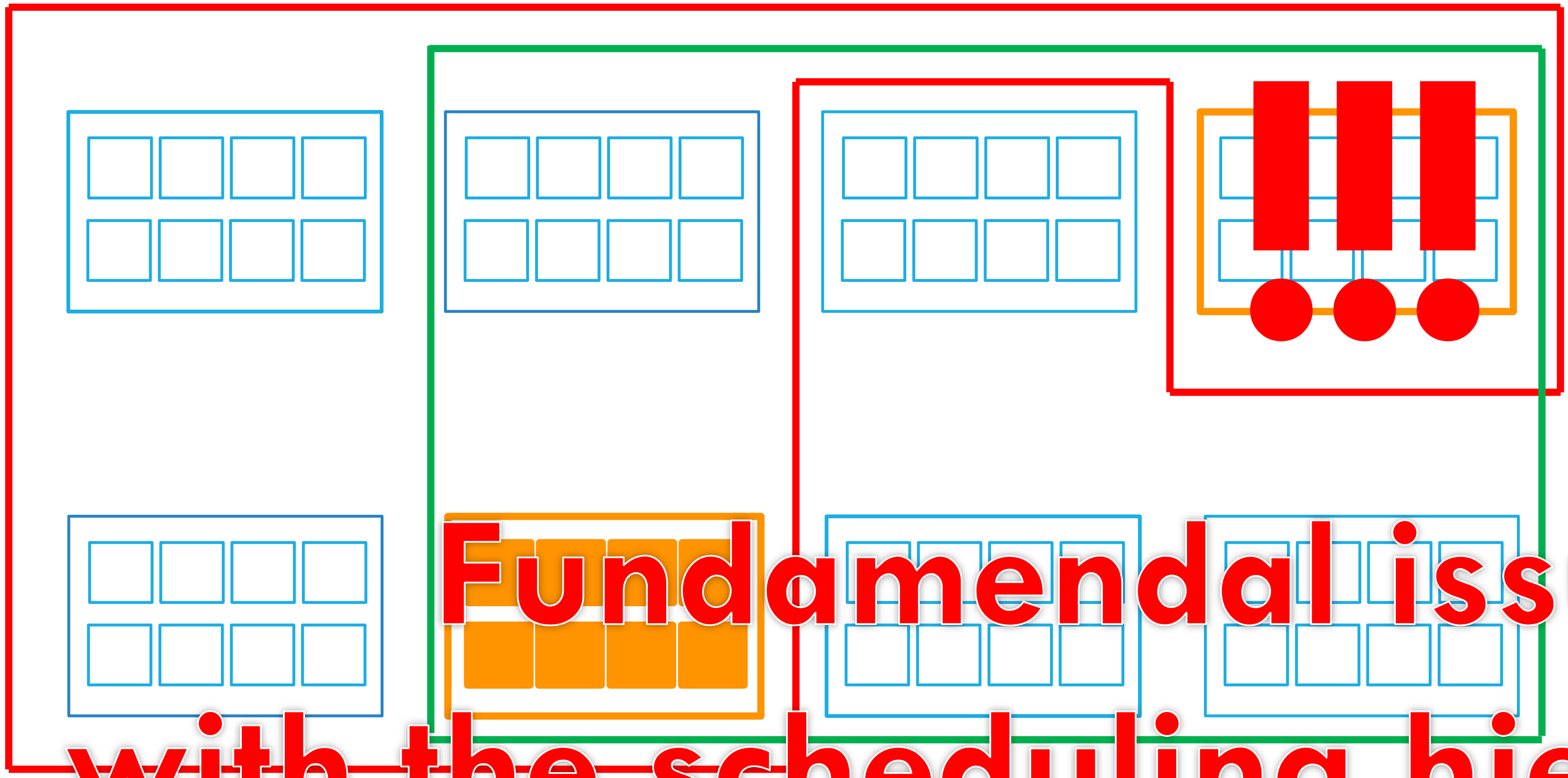

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Fundamendal issue
with the scheduling hierarchy !

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- **Very good improvement for LU because more threads than cores if can’t use 16 cores**
  - Solves spinlock issues (incl. potential convoys)

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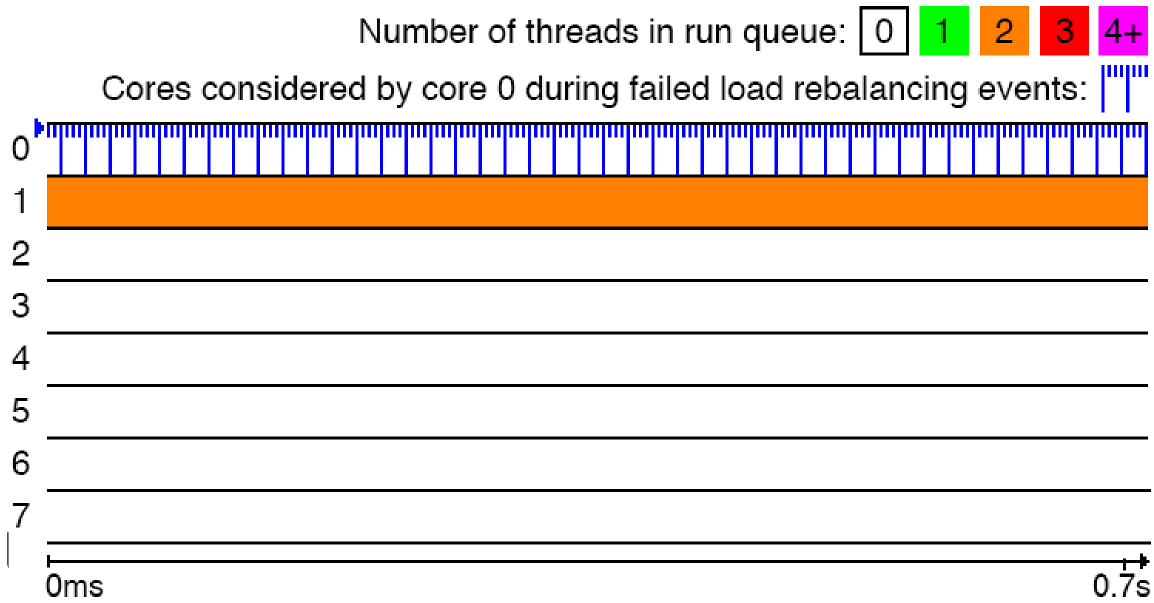

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CG	134	5.4	25x
EP	72	18	4x
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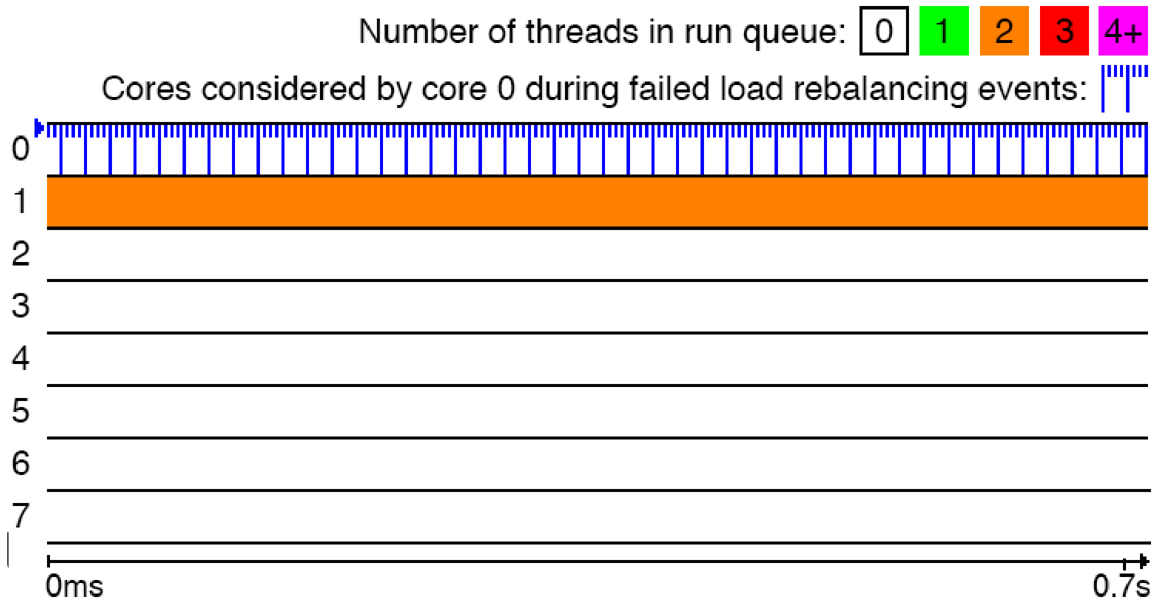

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Wait, does that work?

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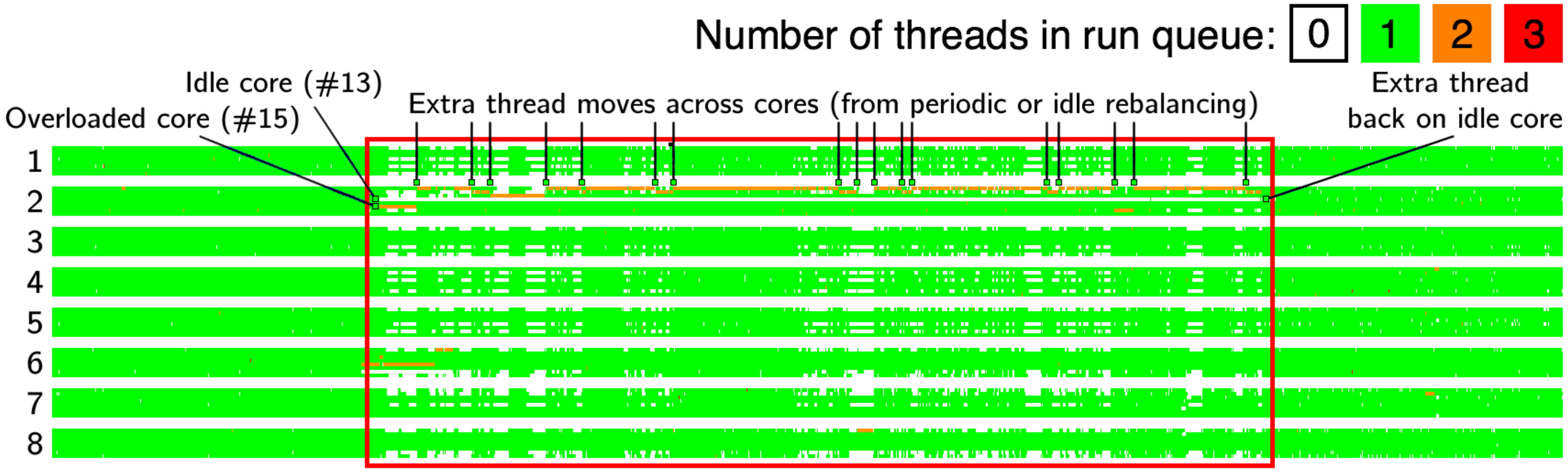

Slowed down execution

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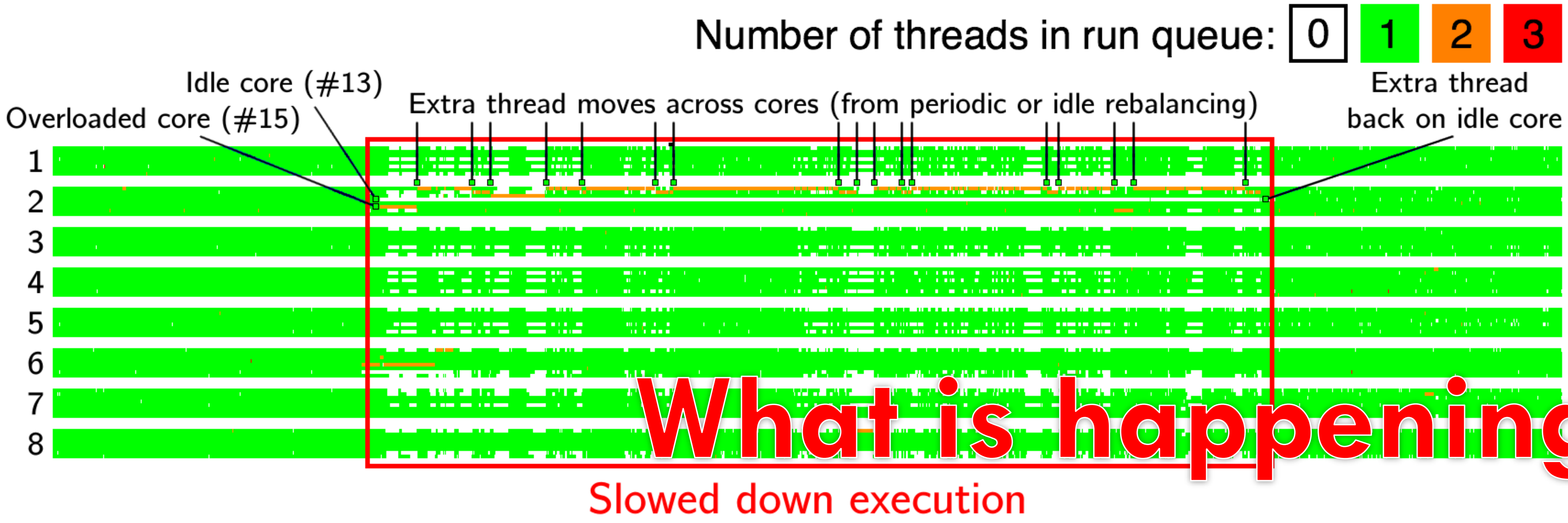
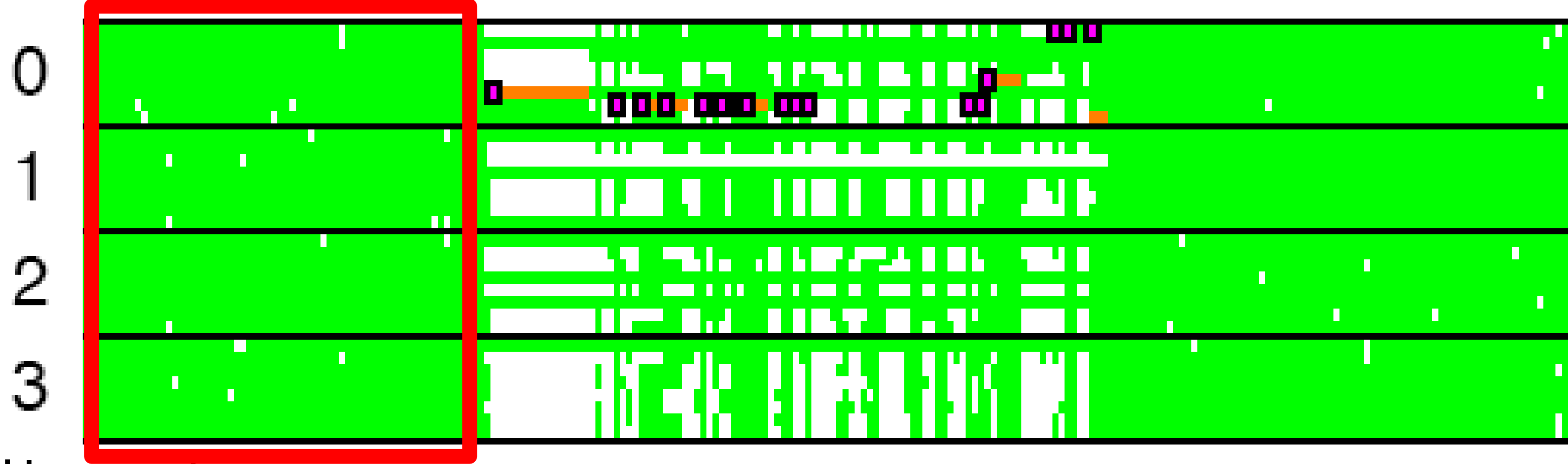


What is happening?

BUG 4/4



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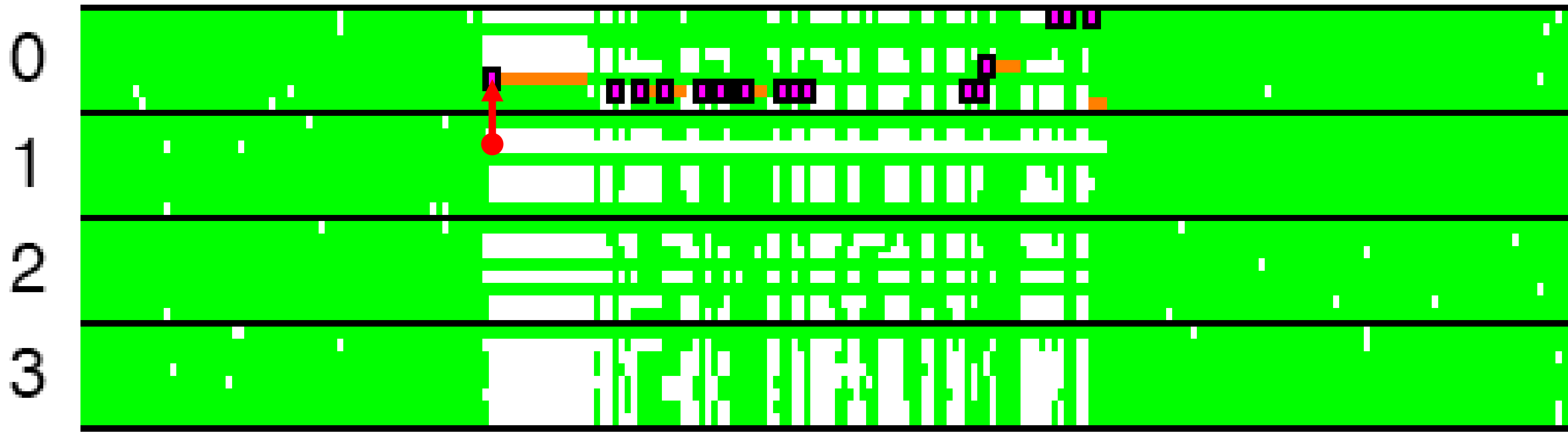

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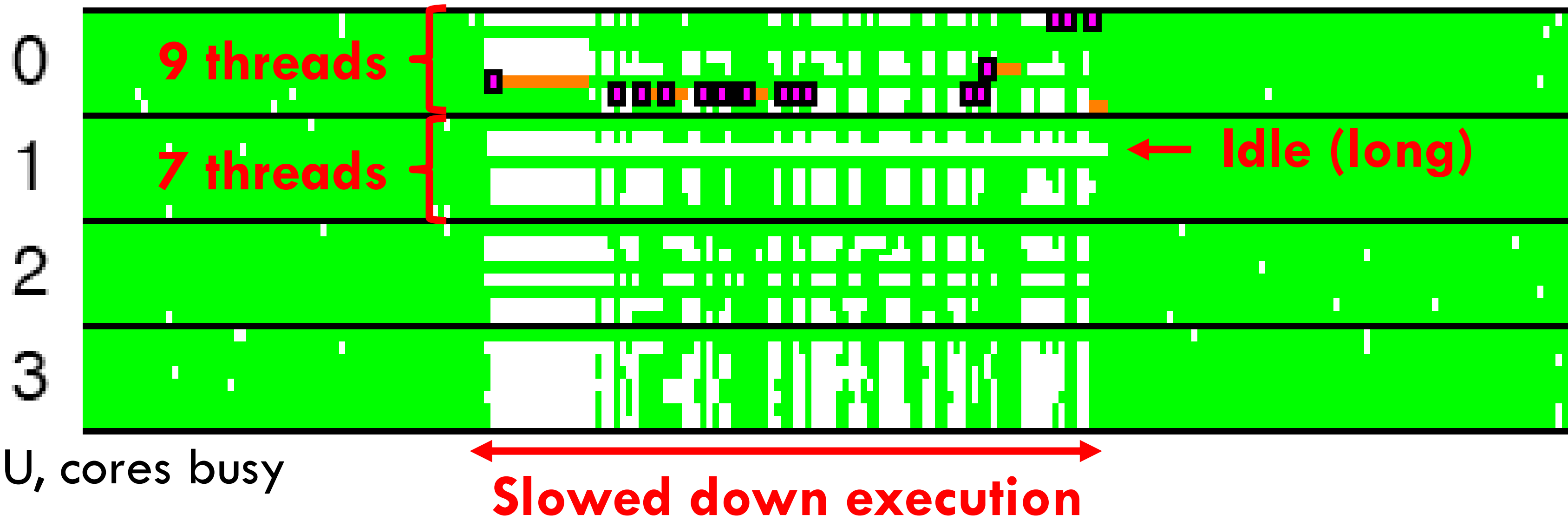

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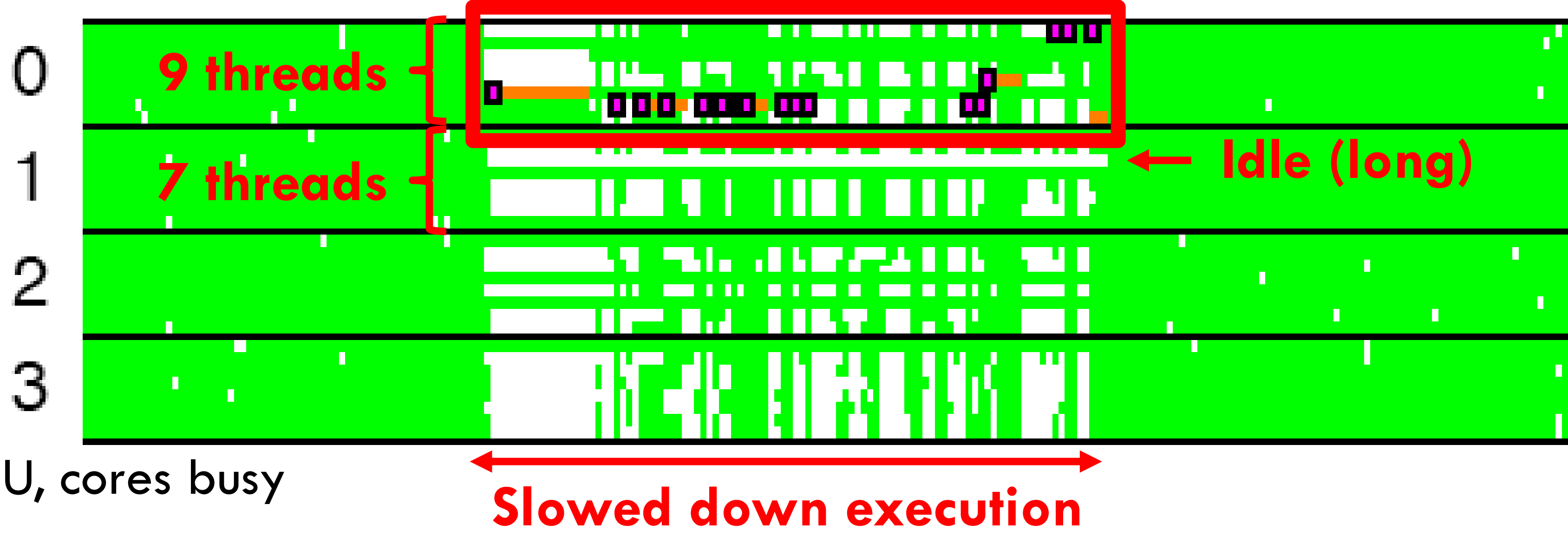

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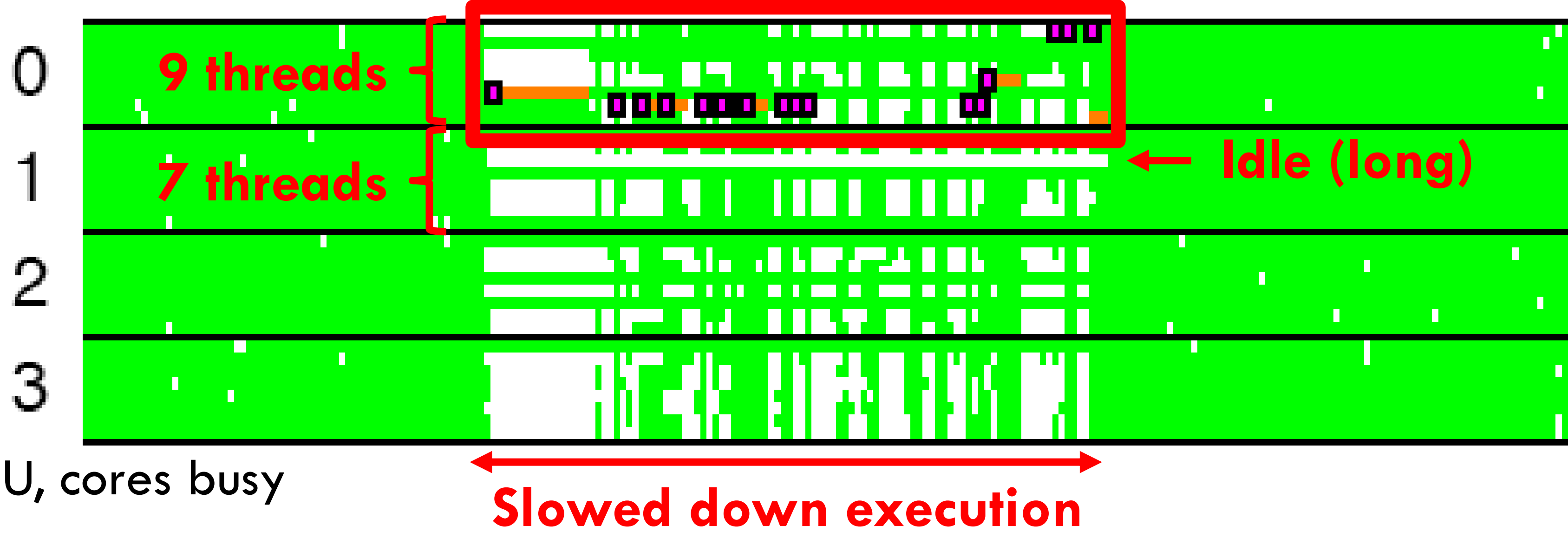

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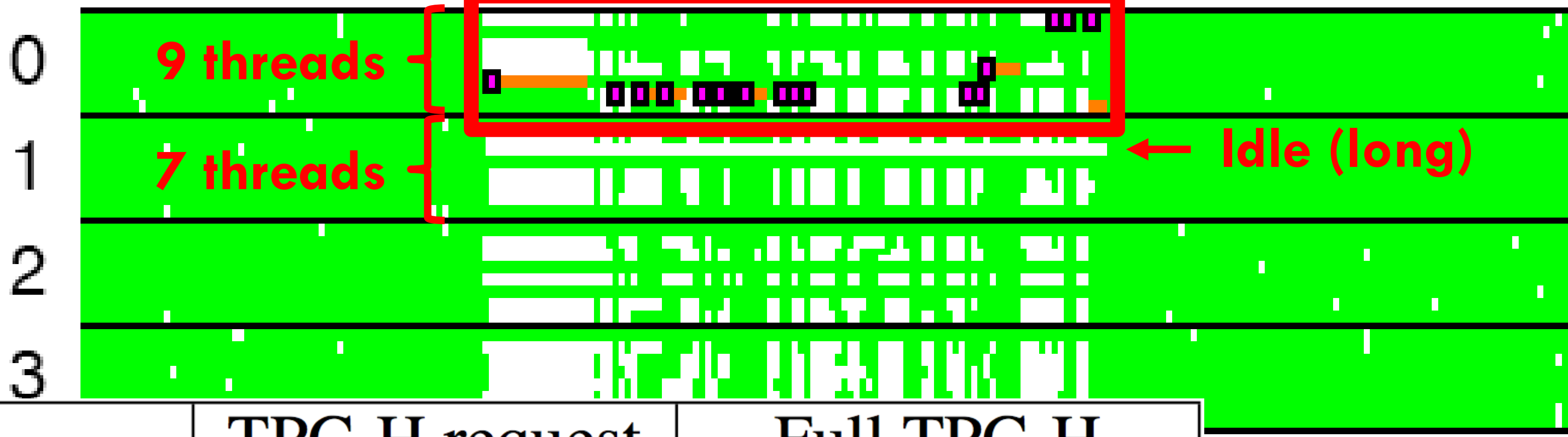

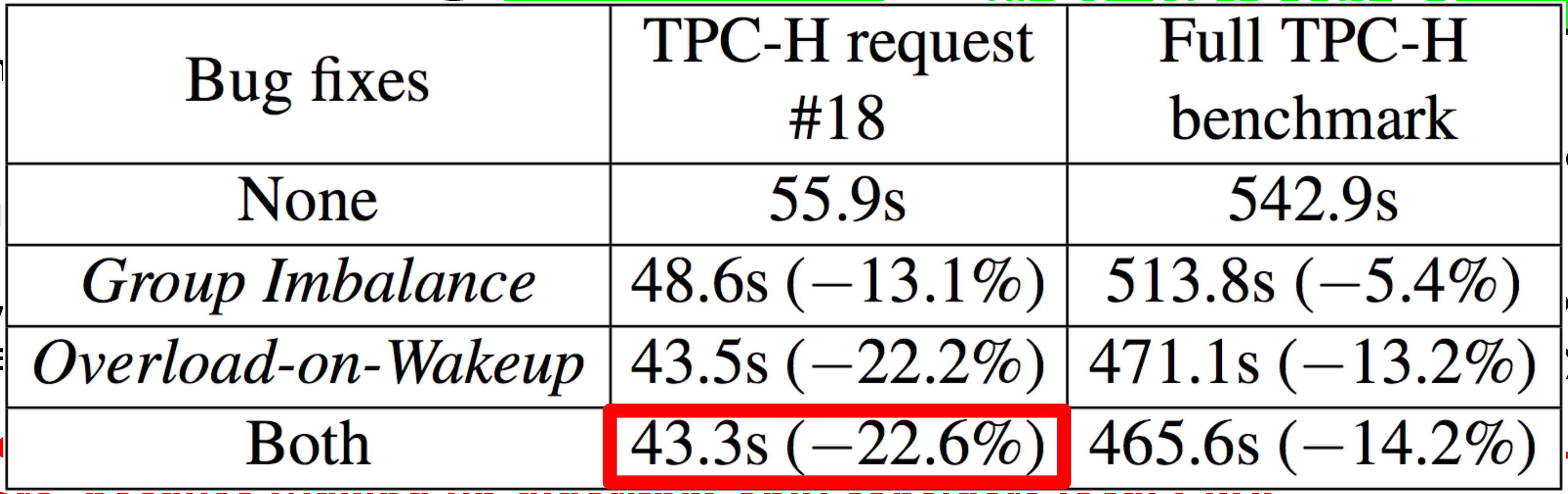

Bug fixes	TPC-H request #18	Full TPC-H benchmark
None	55.9s	542.9s
Group Imbalance	48.6s (−13.1%)	513.8s (−5.4%)
Overload-on-Wakeup	43.5s (−22.2%)	471.1s (−13.2%)
Both	43.3s (−22.6%)	465.6s (−14.2%)

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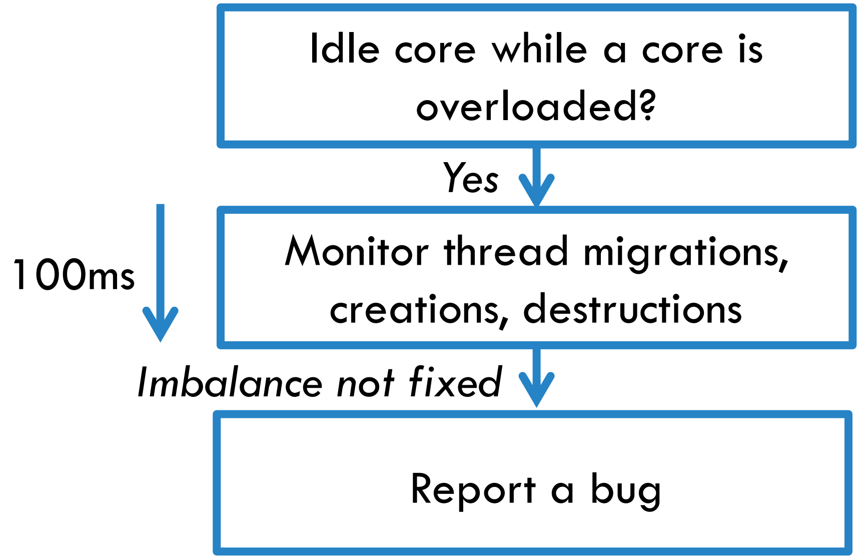
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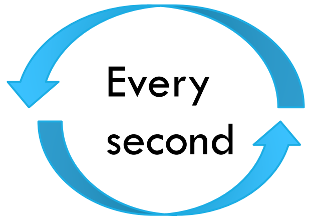

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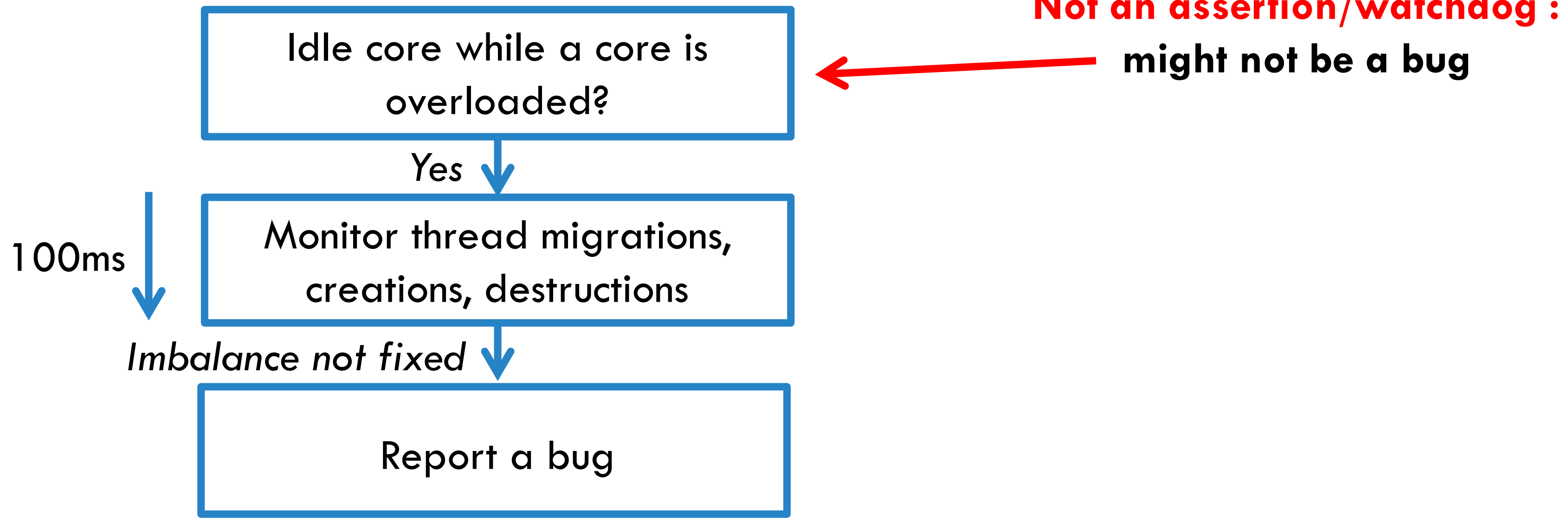
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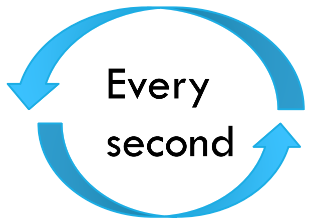

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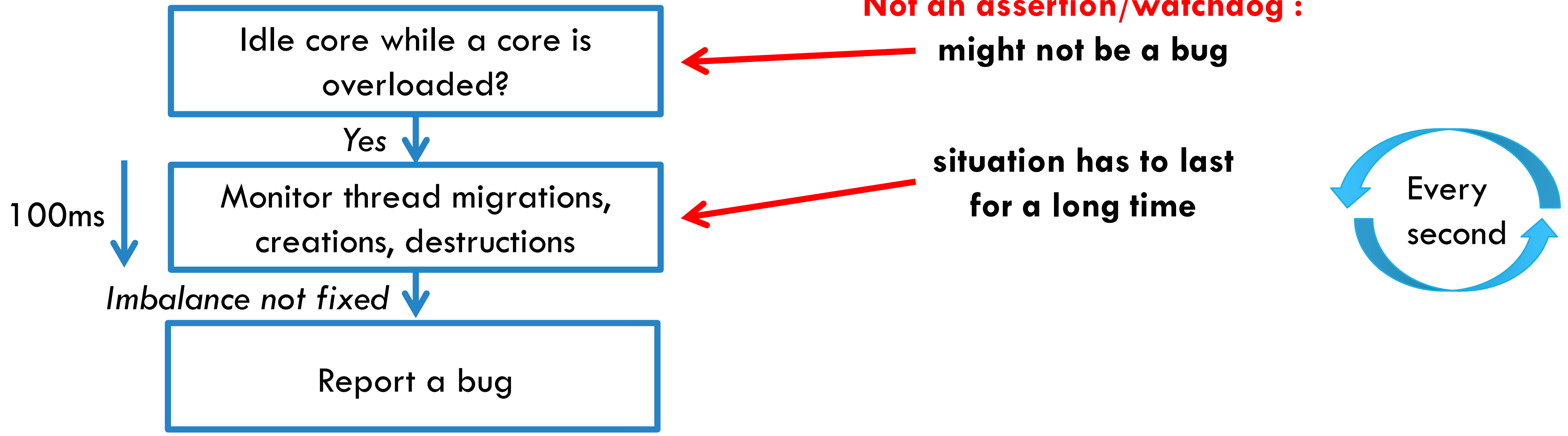

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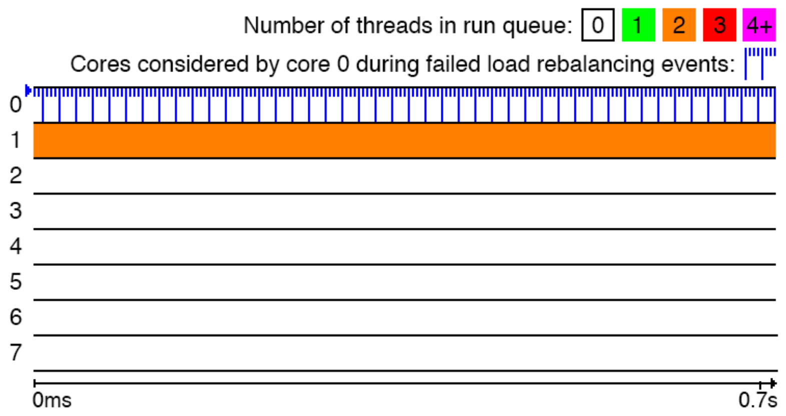

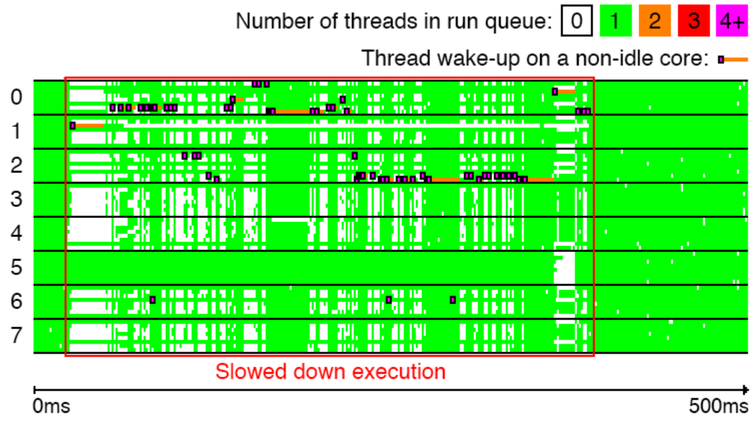

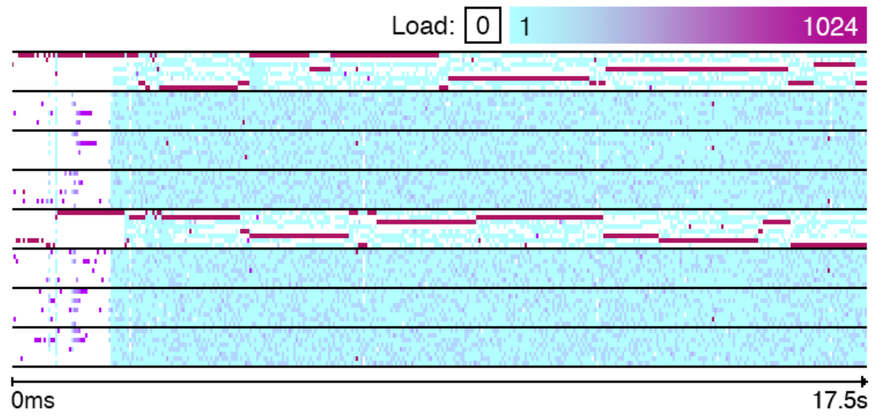

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Your turn!