# THE LINUX SCHEDULER: A DECADE OF WASTED CORES


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  - **Even if you do, would you be able to identify faulty behavior from normal noise?**
  - **Would you ever suspect the scheduler?**

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- **We ended up suspecting the core behavior of the scheduler.**
  - ***We implemented high-resolution tracing tools and saw that some cores were idle while others overloaded…***

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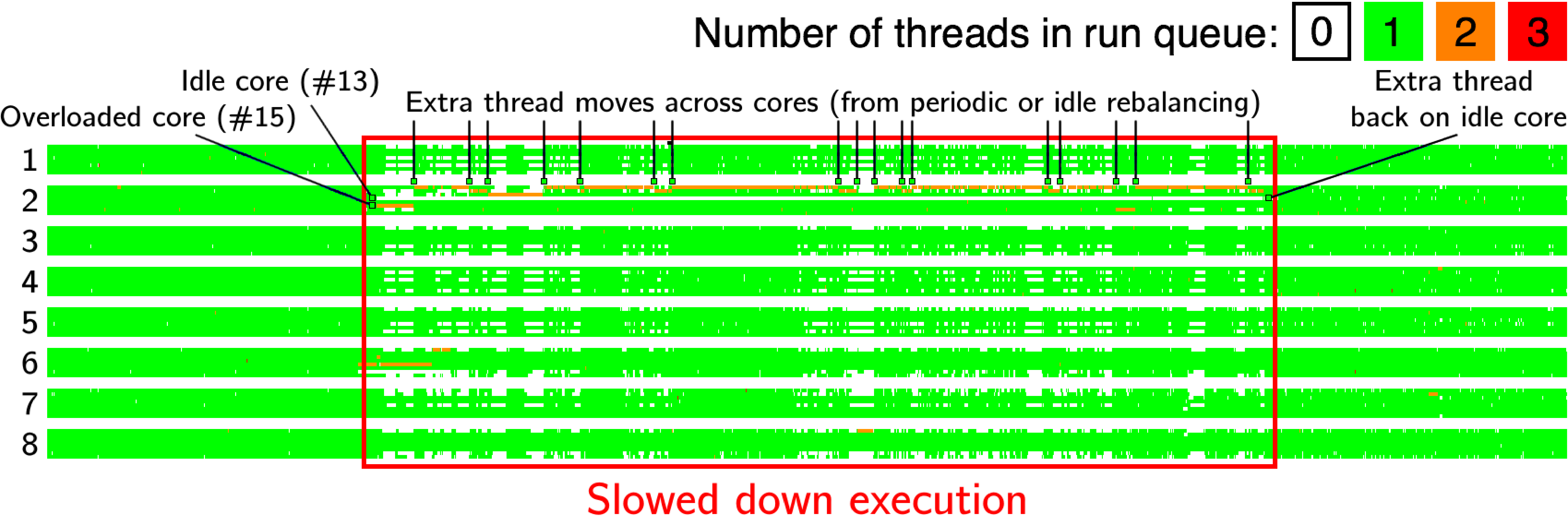

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- **After fixing some of the bugs :**
  - 12-23% performance improvement on a popular database with TPC-H
  - 137× performance improvement on HPC workloads
- **Not always possible to provide a simple, working fix…**
  - Intrisic problems with the design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

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***Need convincing? Let's go through it together…***

*…starting with a bit of background…*

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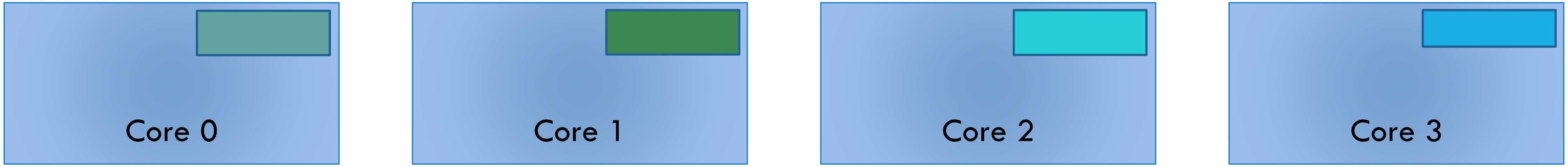

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One runqueue where threads
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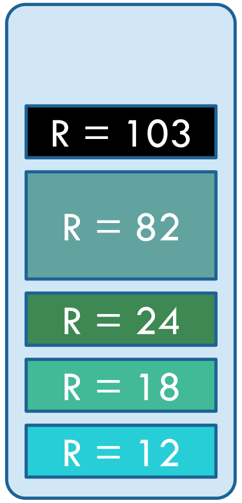


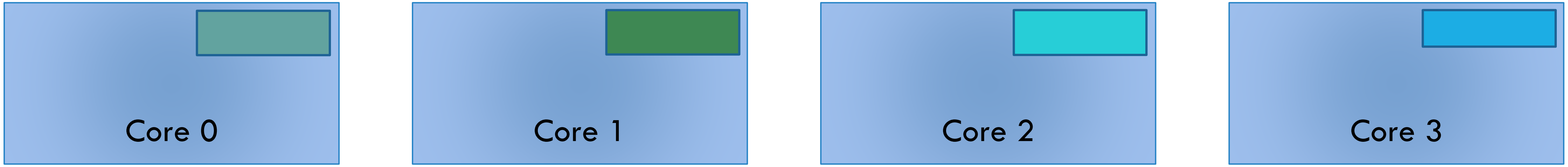

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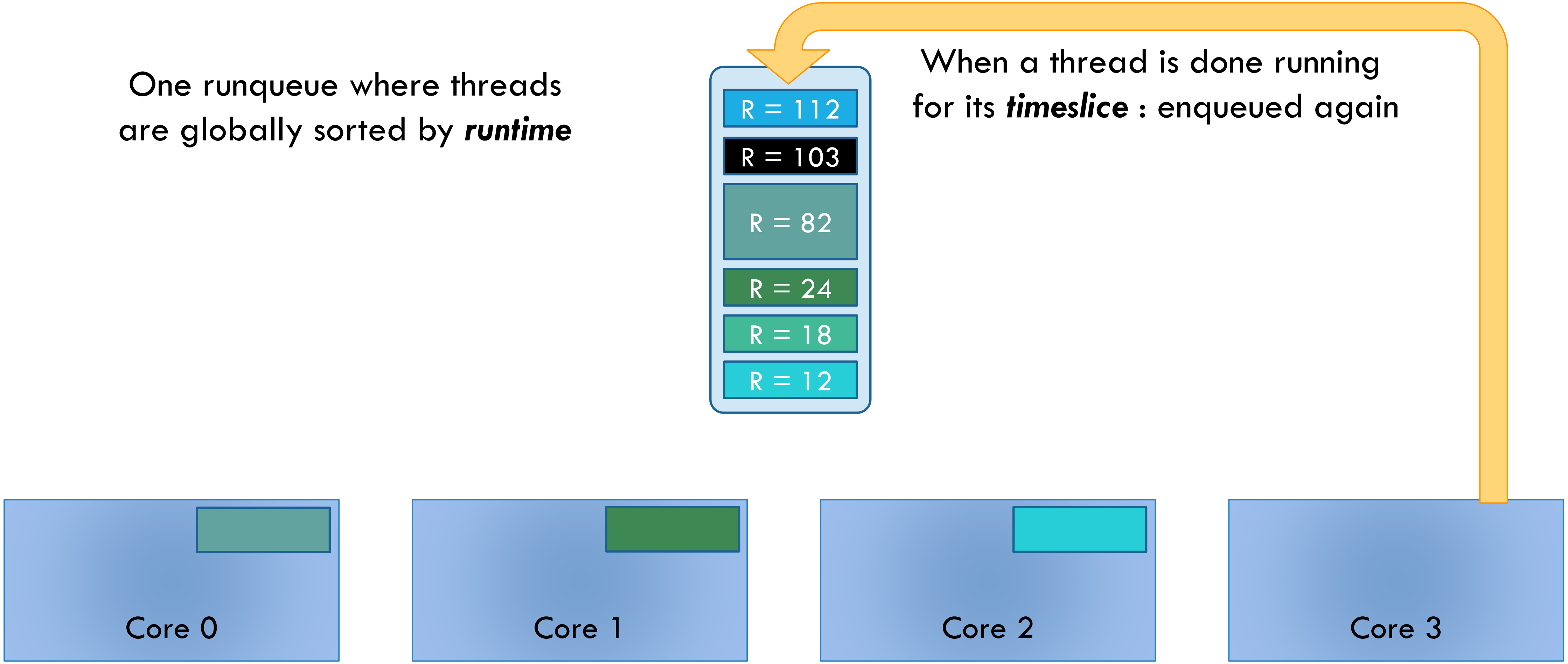

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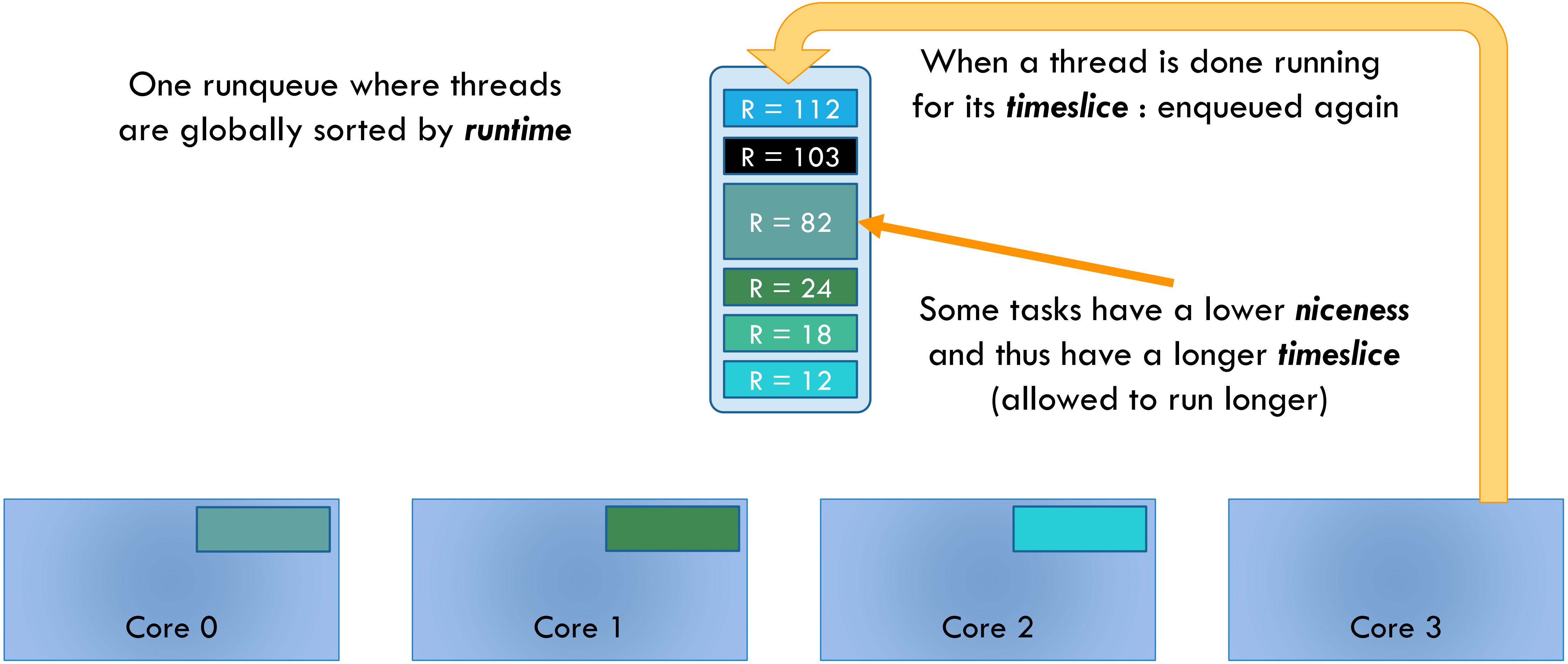


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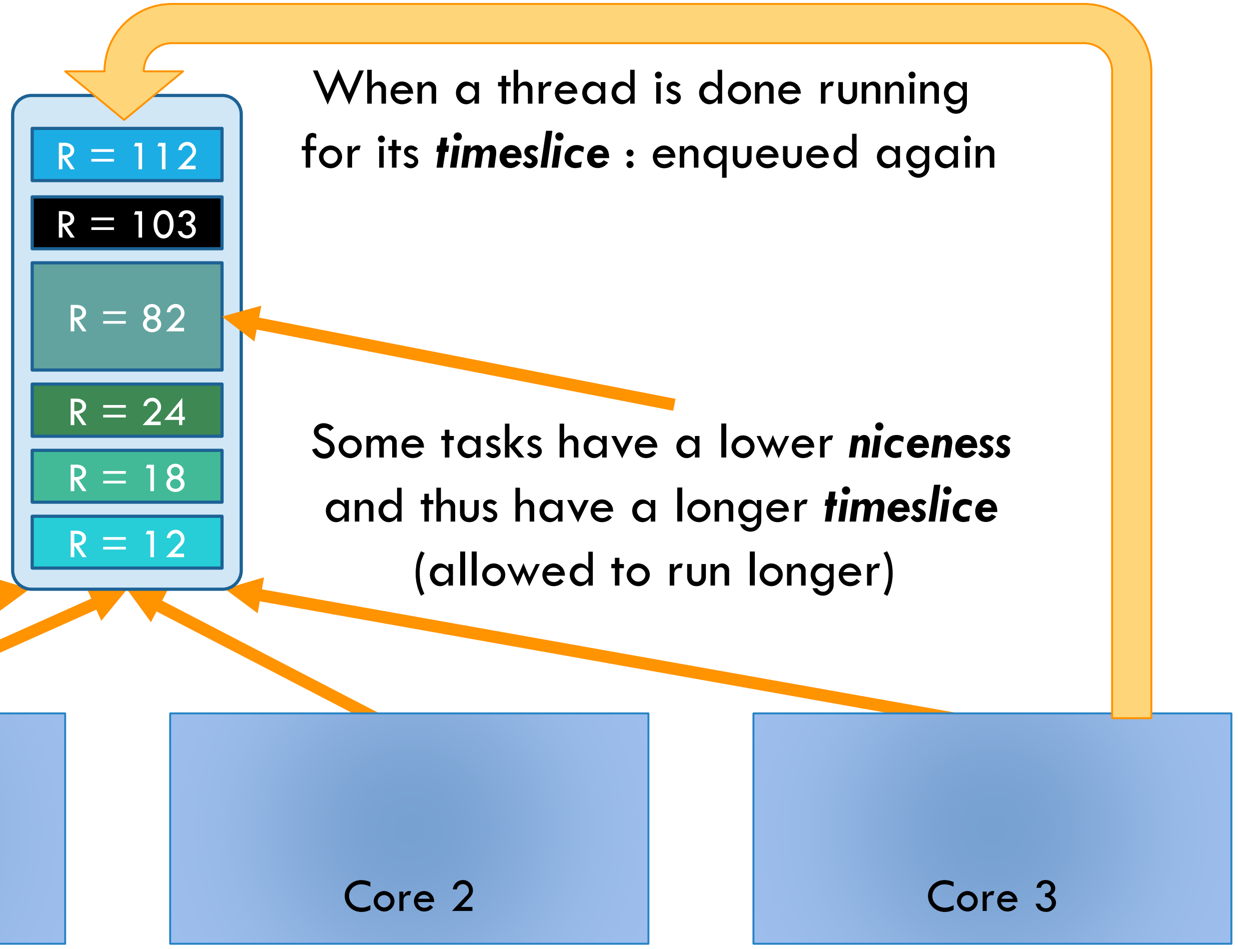

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**Of course, cannot work with a single runqueue because of contention**

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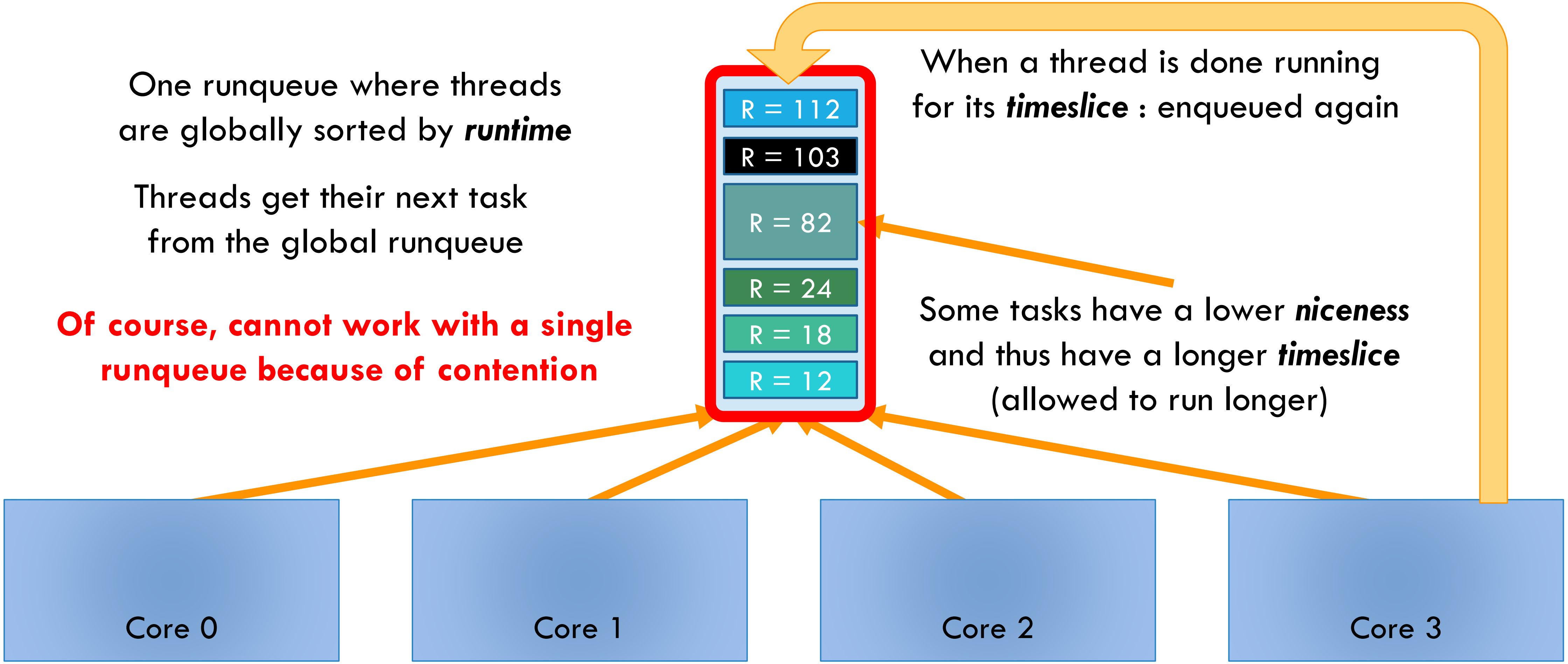

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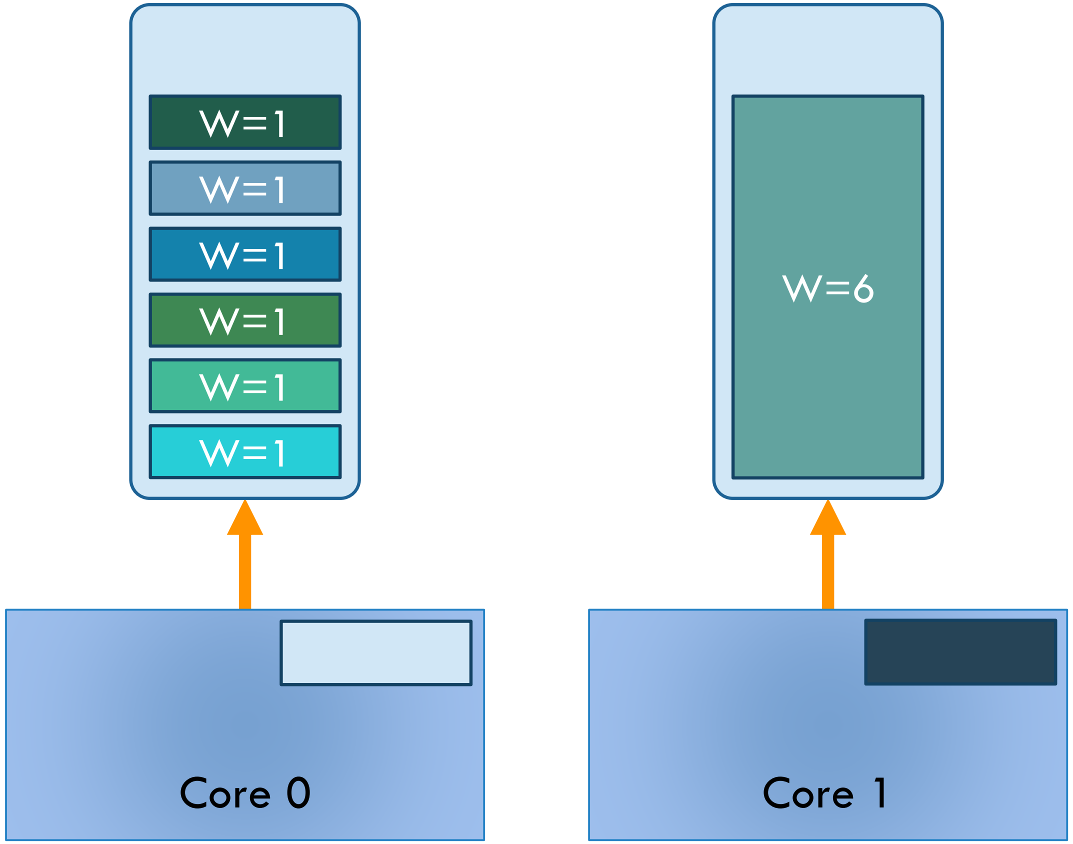
- **One runqueue per core** to avoid contention



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- **One runqueue per core** to avoid contention
- **CFS** **periodically** **balances "loads":**

**load(task) = weight[1] x % cpu use[2]**

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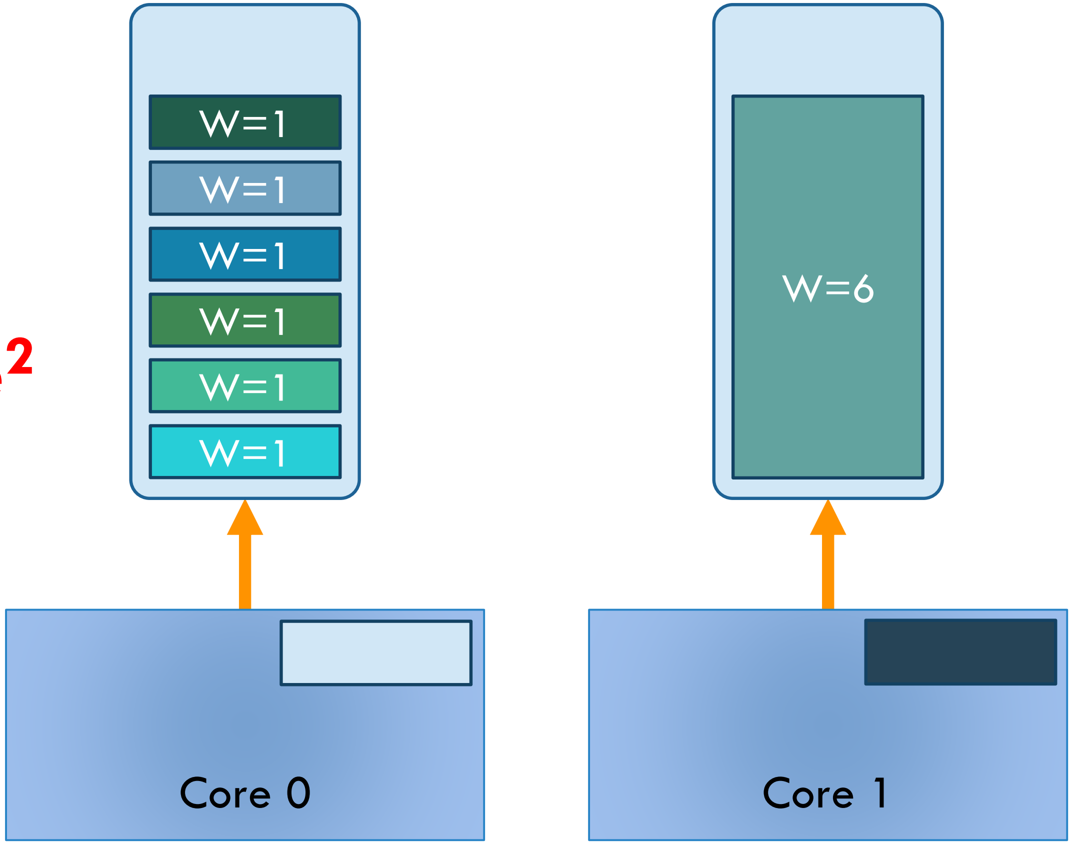

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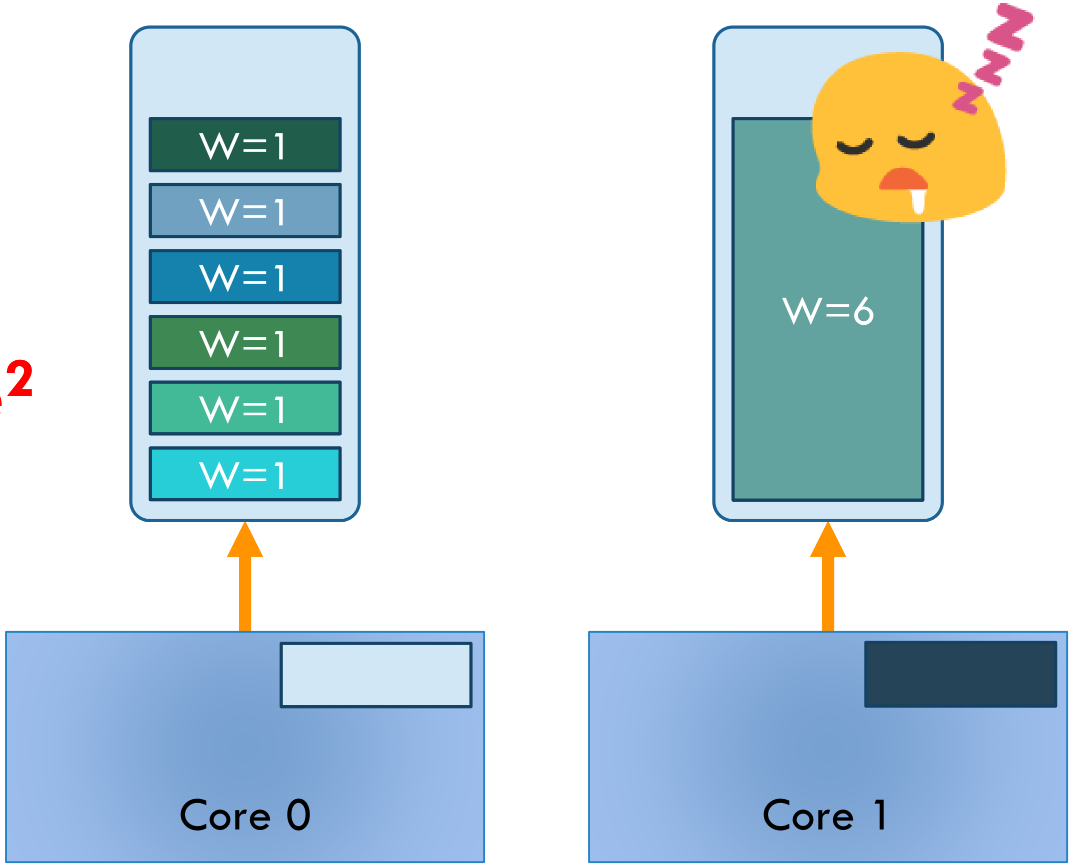

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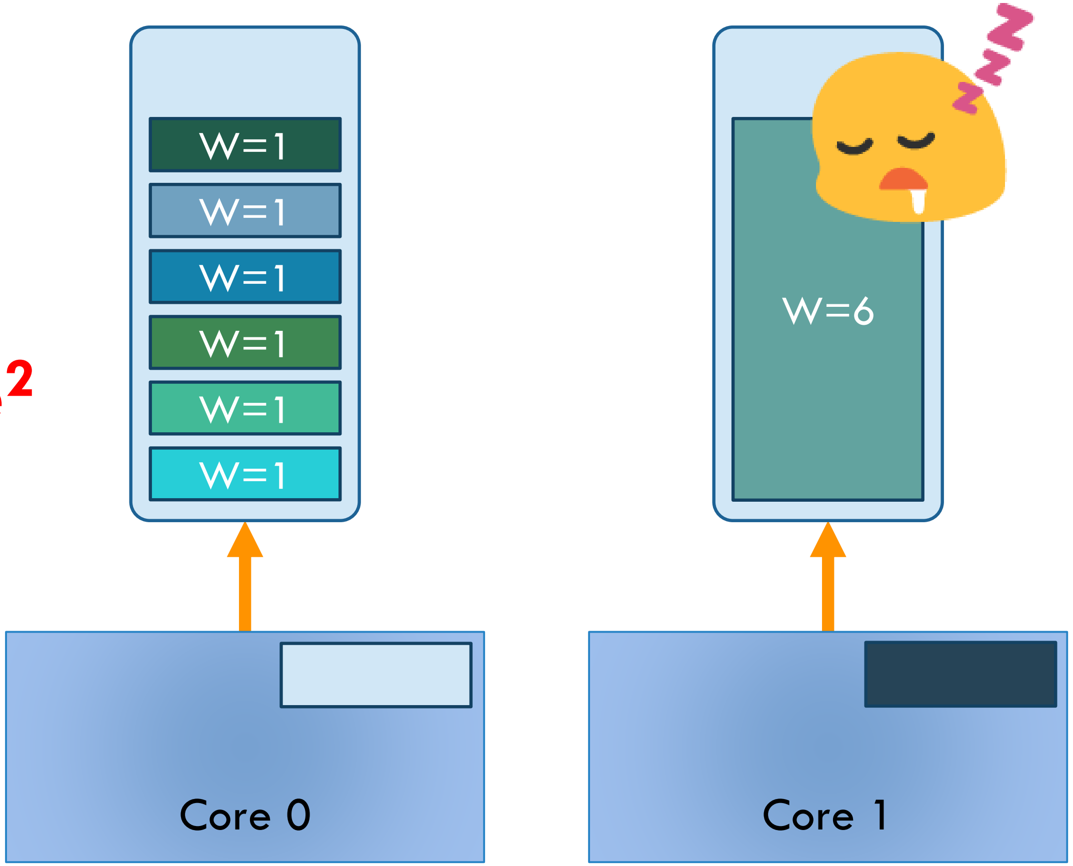


- **Since there can be many cores: hierarchical approach!**

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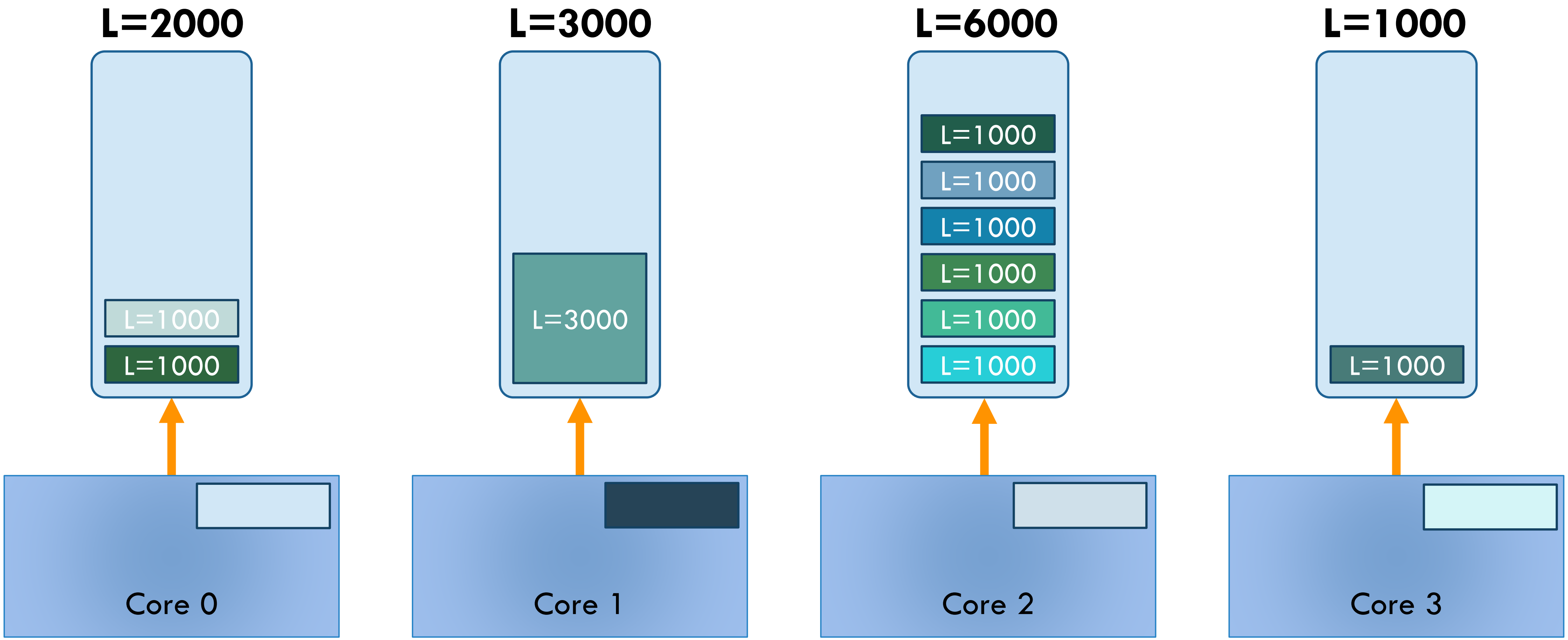

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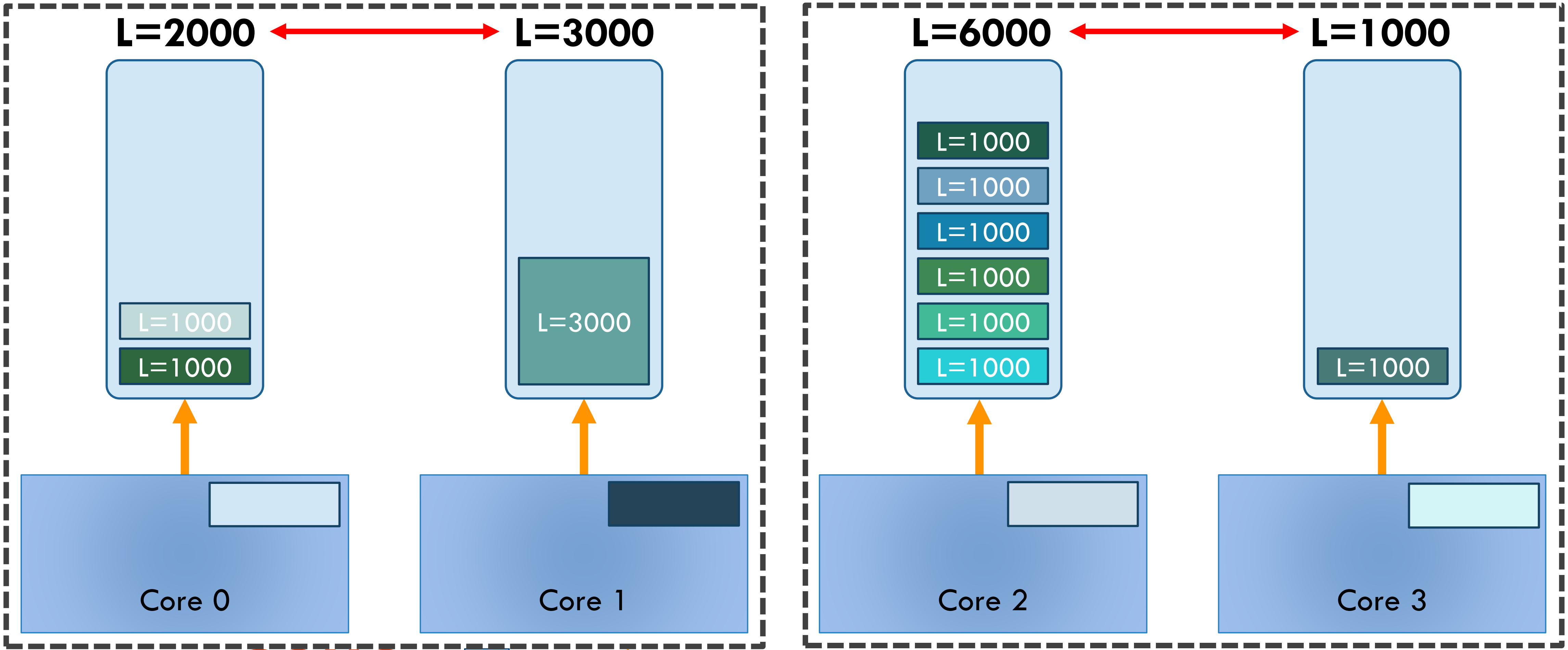

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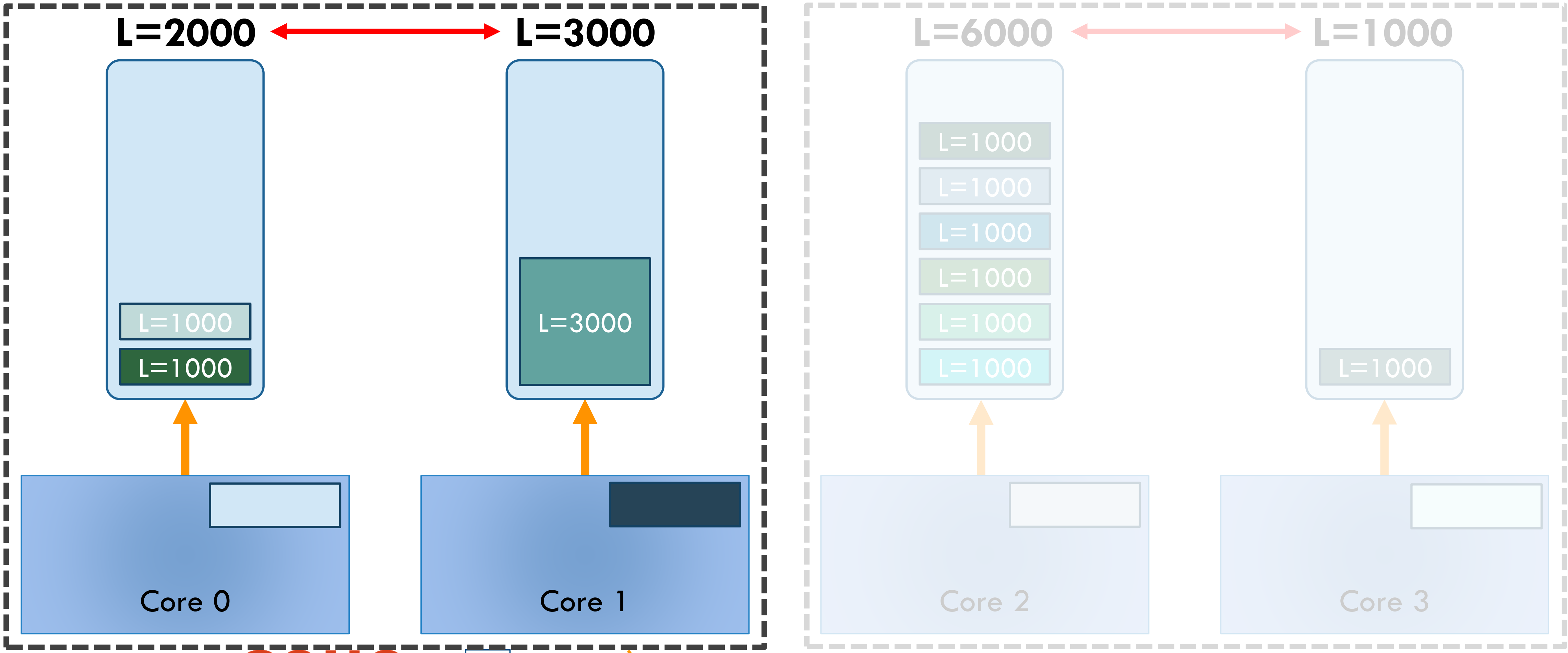

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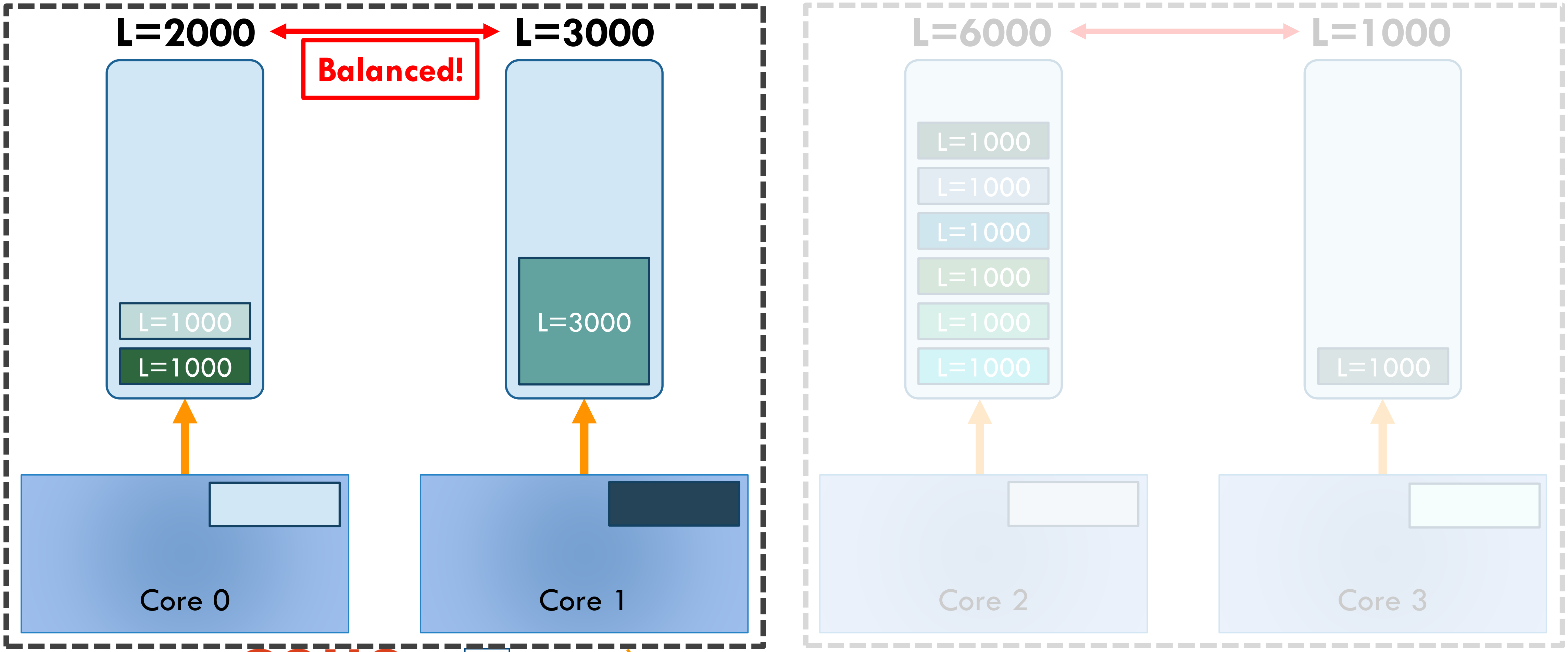

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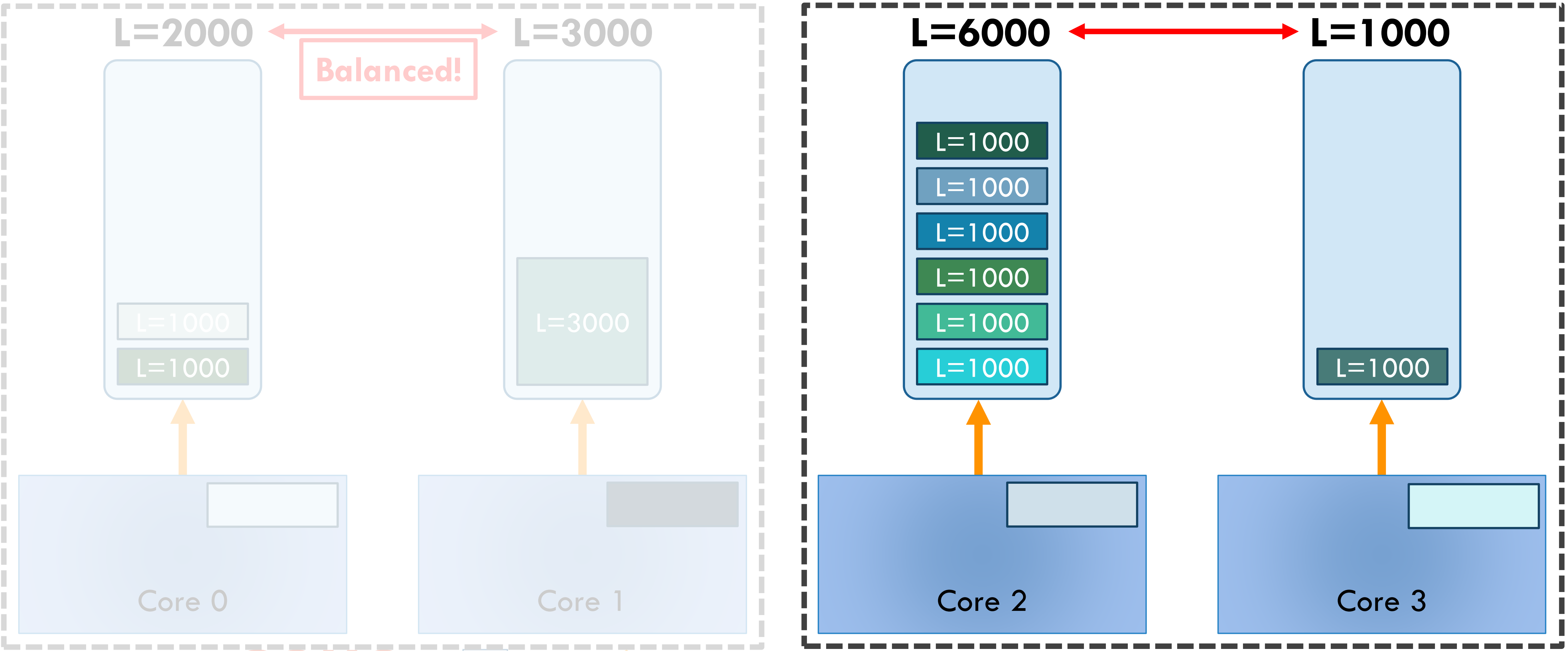

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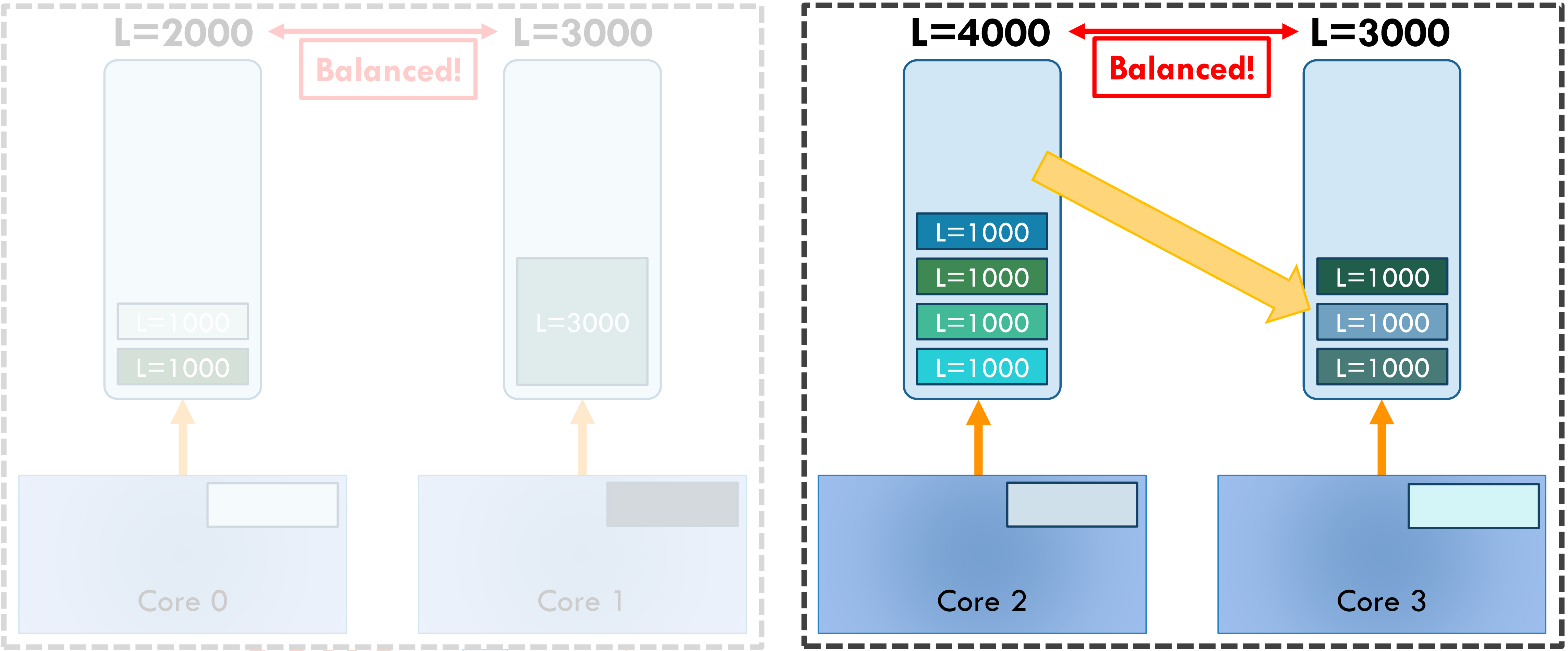

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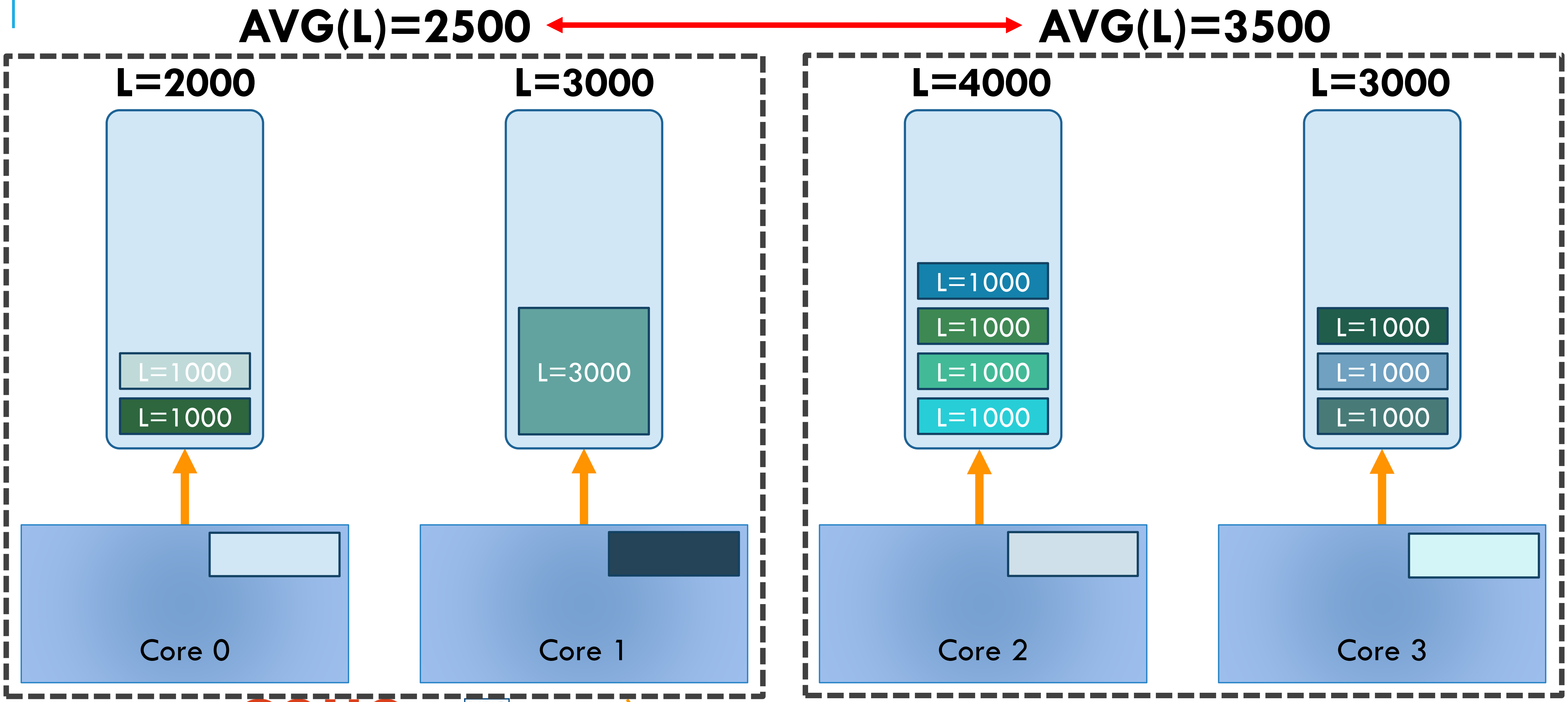

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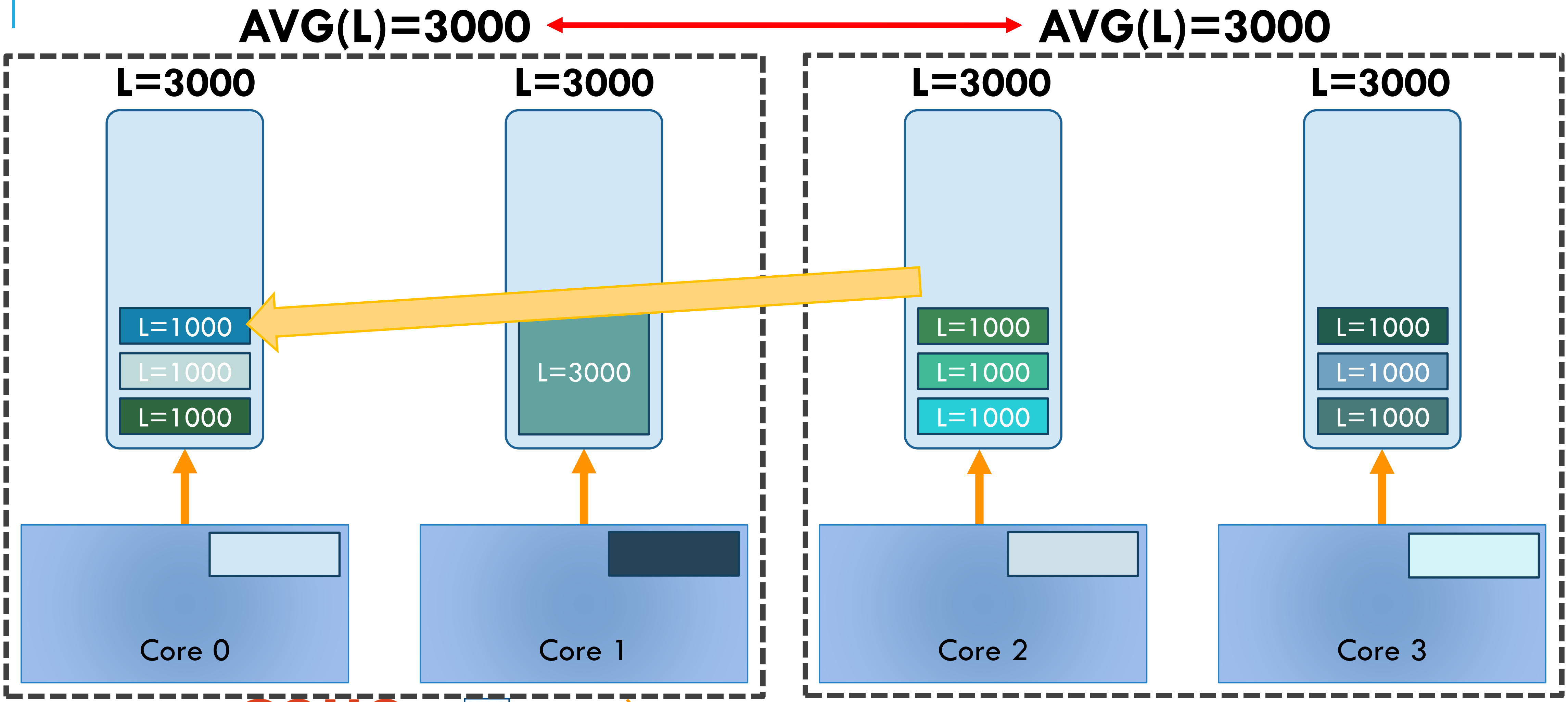

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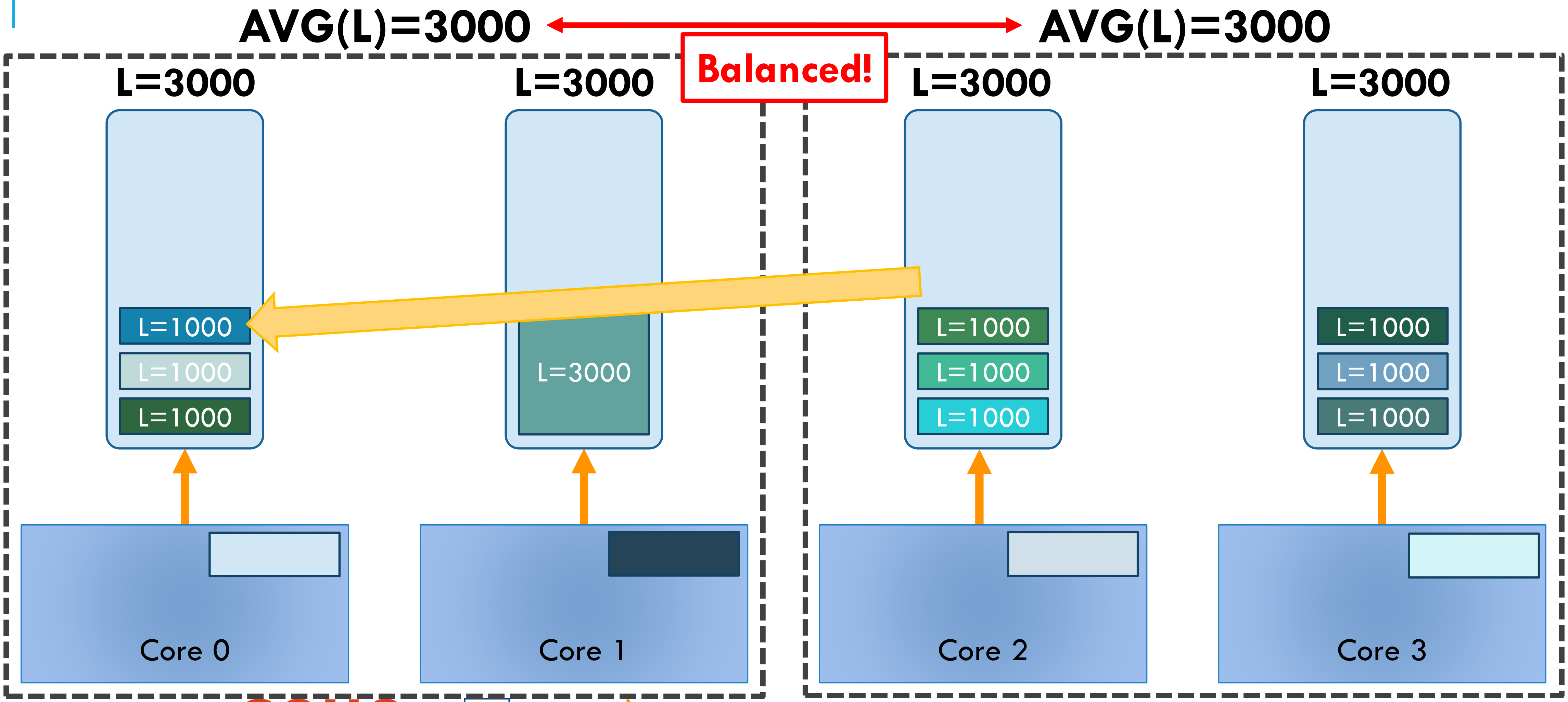

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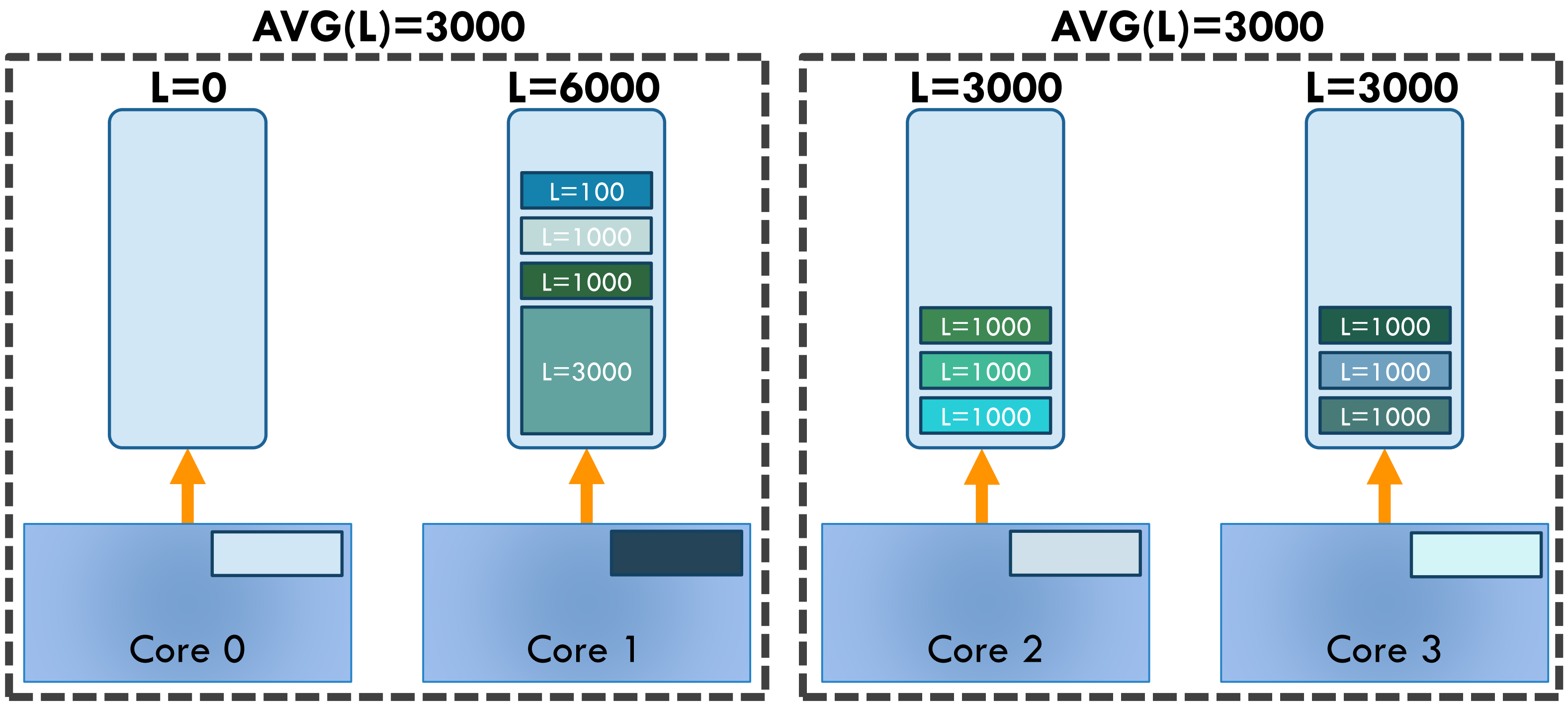

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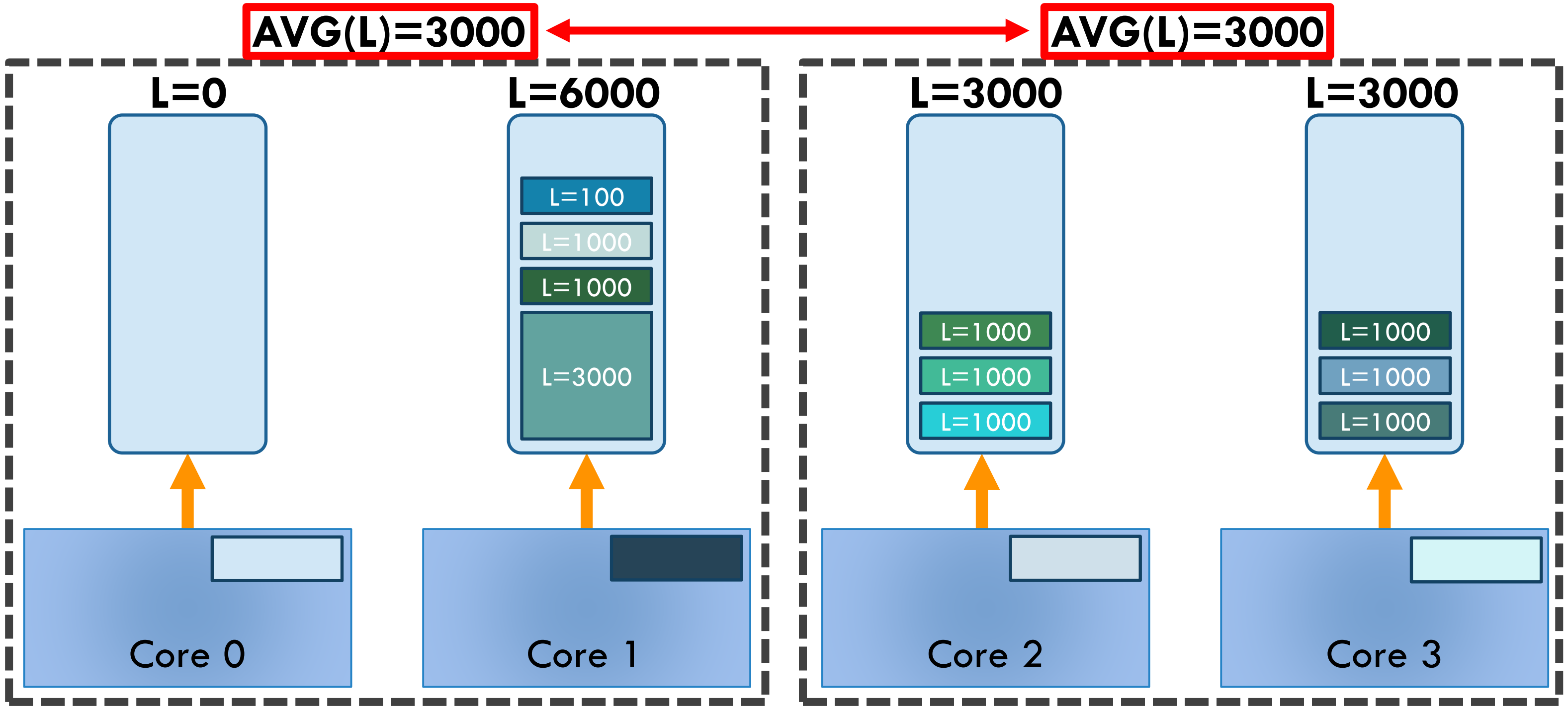

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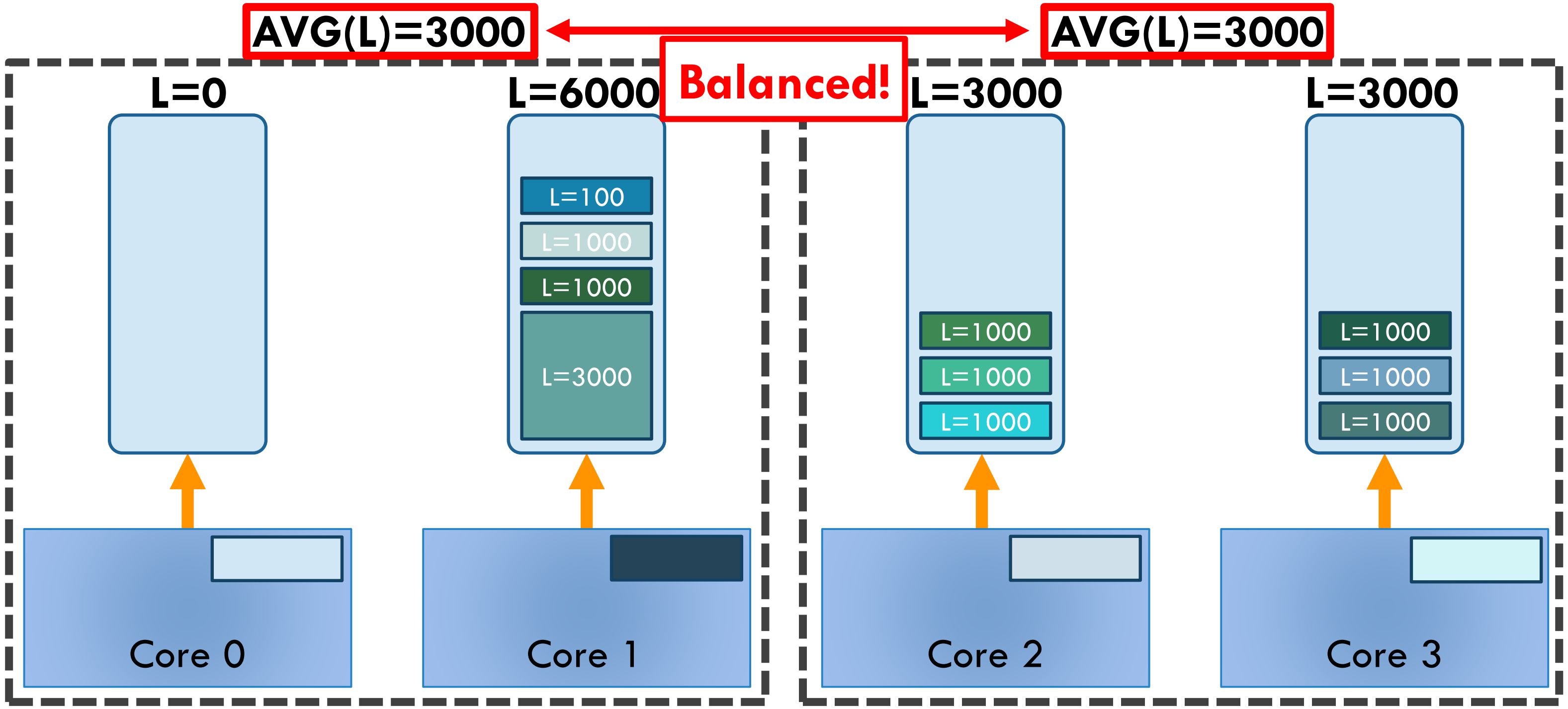

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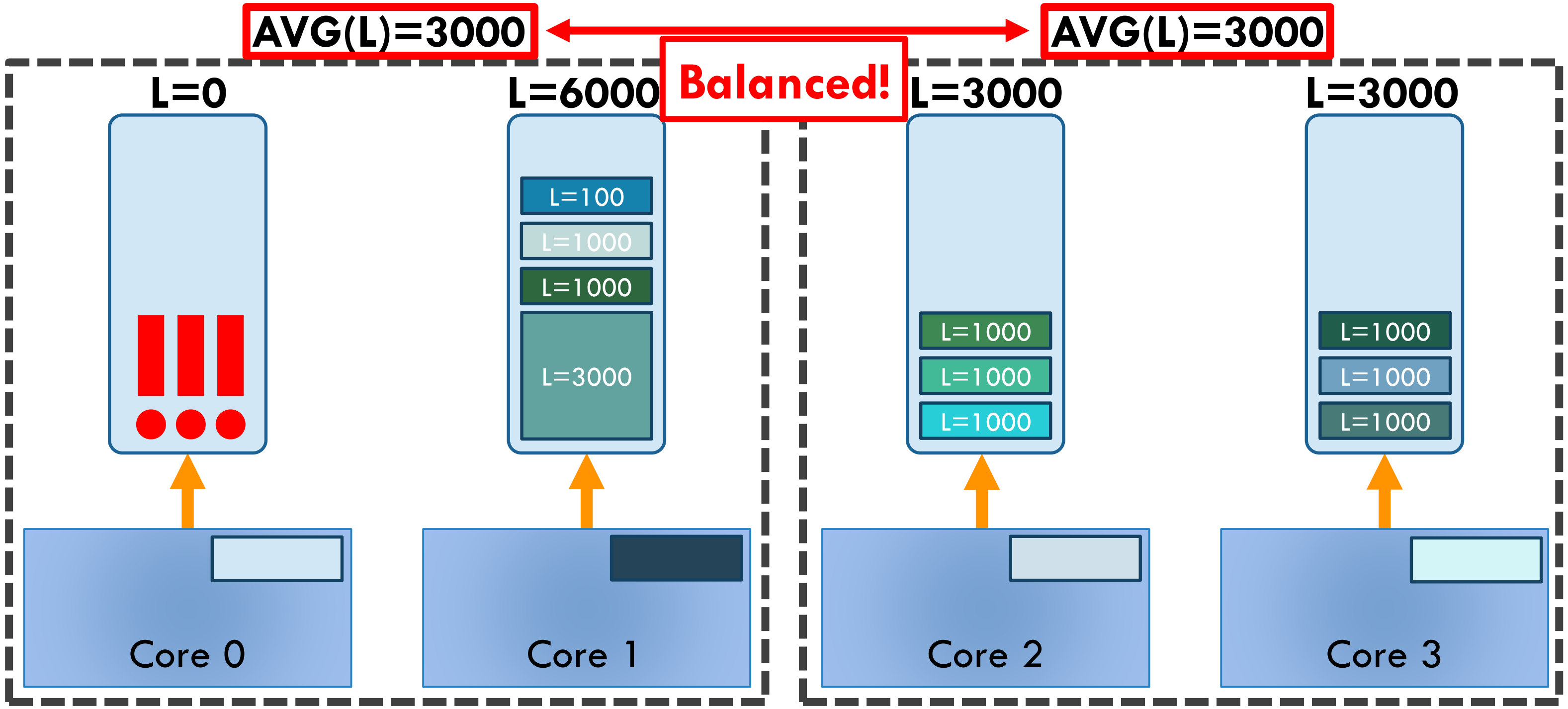

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- **Objective:** making sure that launching lots of threads from one terminal doesn't prevent other processes on the machine (potentially from other users) from running.
  - Otherwise, easy to use more resources than other users by spawning many threads...

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Session (tty) 1

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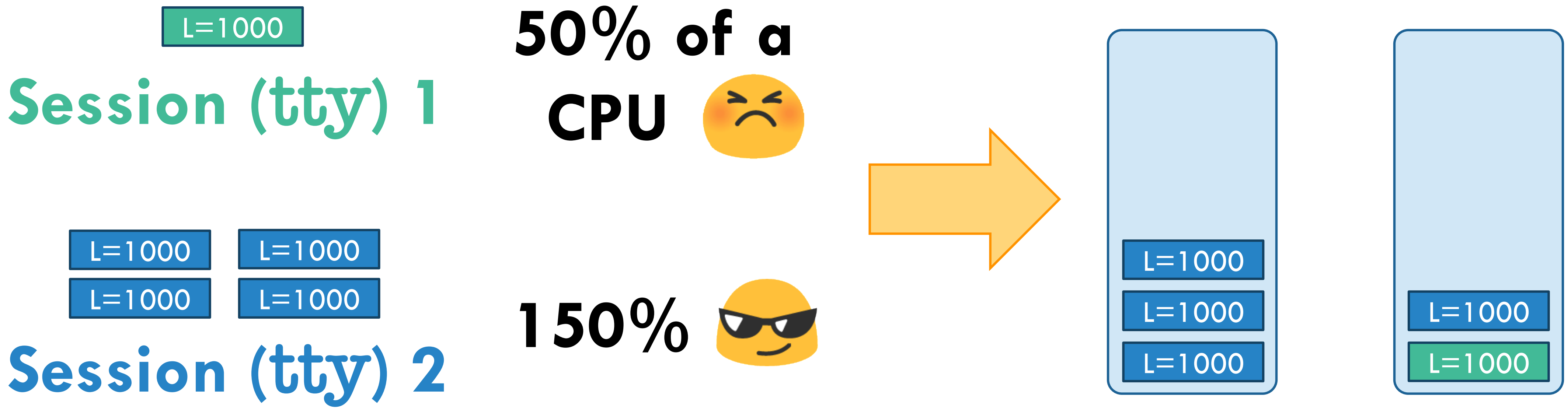

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**100% of a CPU** 🙂

L=250 L=250
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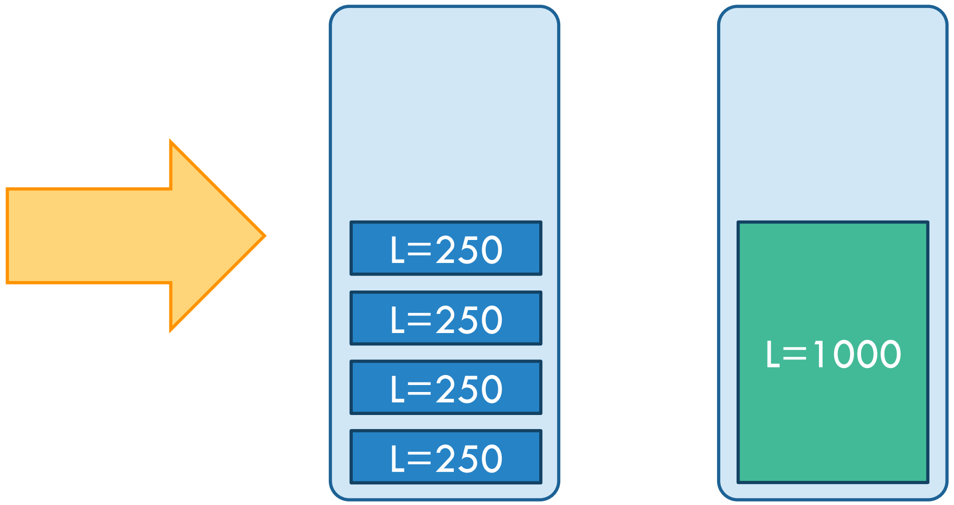
**100% of a CPU** 🙂



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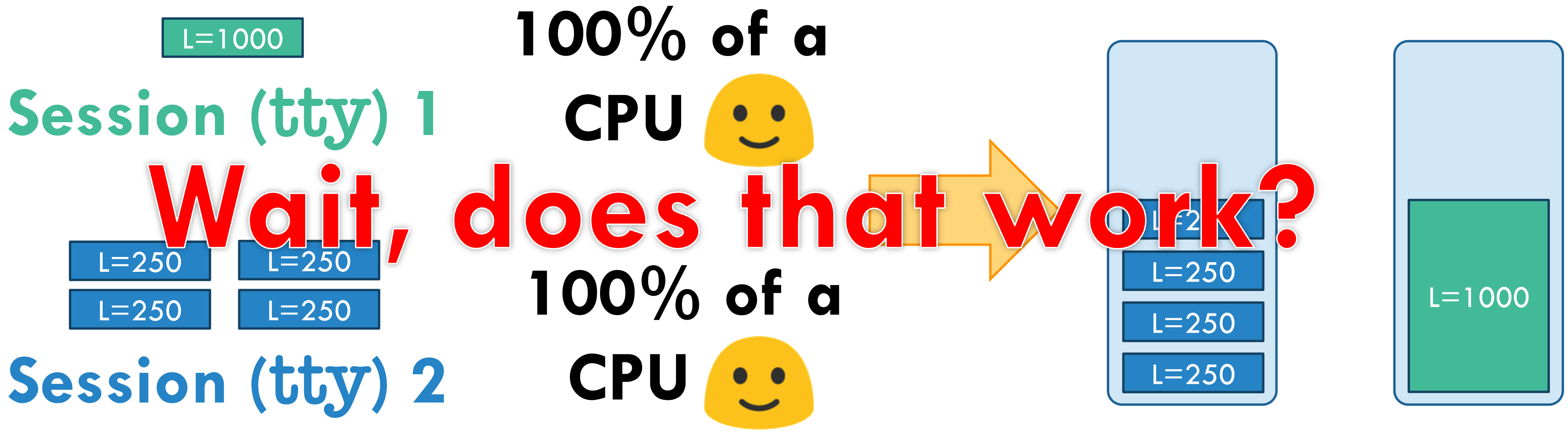

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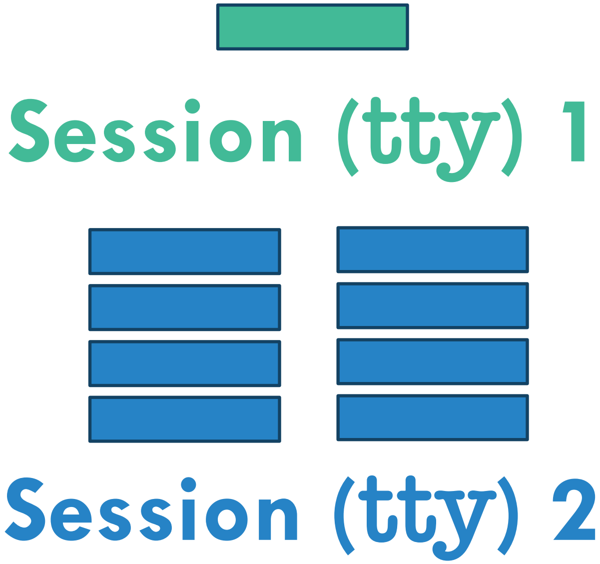

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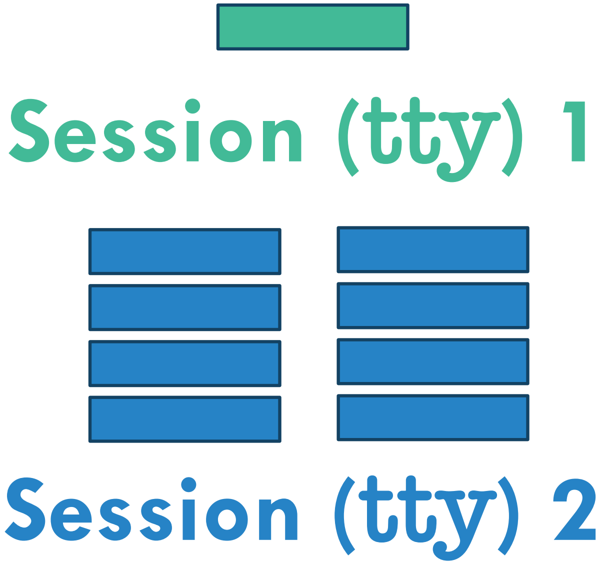


$$
\begin{aligned}
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&= 100 \times 10 \;{\color{red}/}\; {\color{red}1} \\
&= {\color{red}1000}
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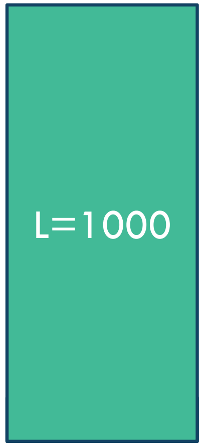


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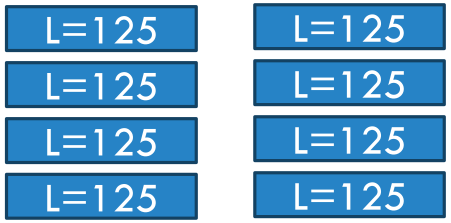
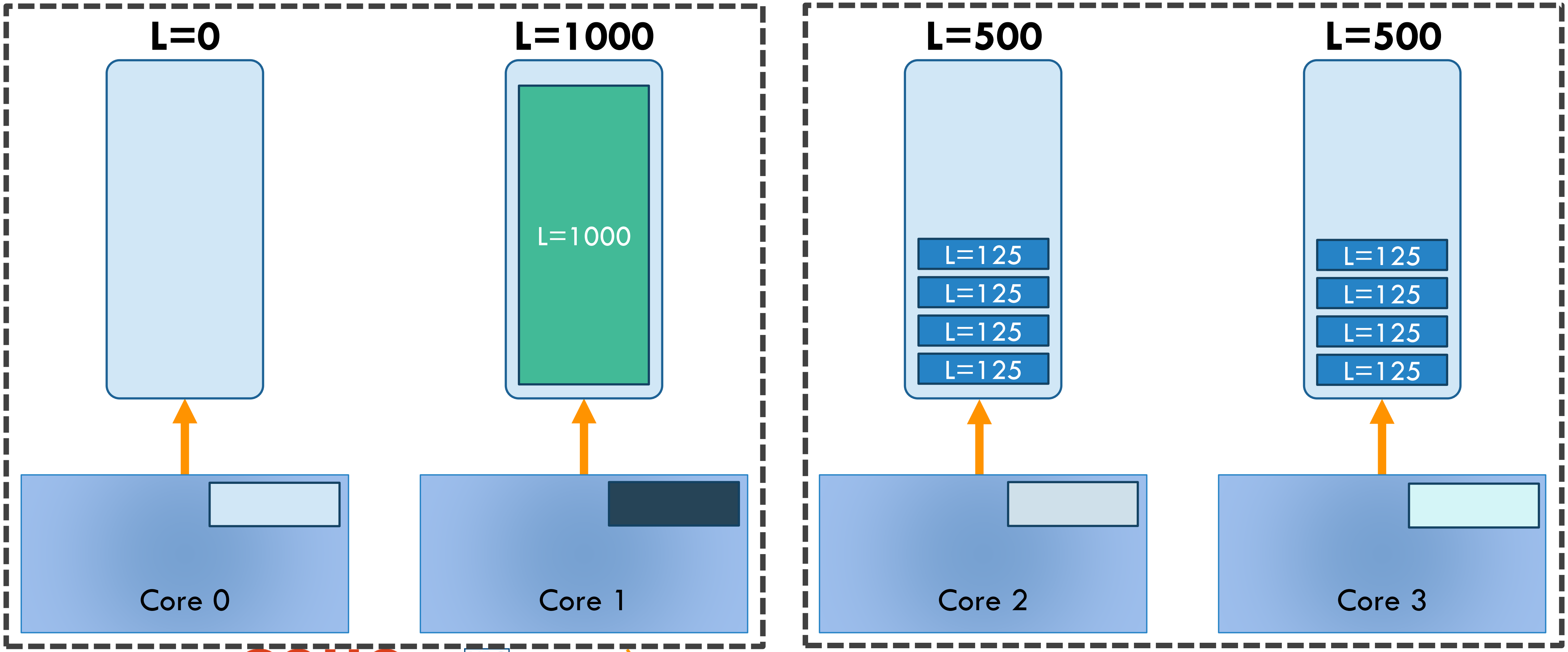



Session (tty) 2

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

# BUG 1/4: GROUP IMBALANCE



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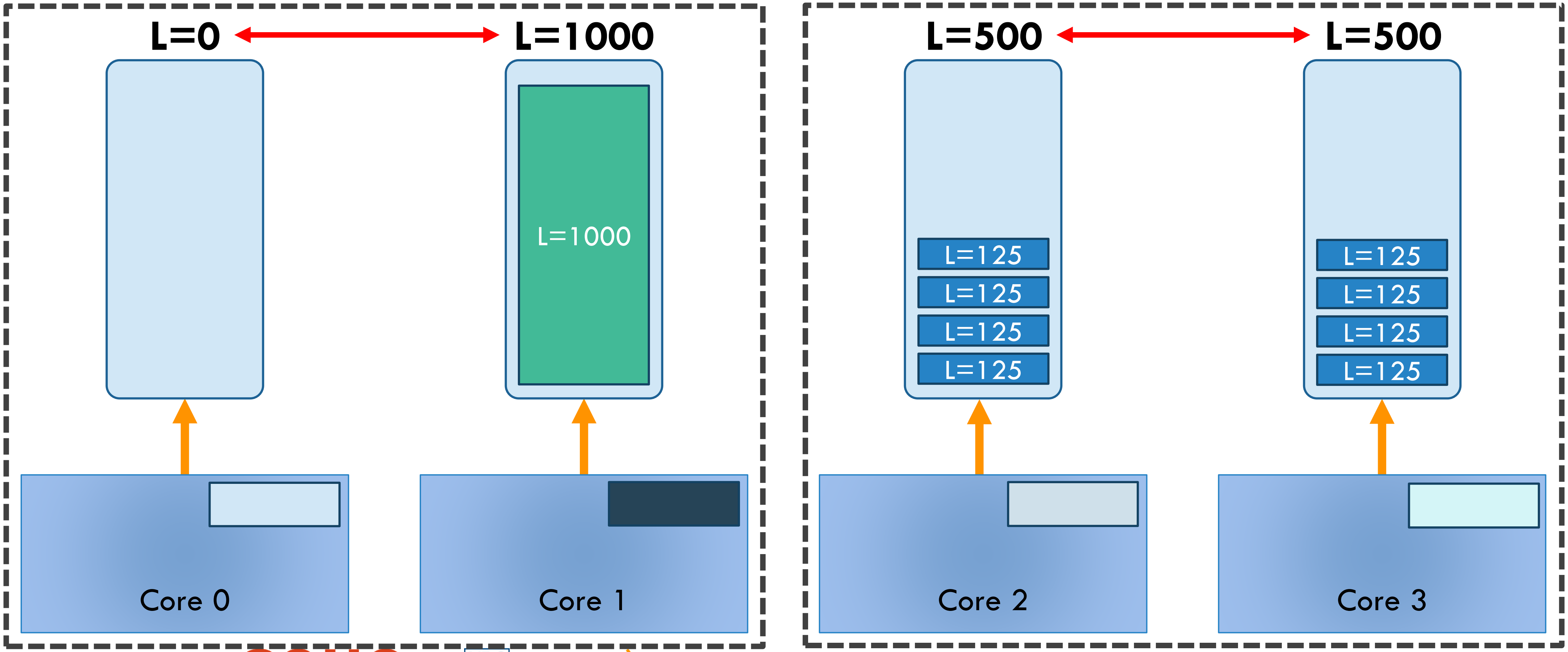

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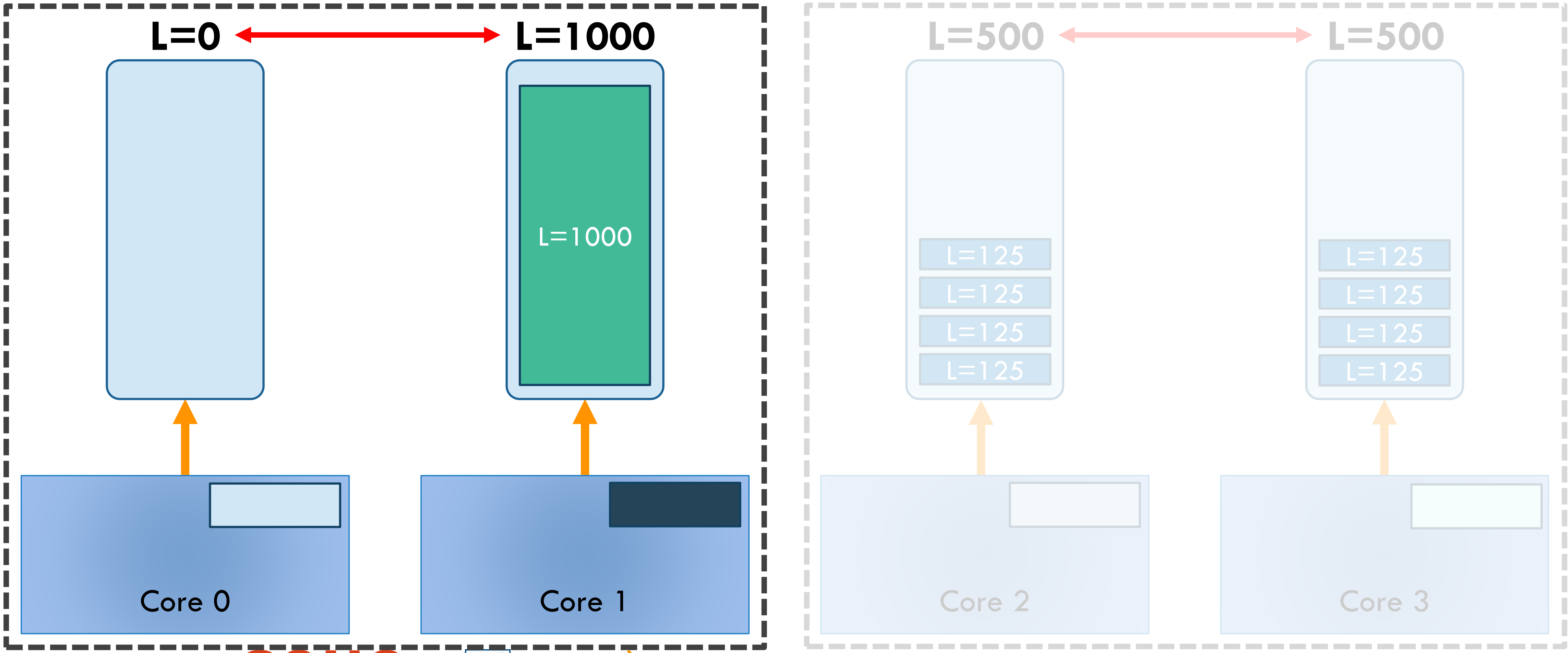

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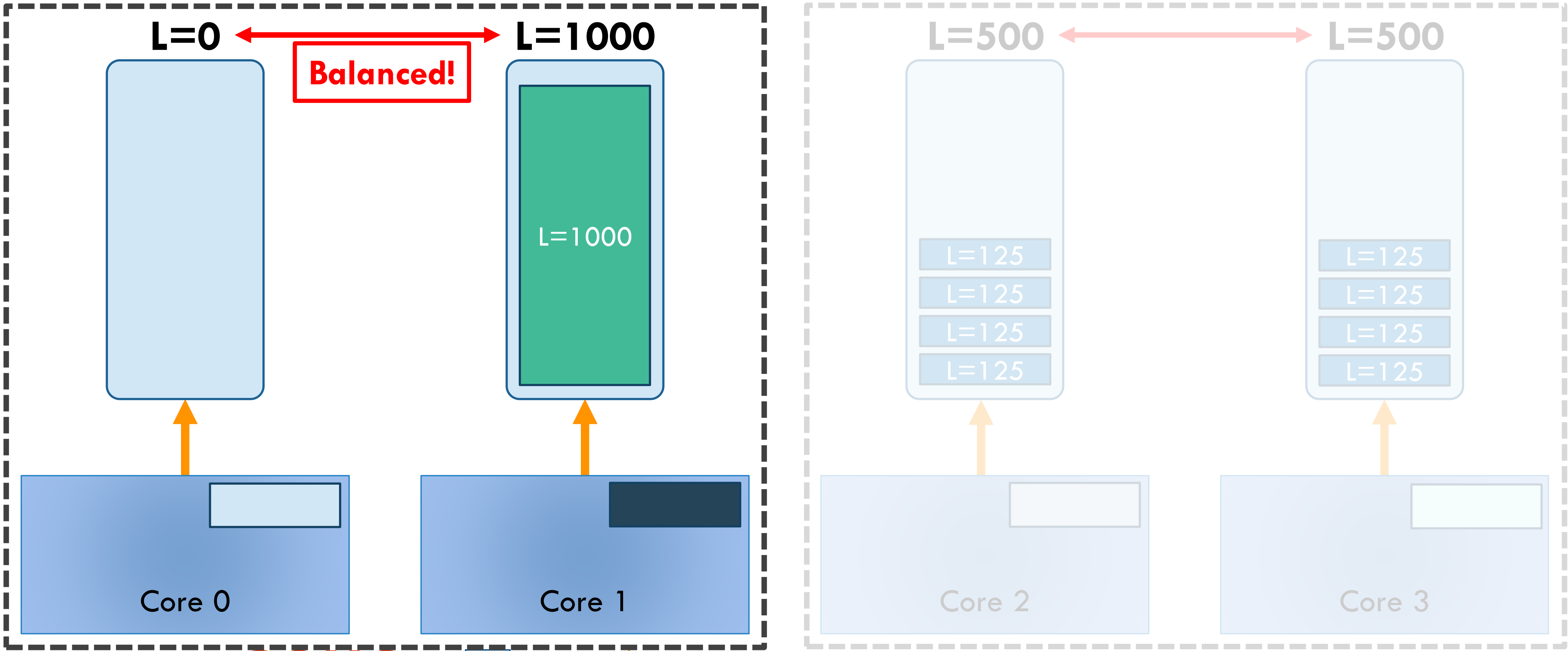

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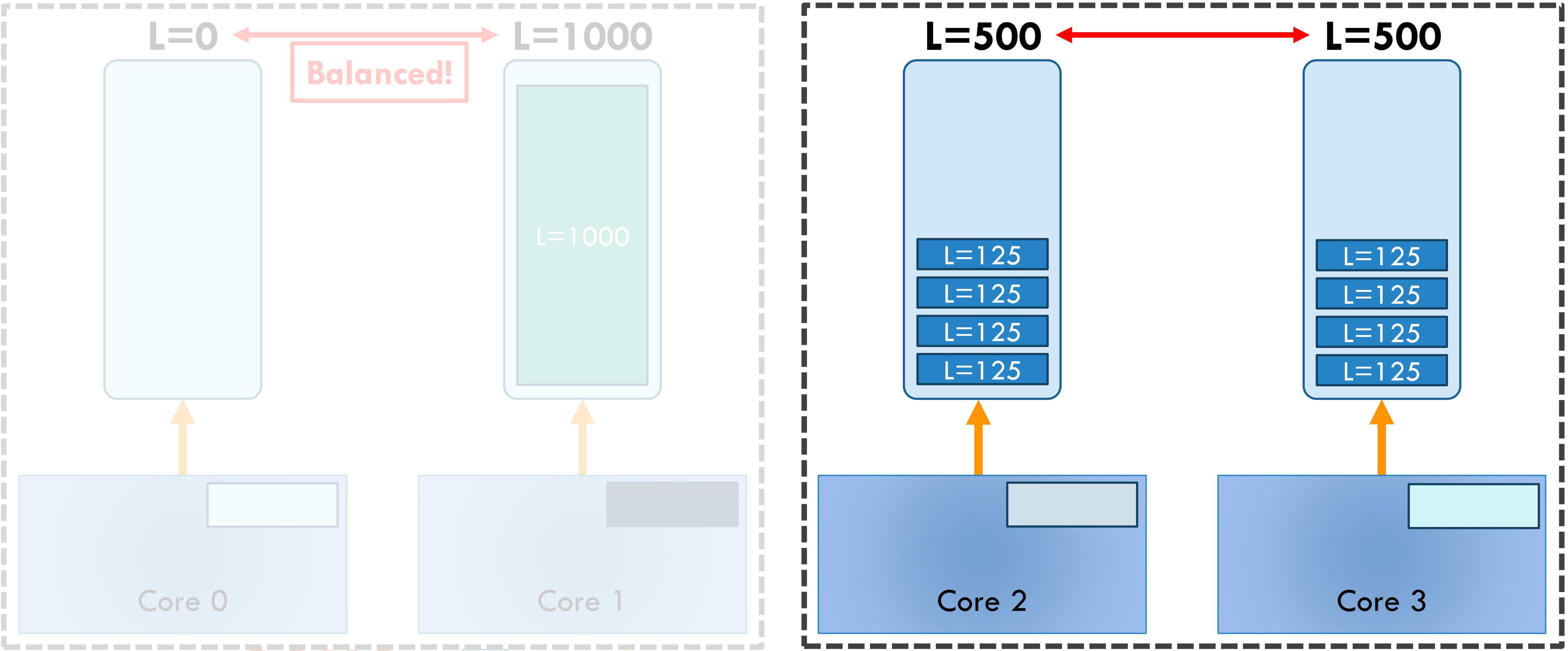

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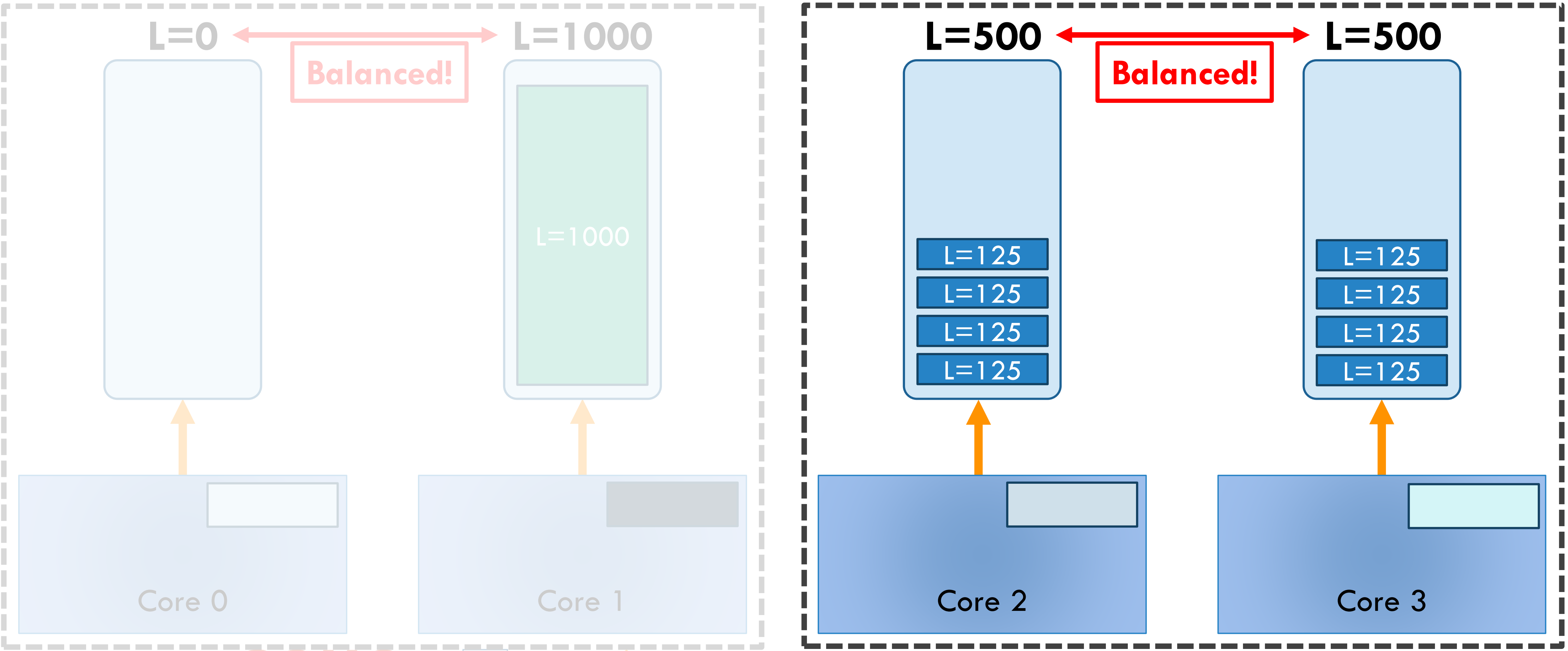

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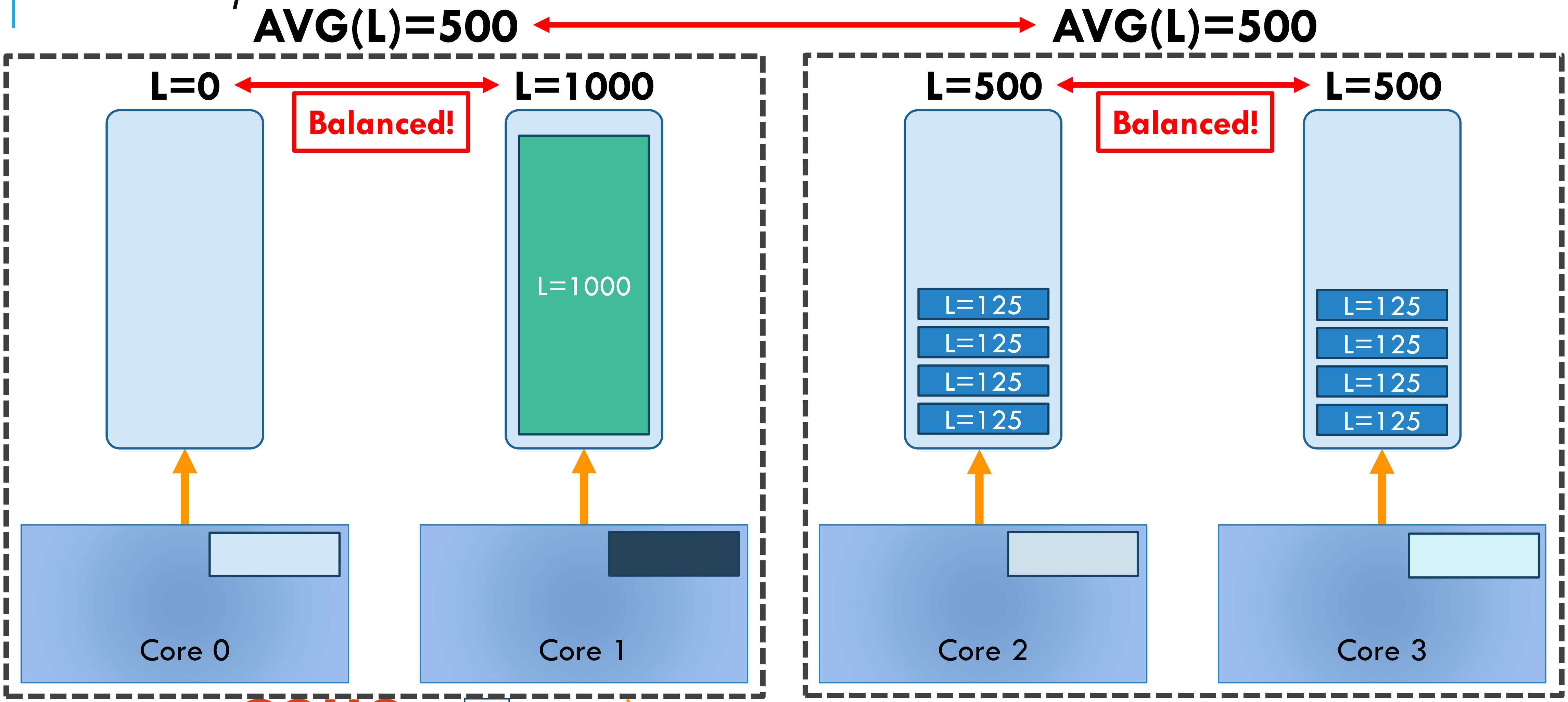

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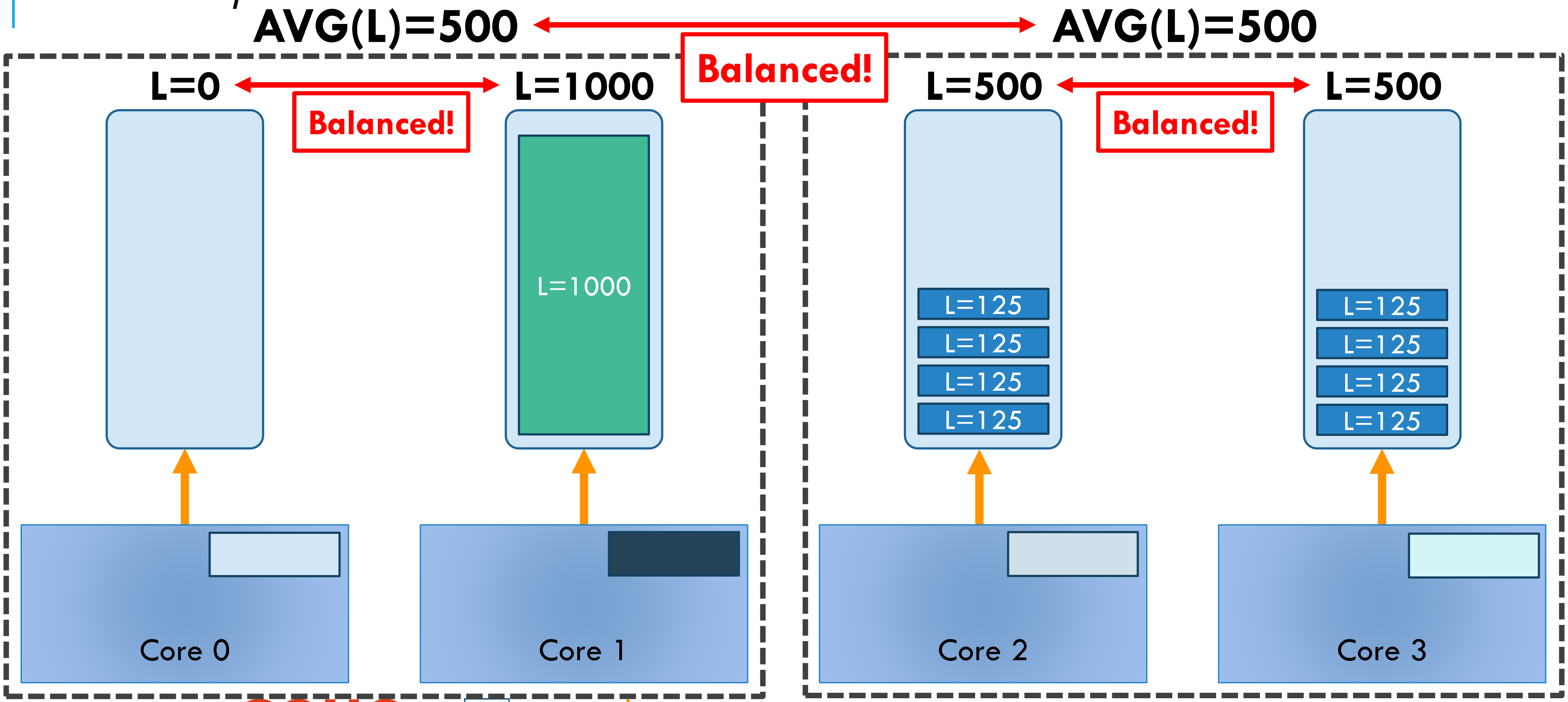

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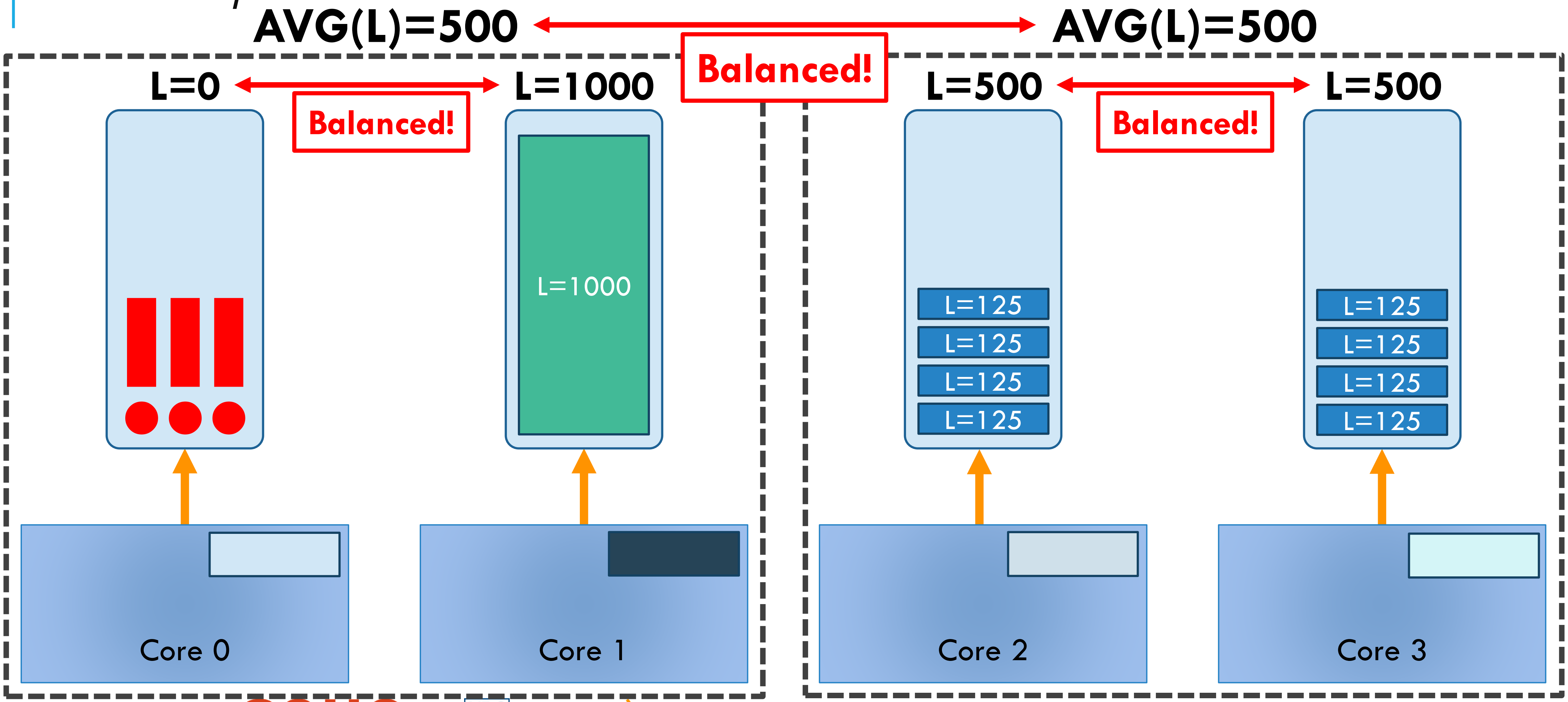

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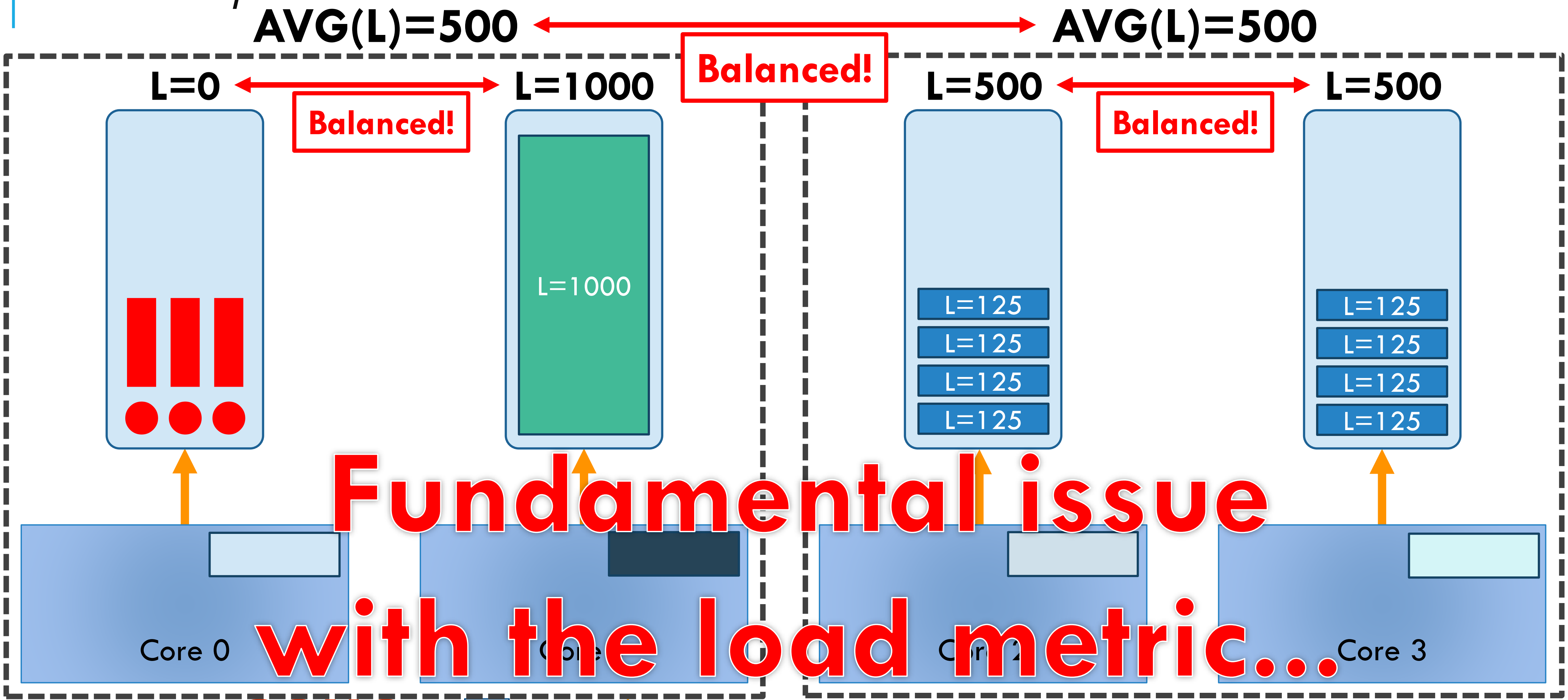


**Fundamental issue with the load metric…**

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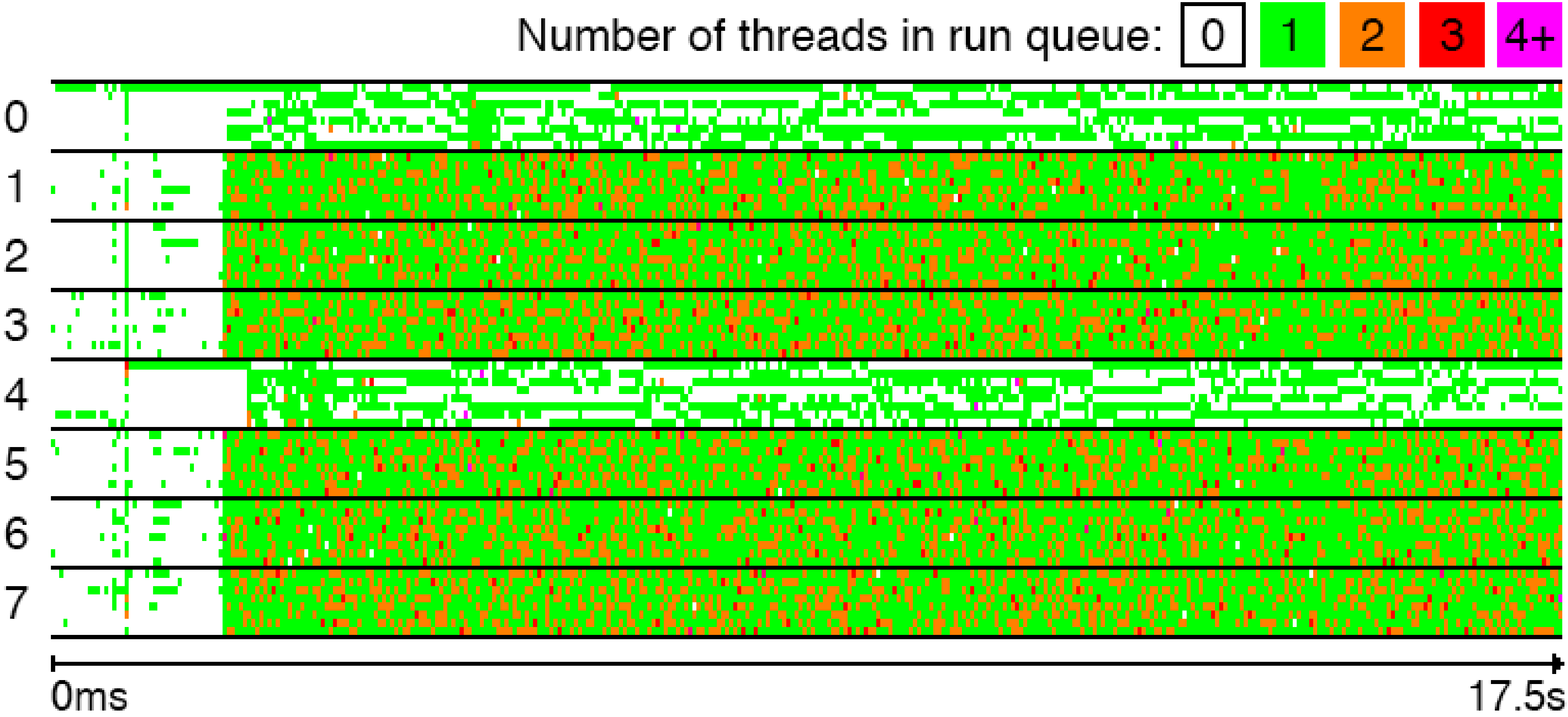


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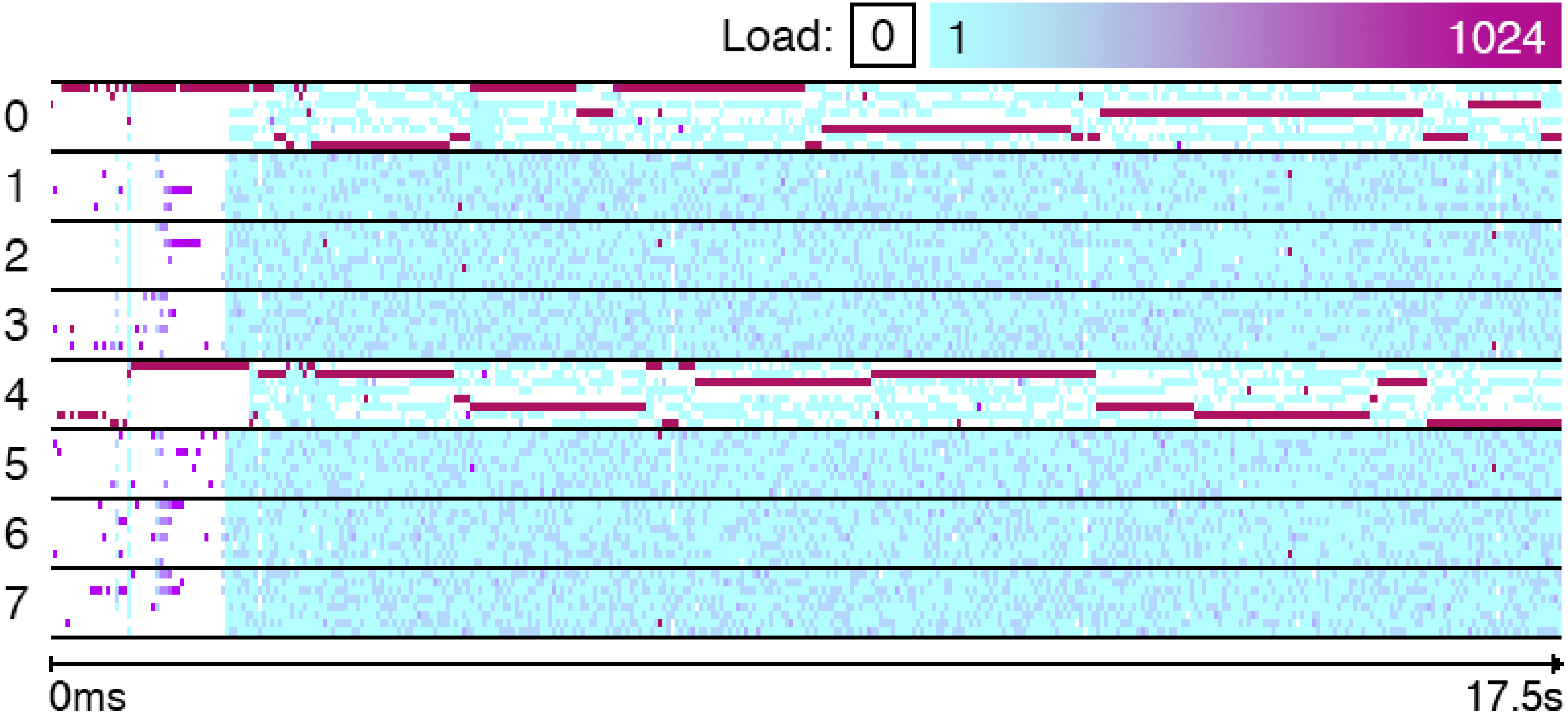


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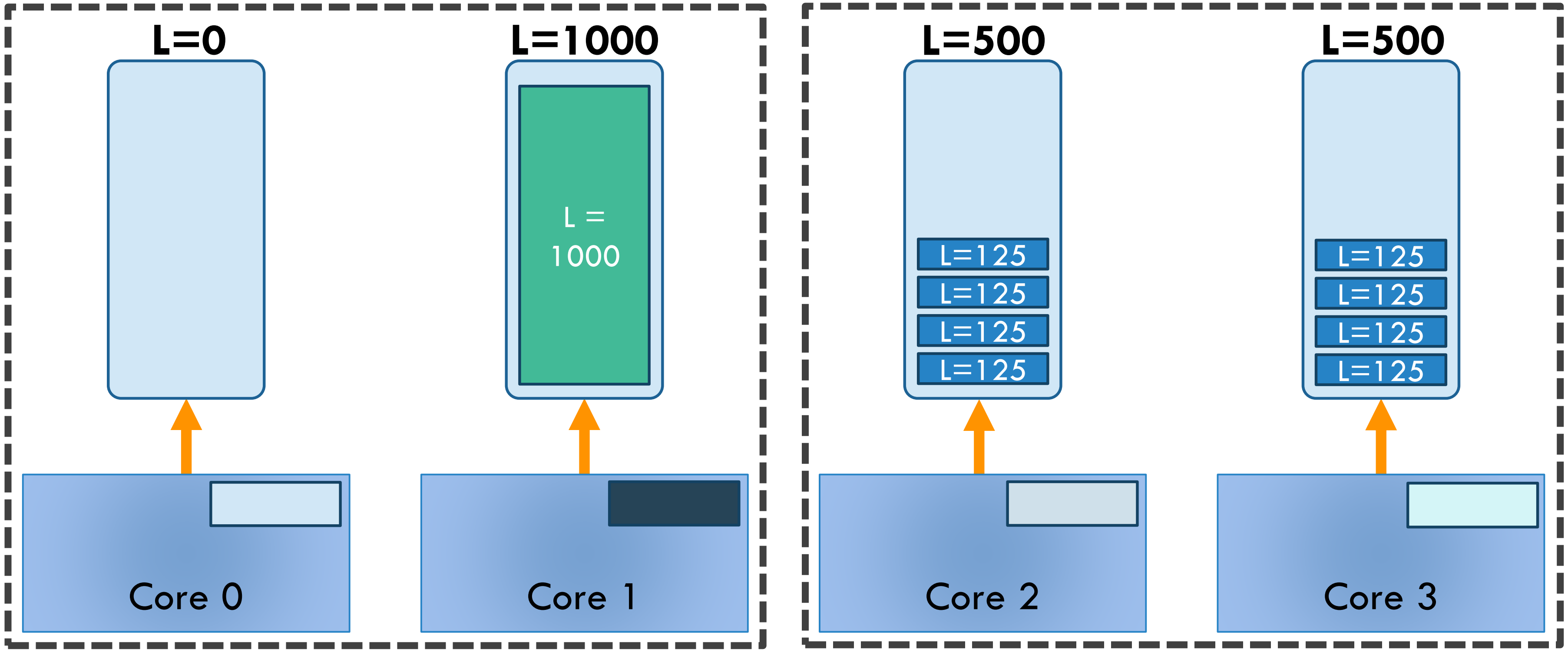

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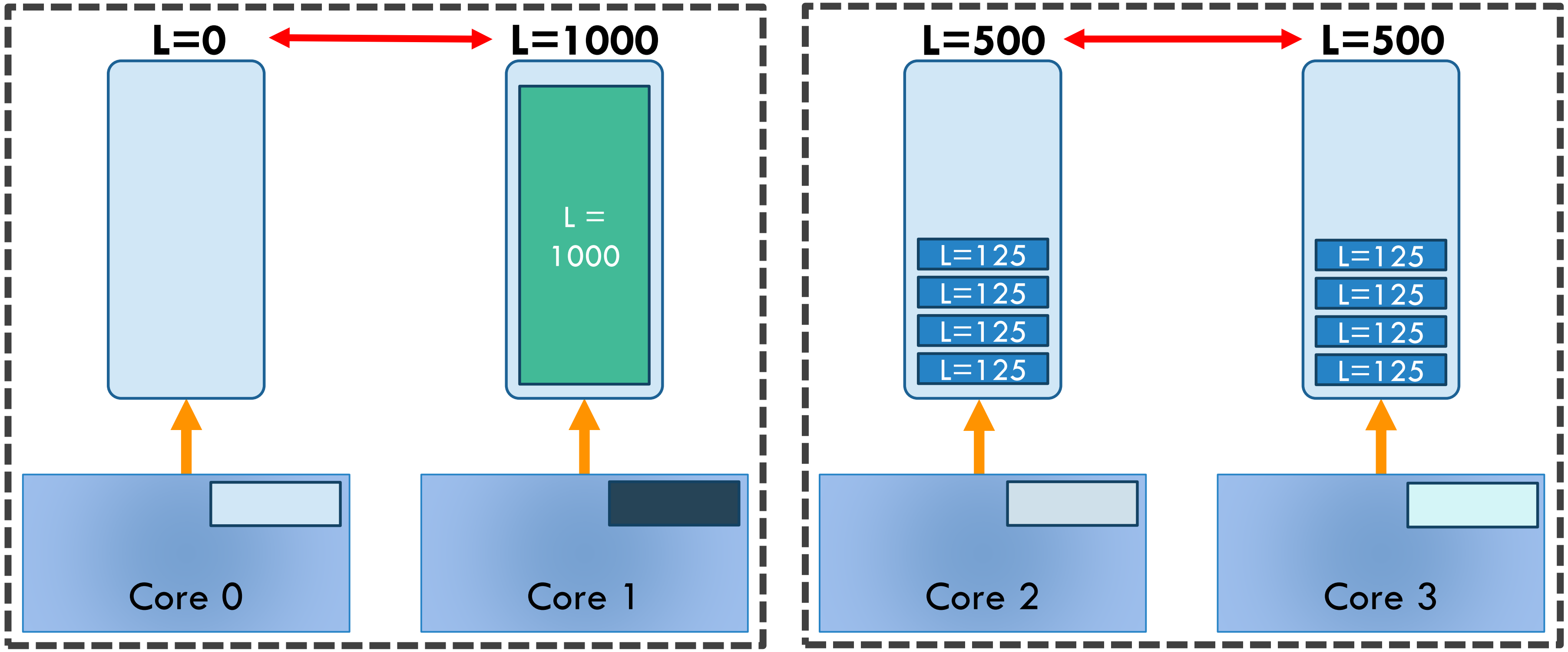

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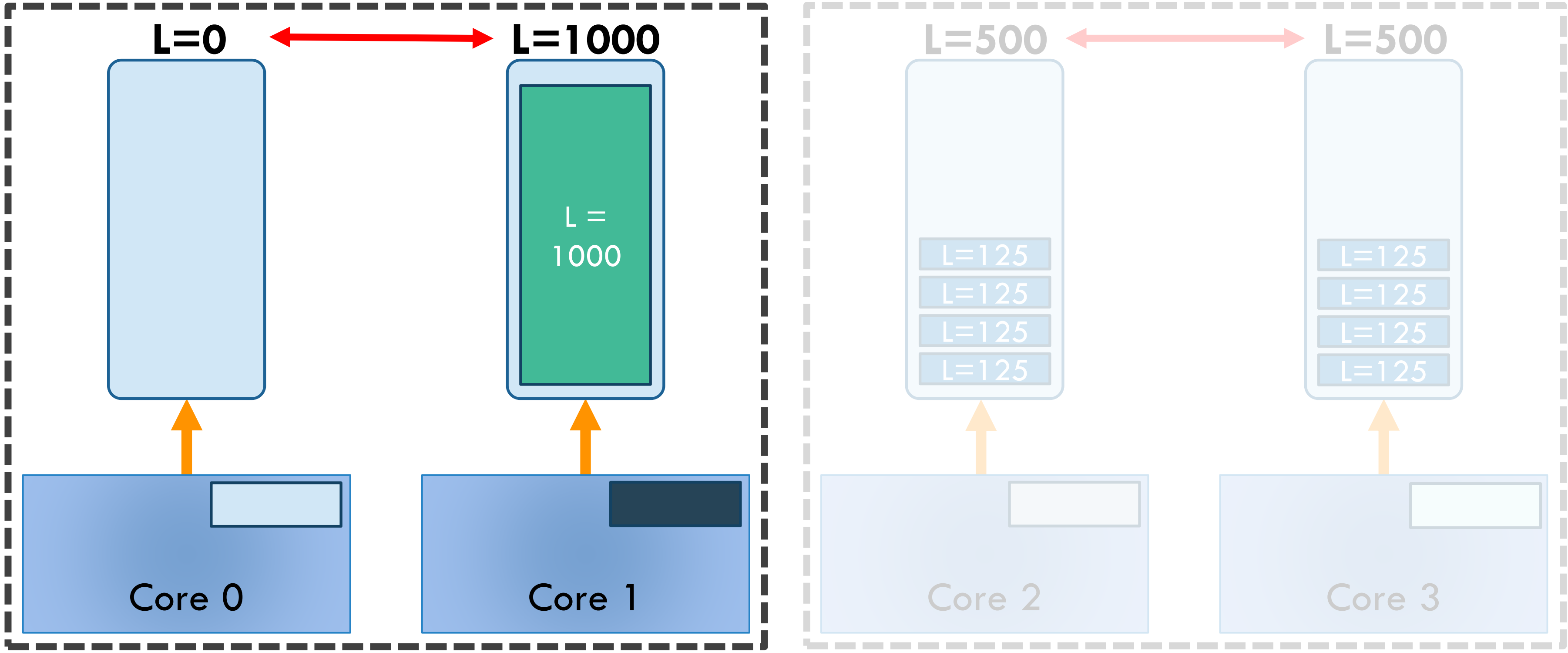

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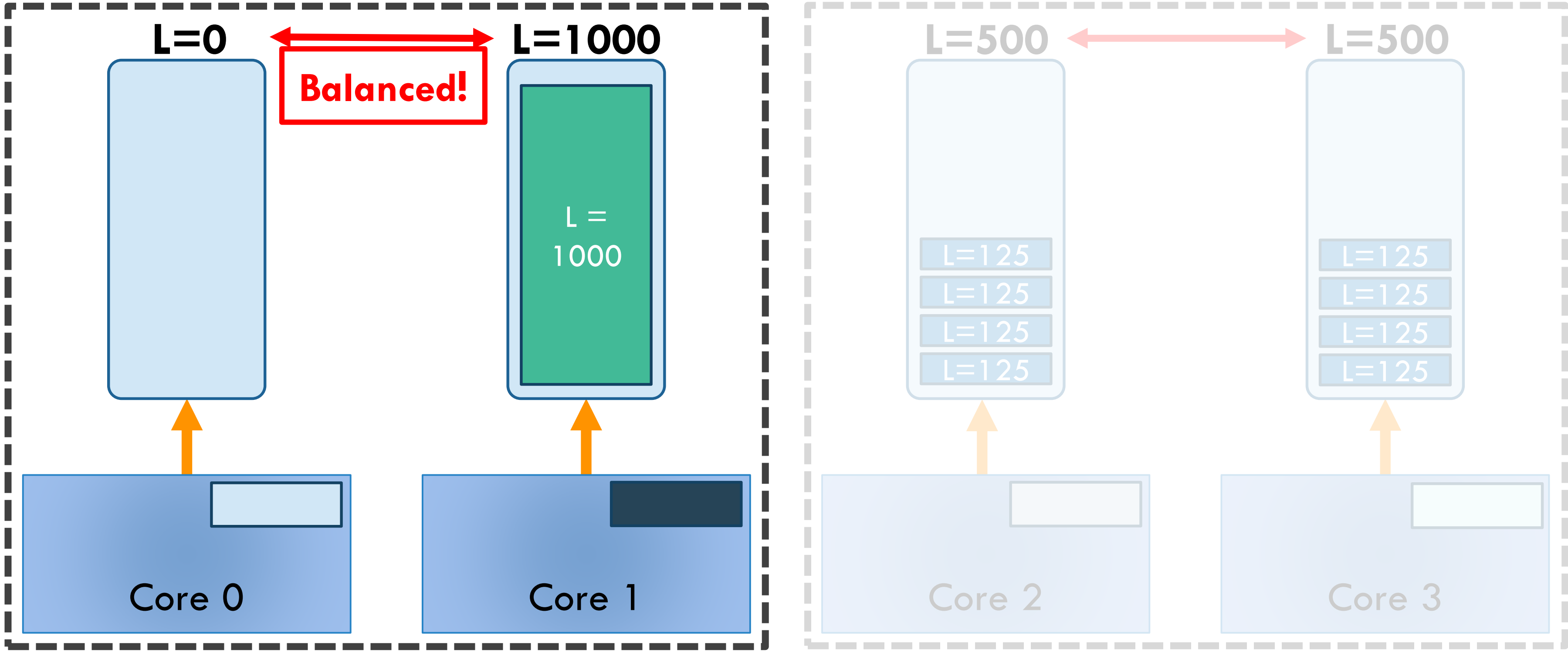

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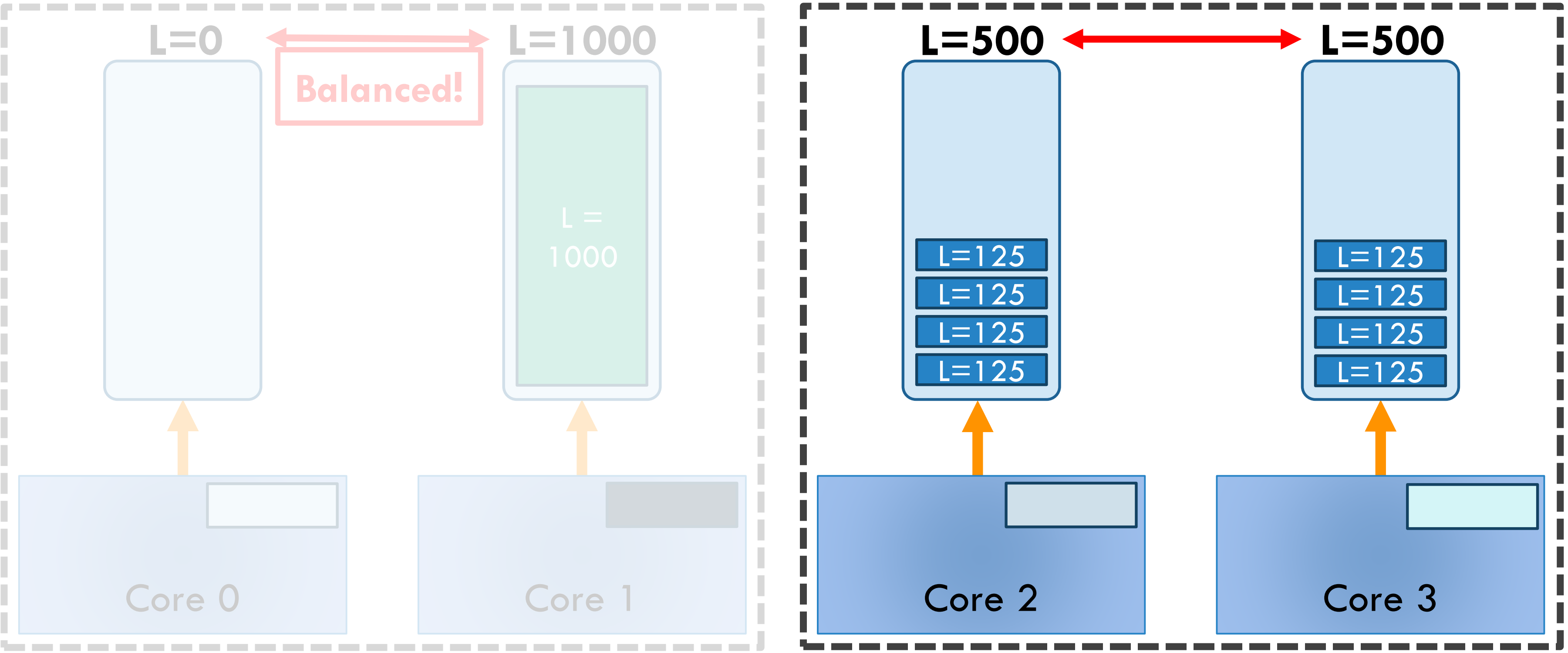

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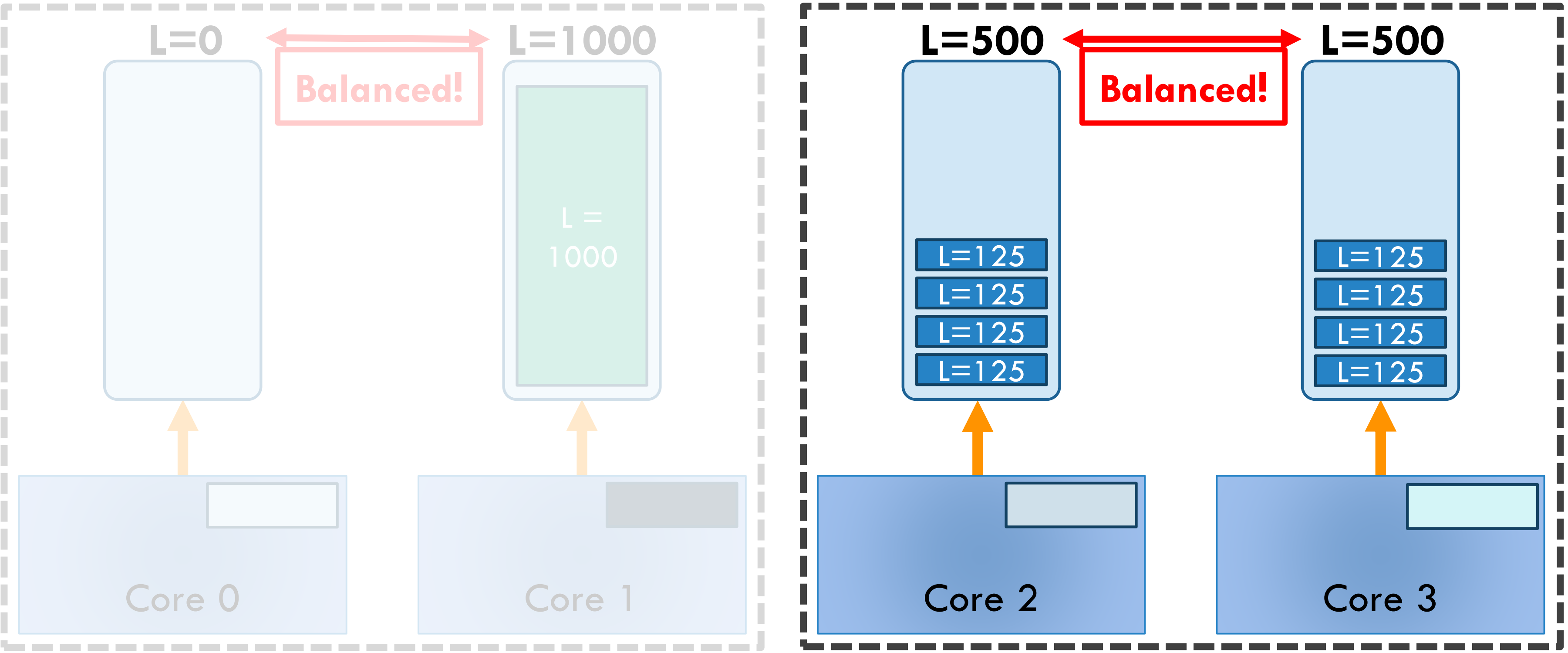

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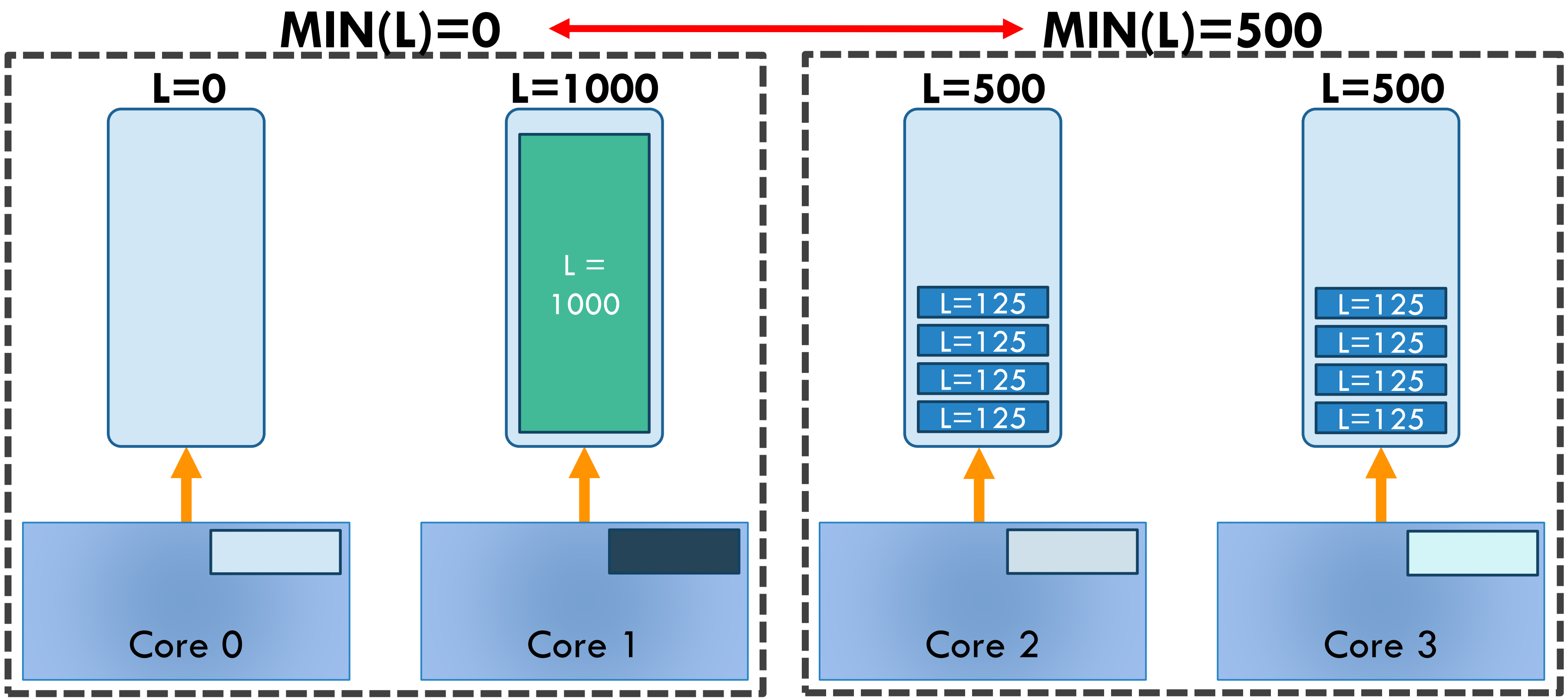

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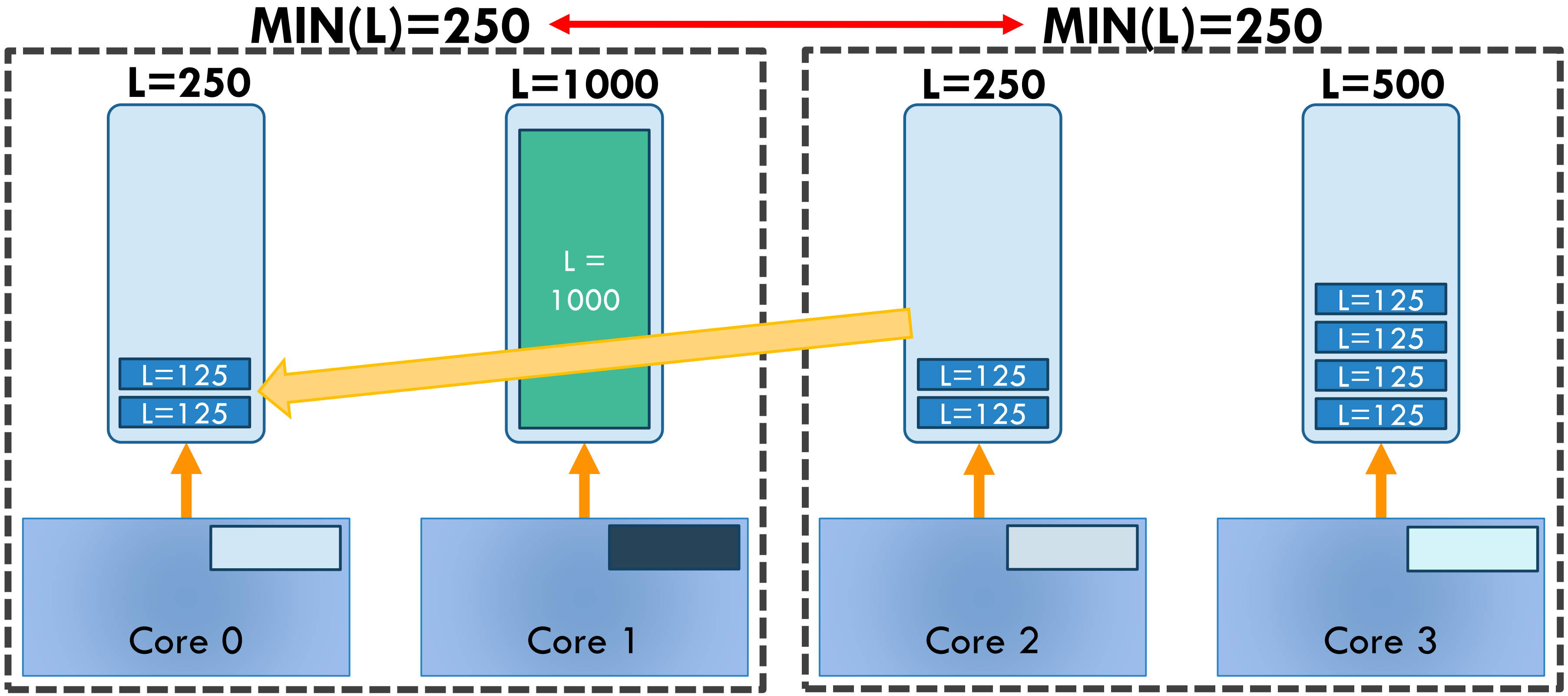

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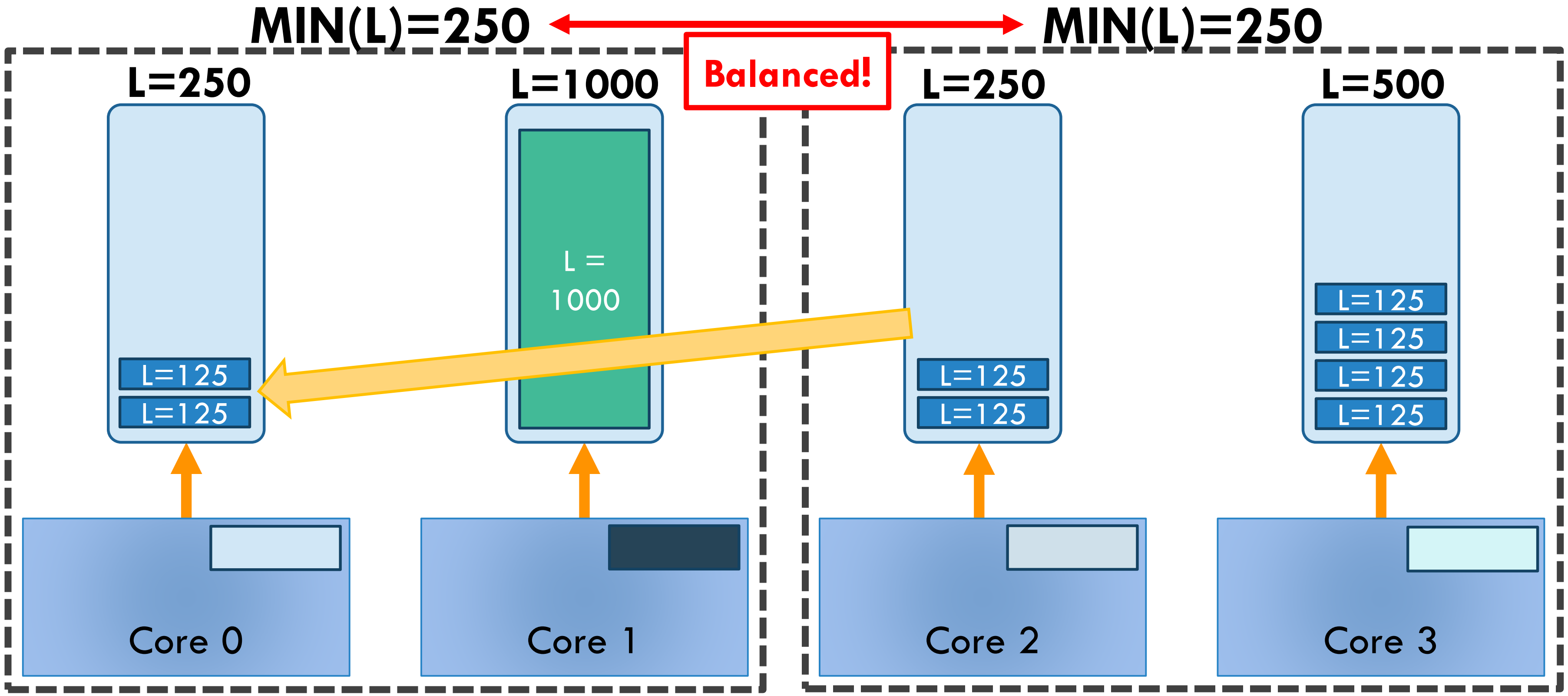

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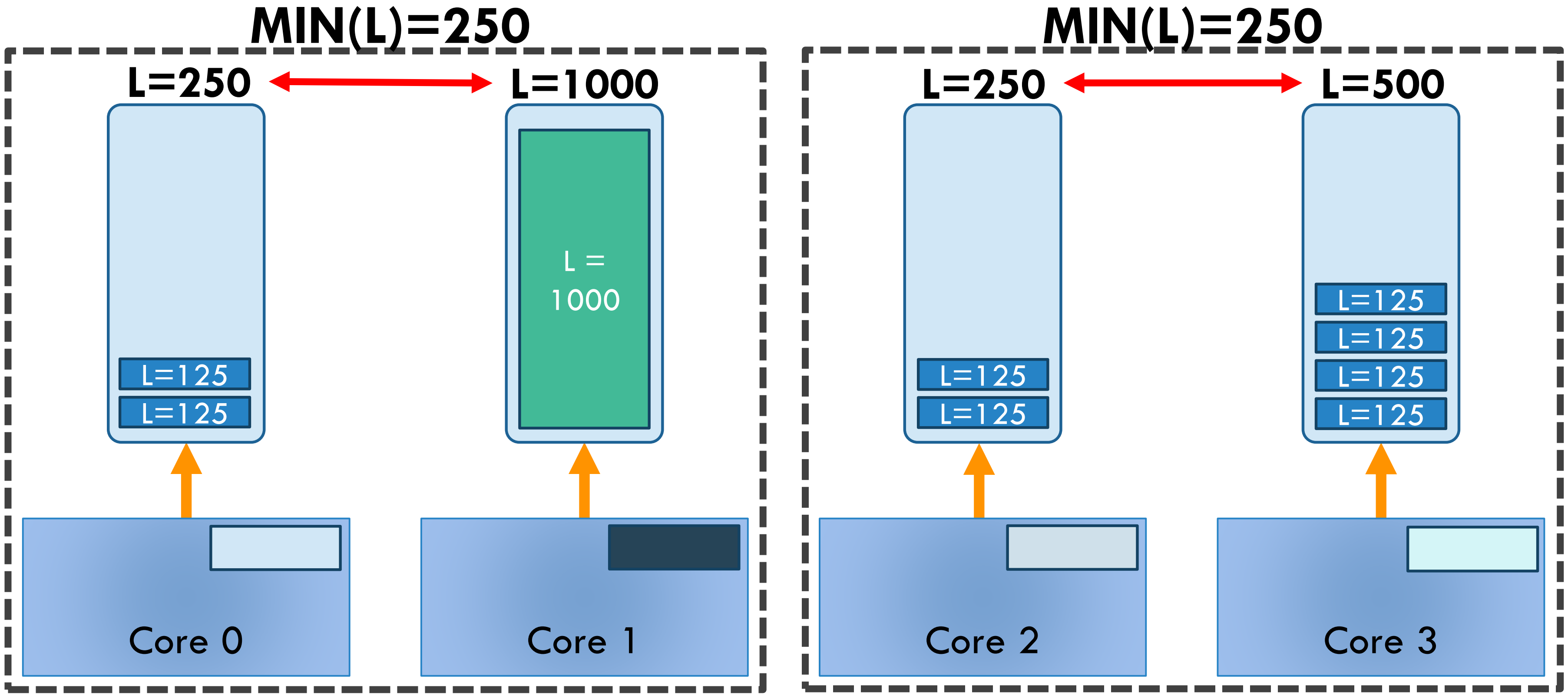

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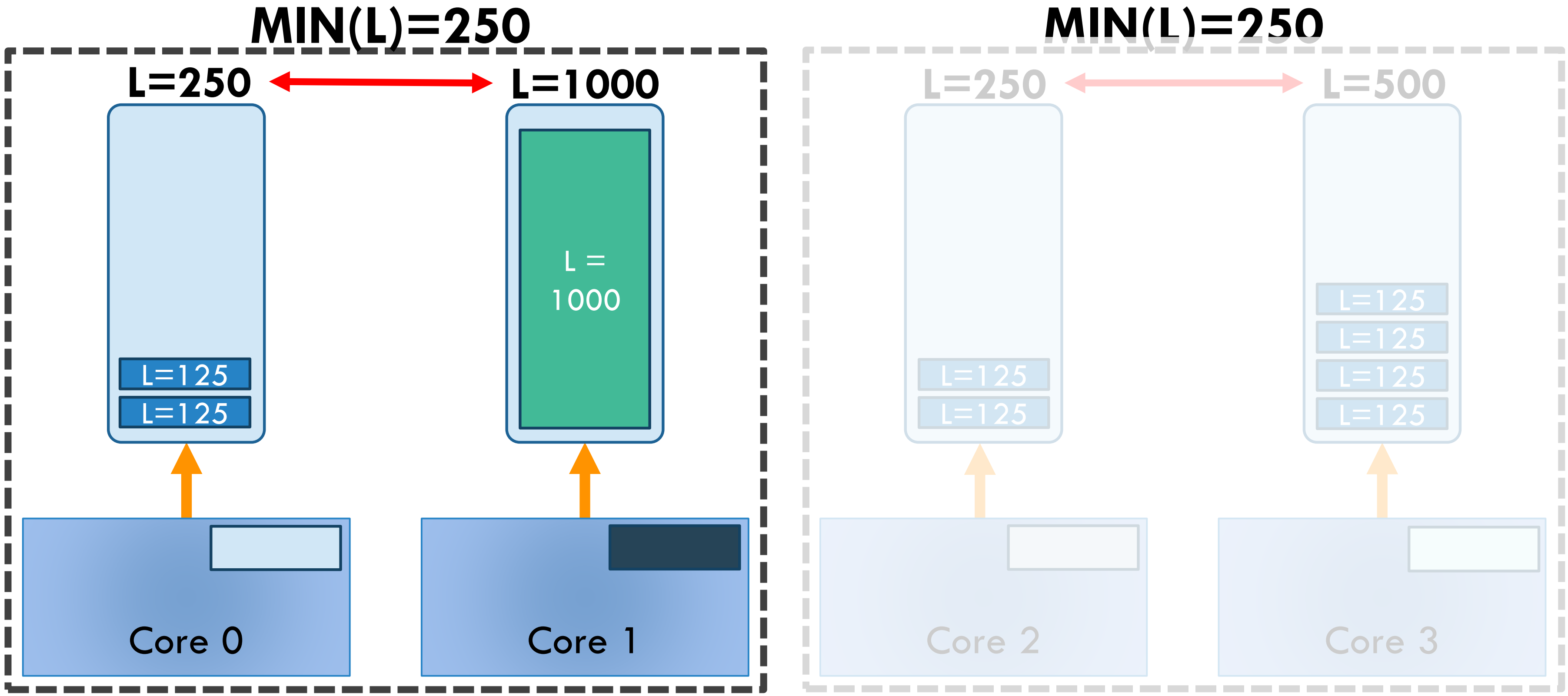

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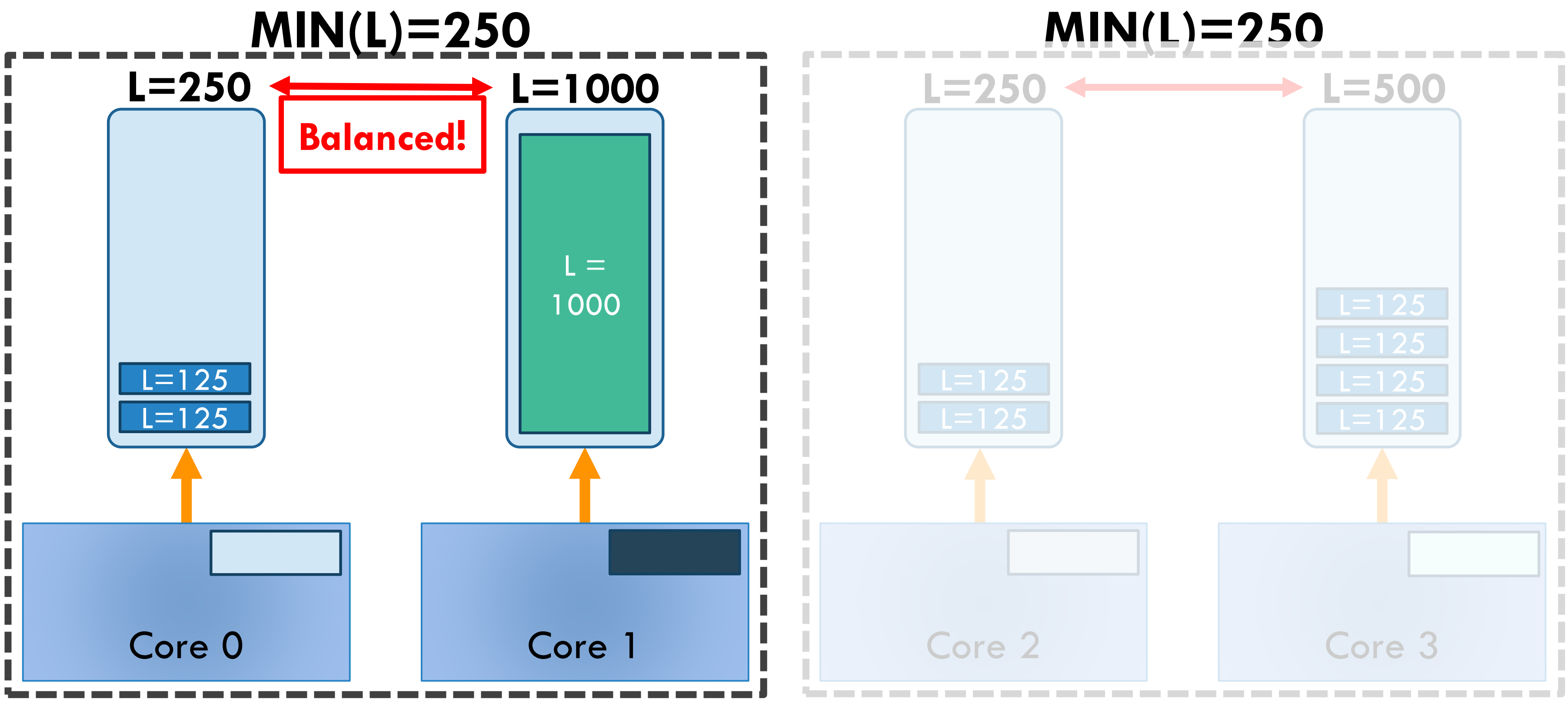

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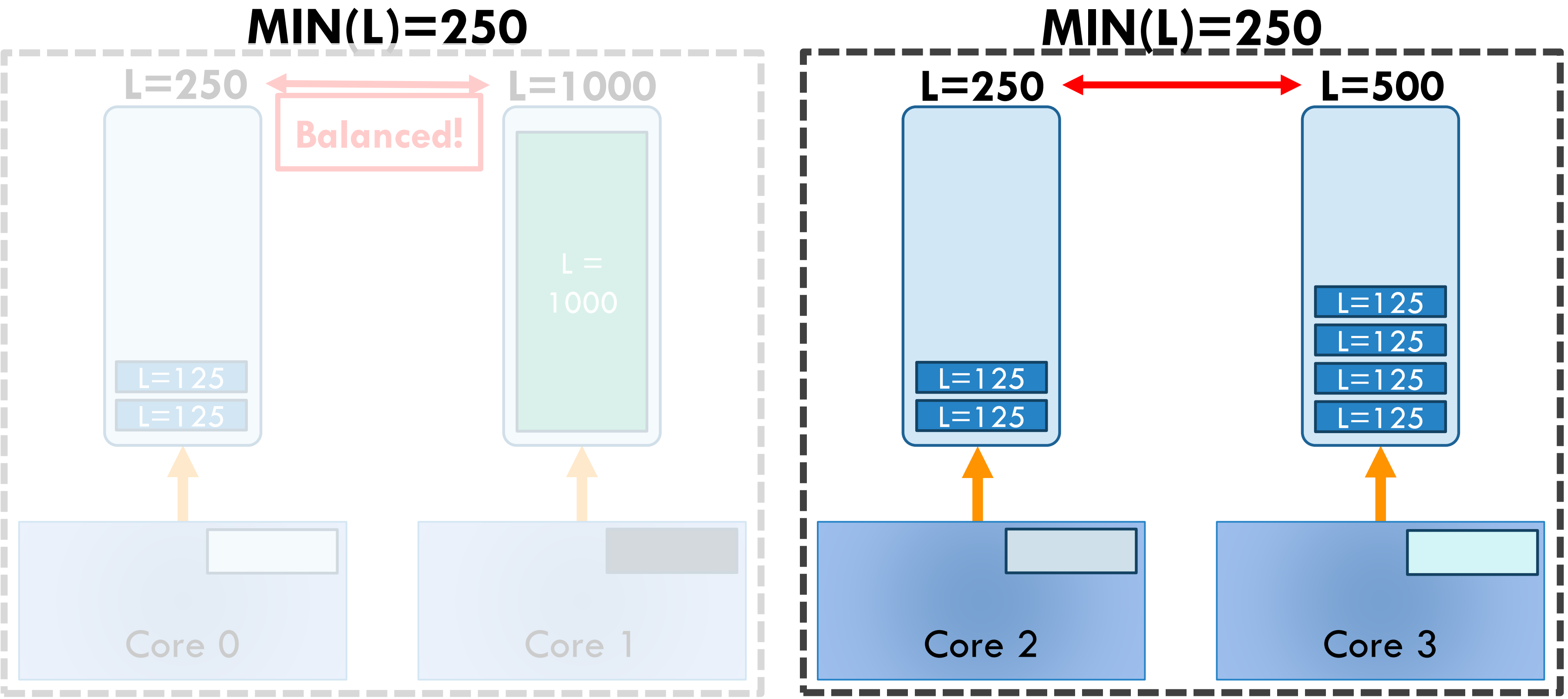

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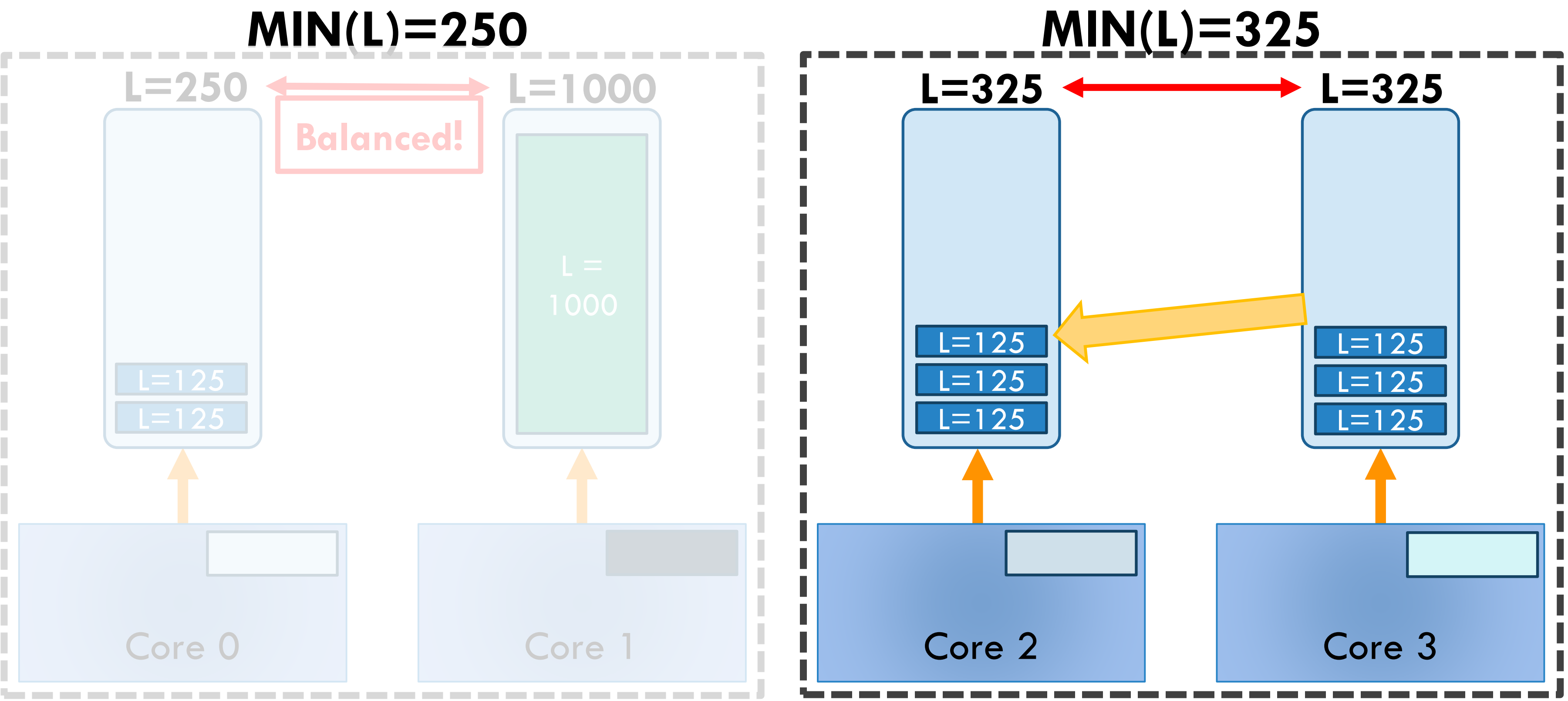

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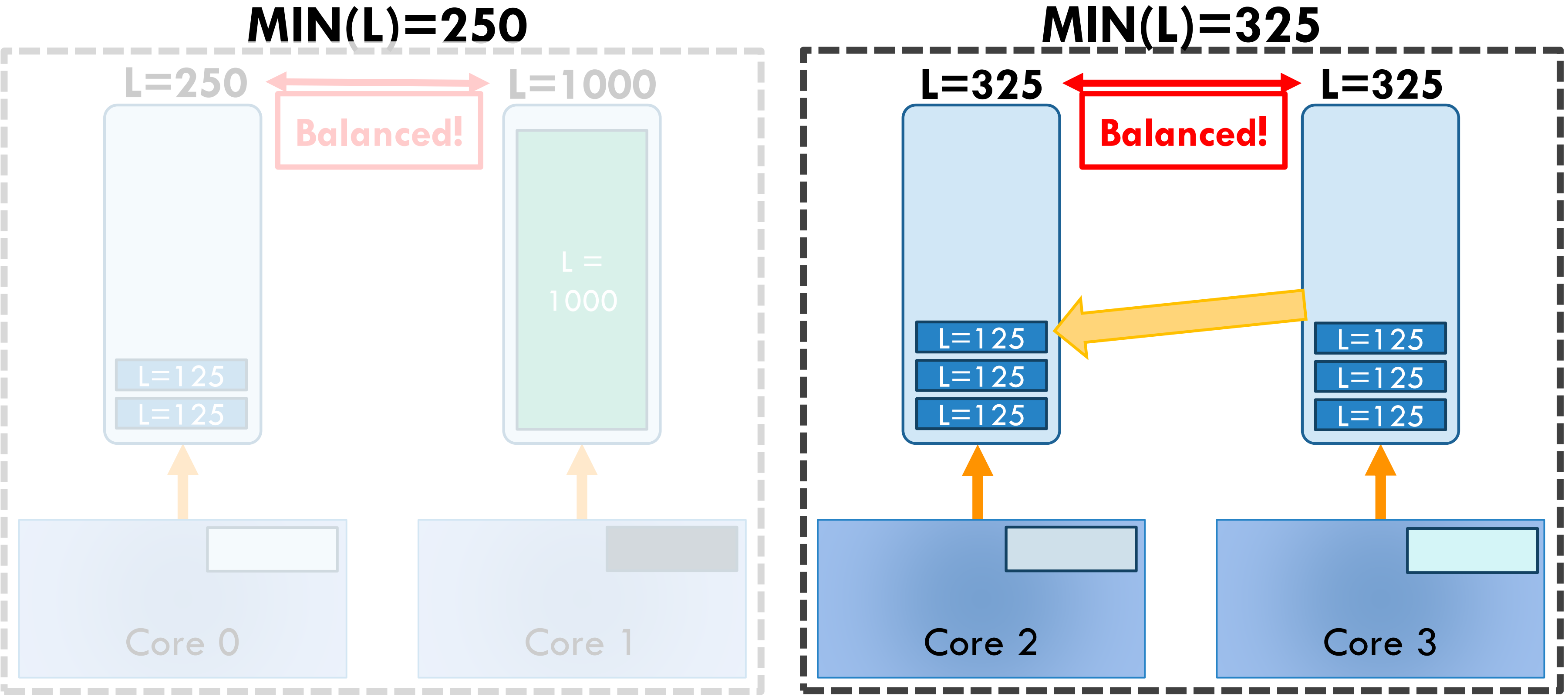

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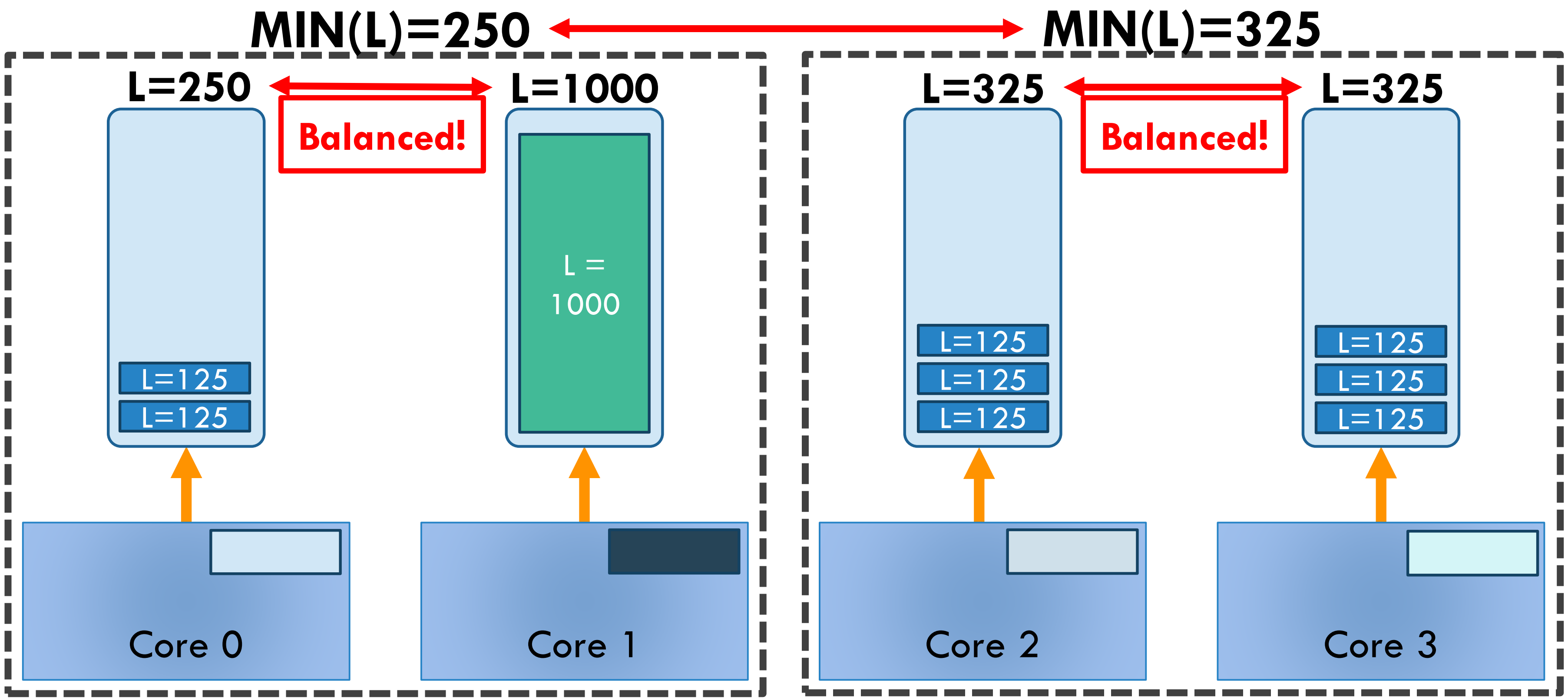

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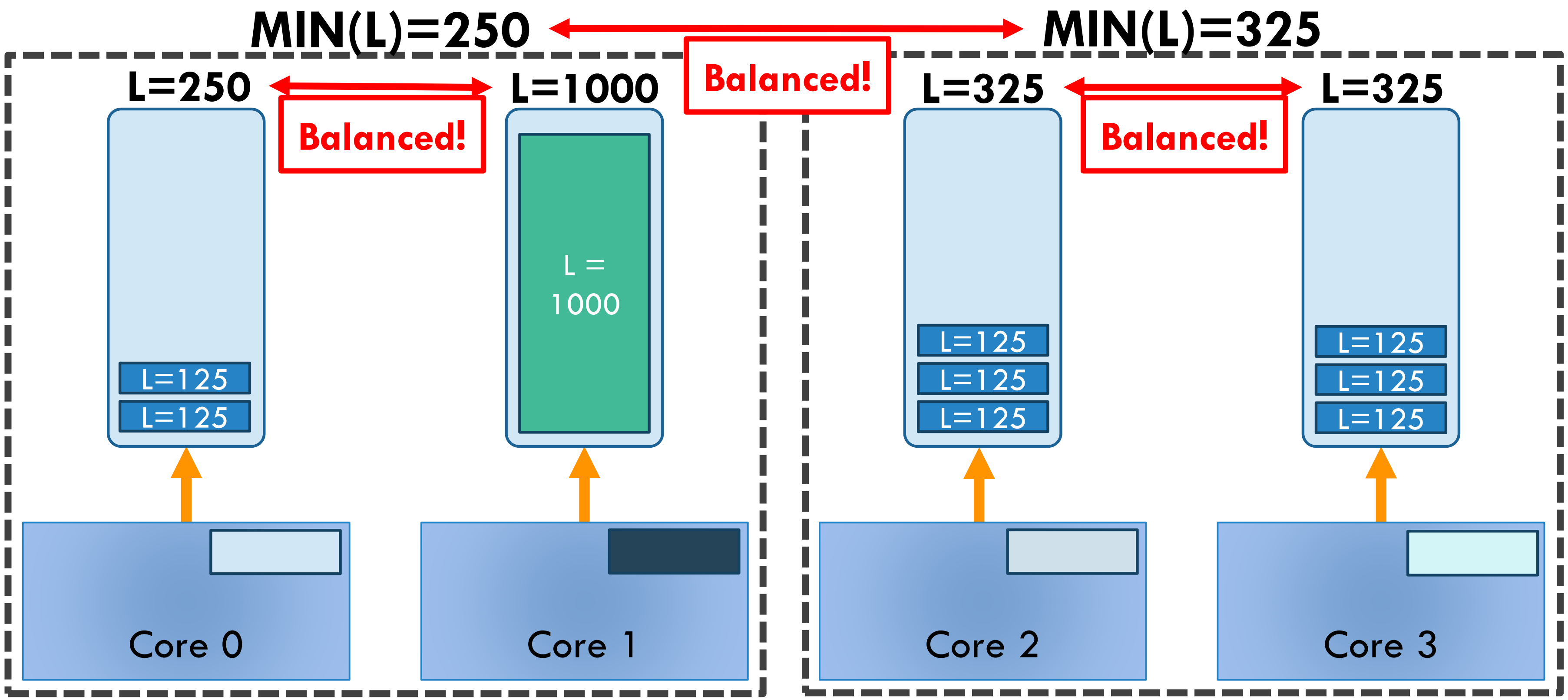

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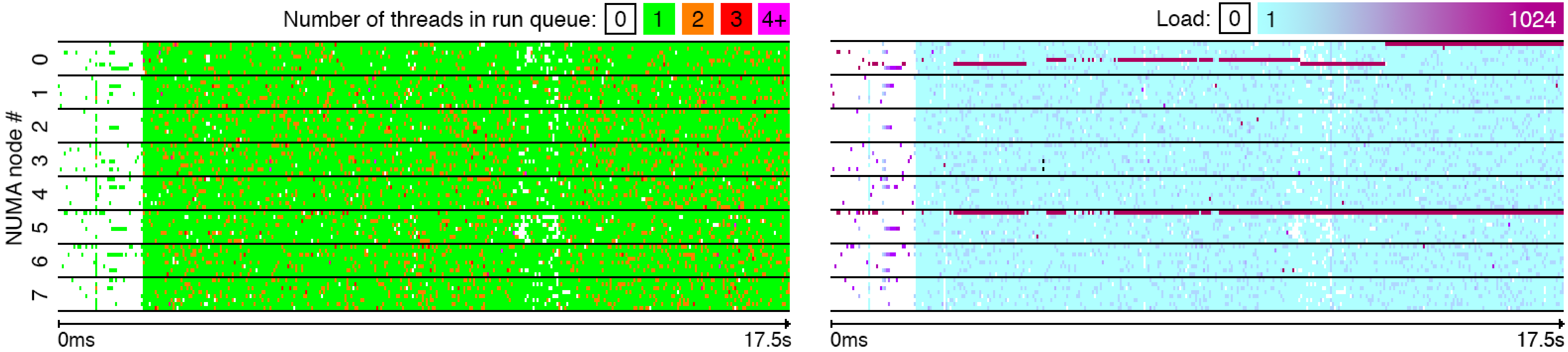

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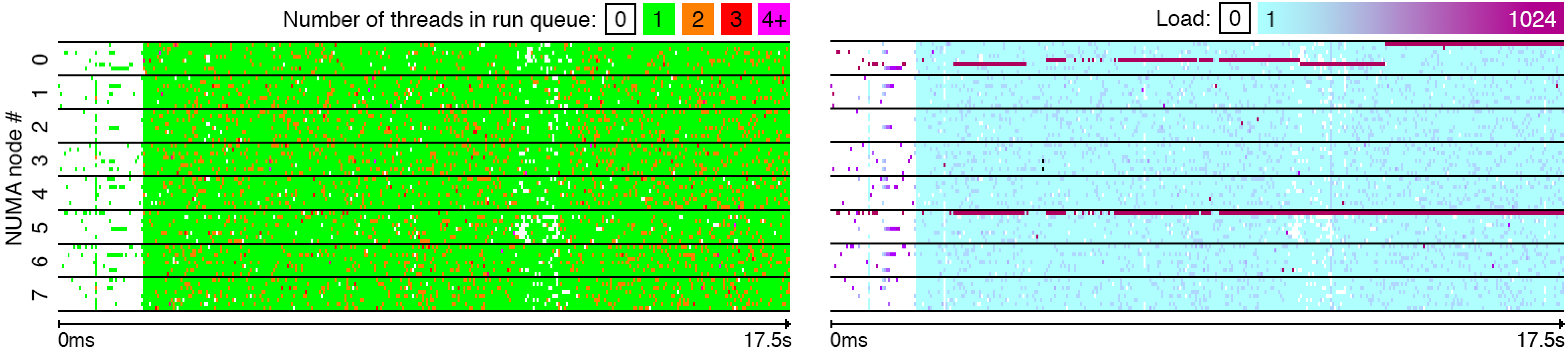


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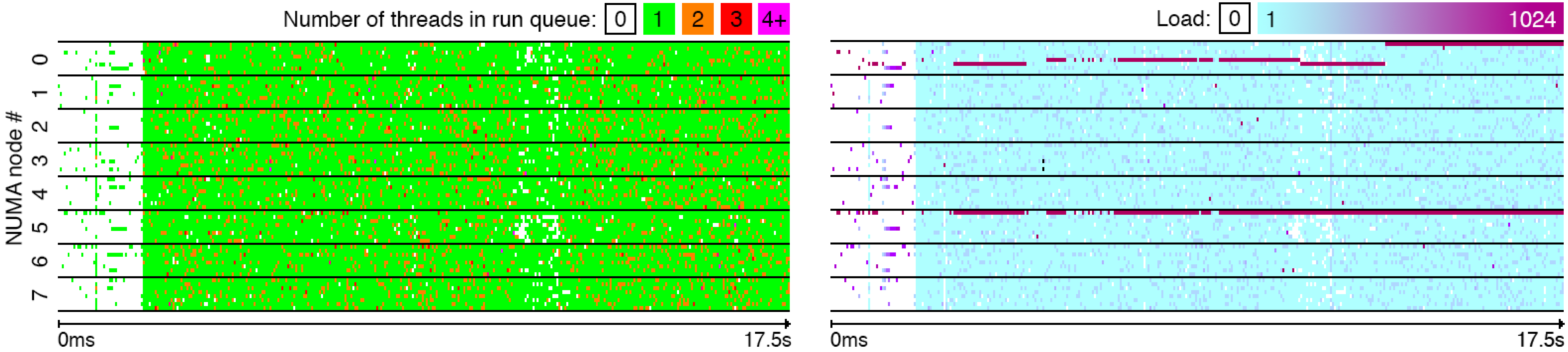


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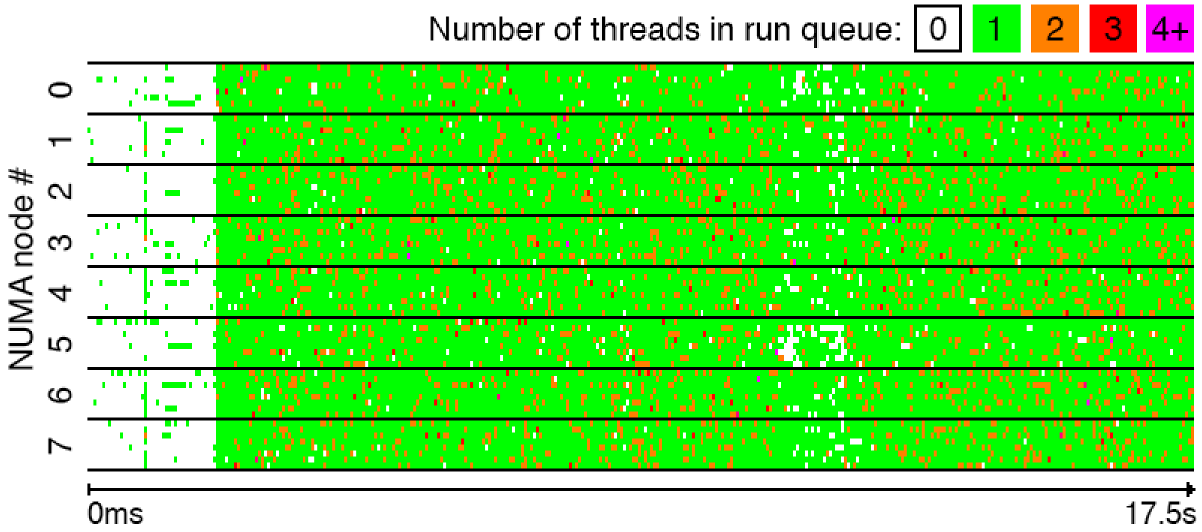


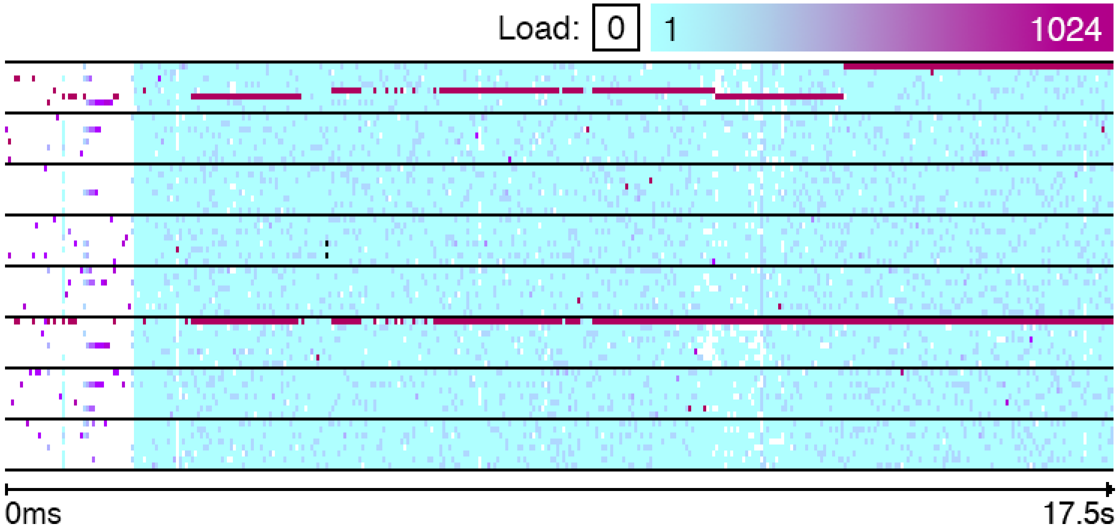


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  - *May cause lots of unnecessary rebalancing. Revamping load calculations needed?*

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

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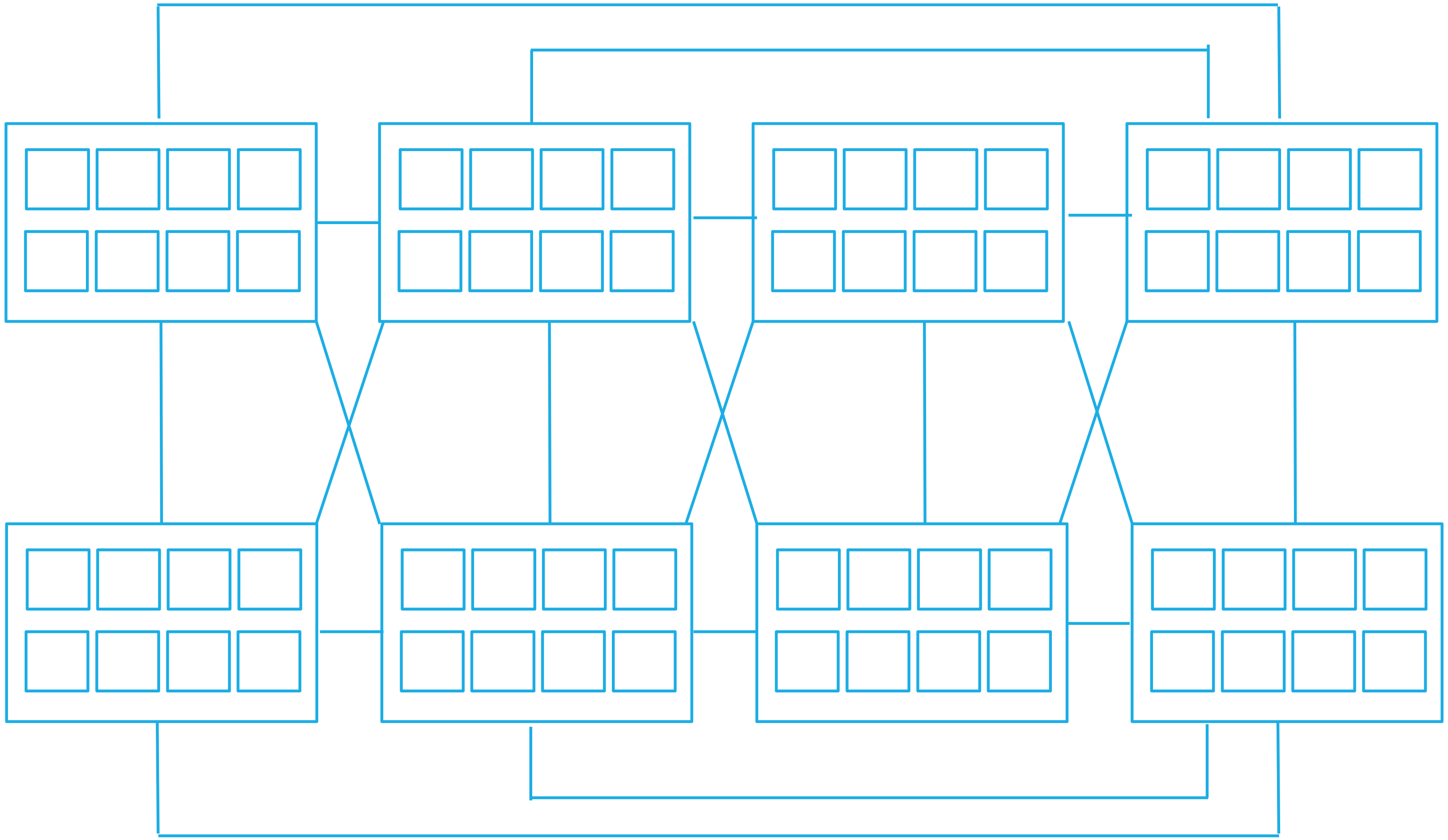

**Bulldozer 64-core:**
Eight CPUs, with
8 cores each,
**non-complete**
**interconnect graph!**

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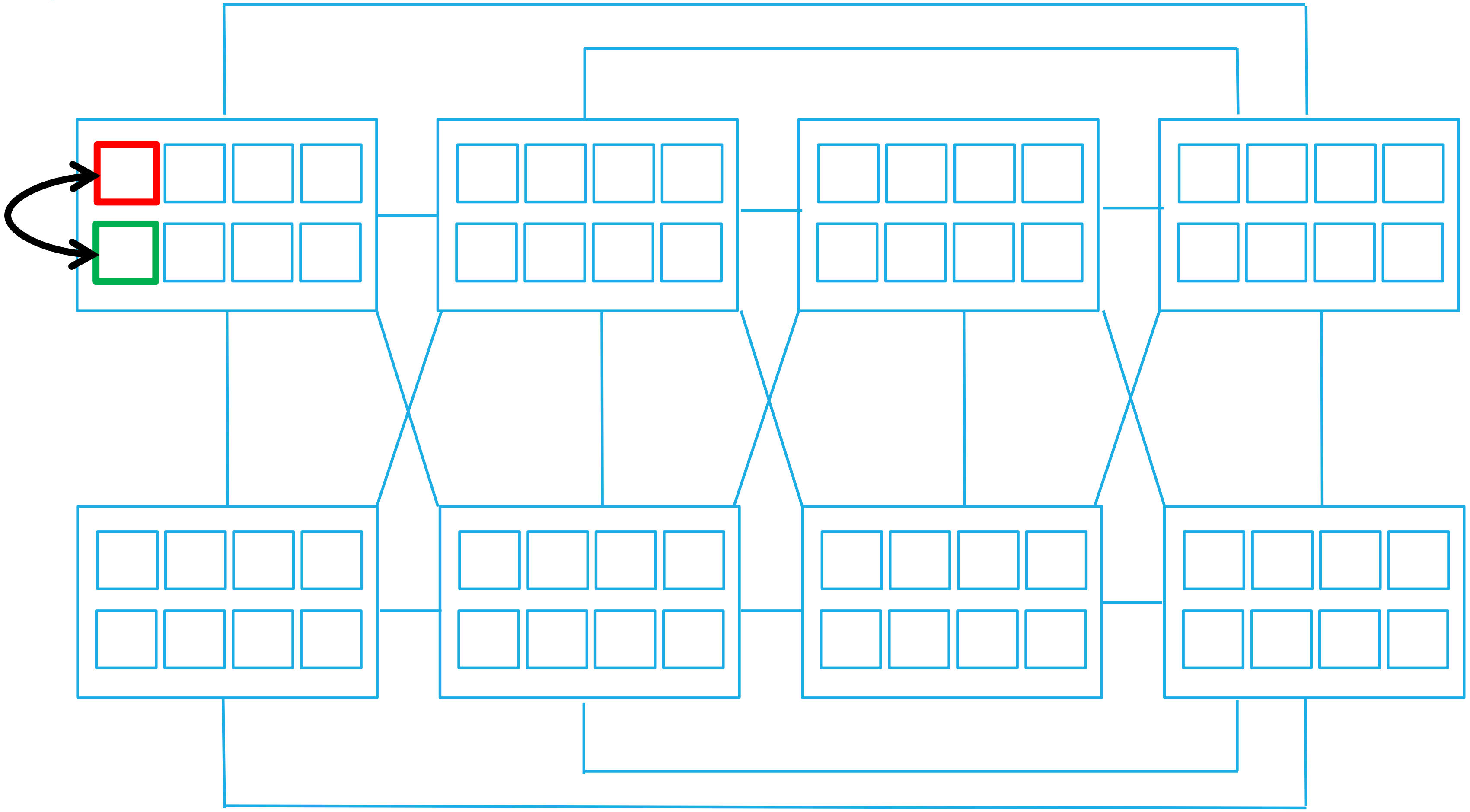

At the **first level**, the **first core** balances load with the other core **on the same pair** (because they share resources, high affinity)

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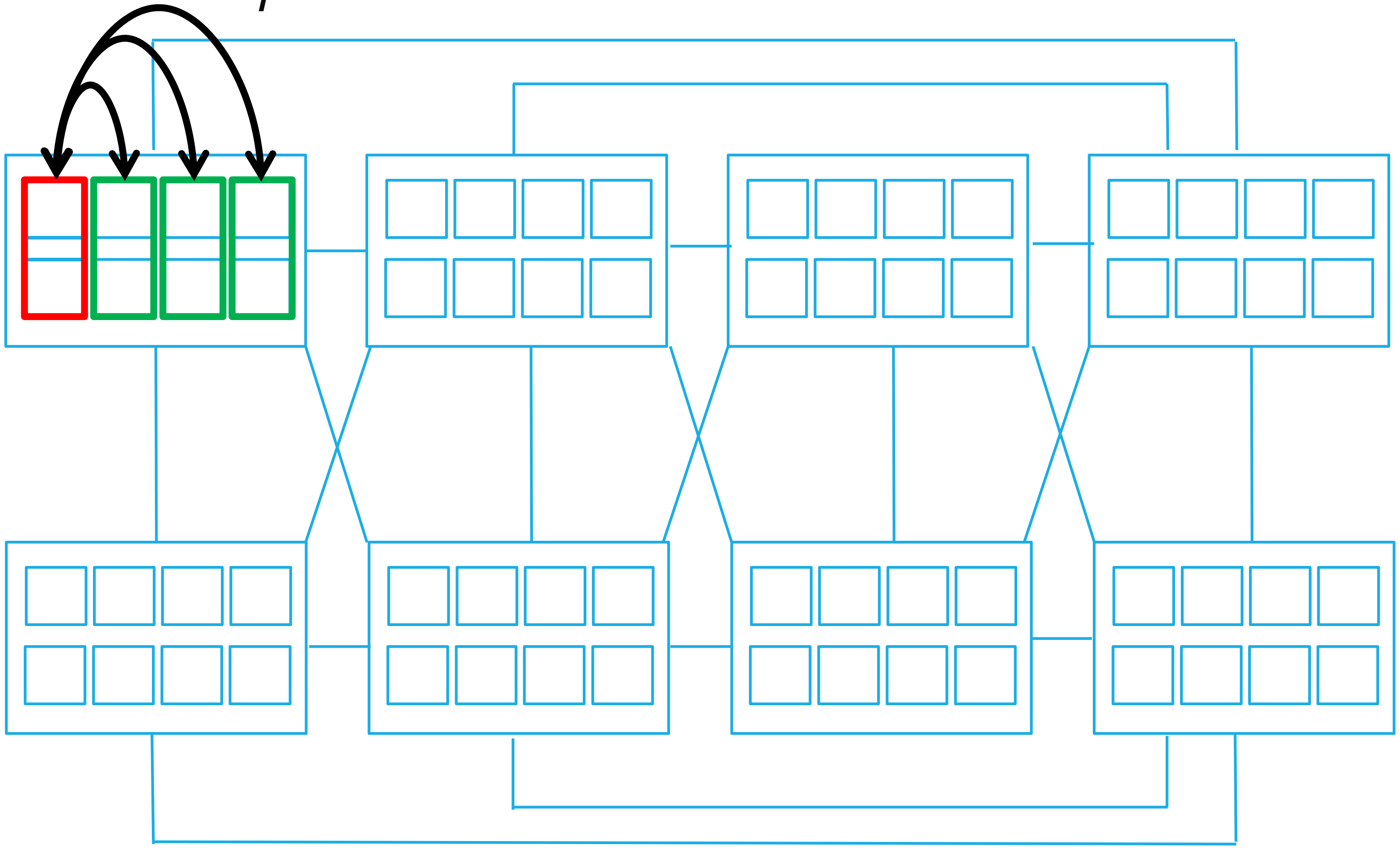

At the **2nd level**, the **first pair** balances load with other pairs **on the same CPU**

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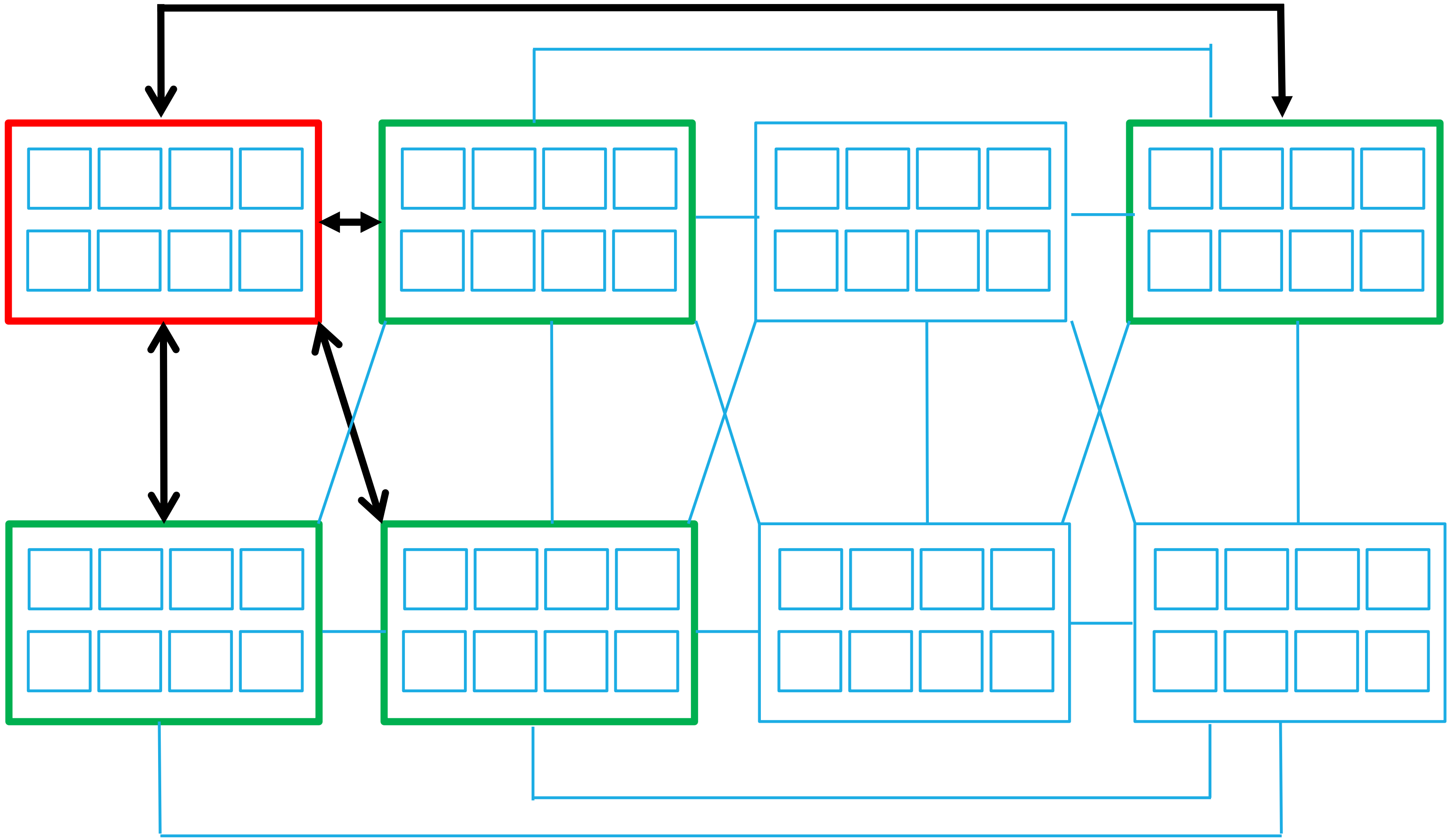

At the **3rd level**, the **first CPU** balances load with **directly connected CPUS**

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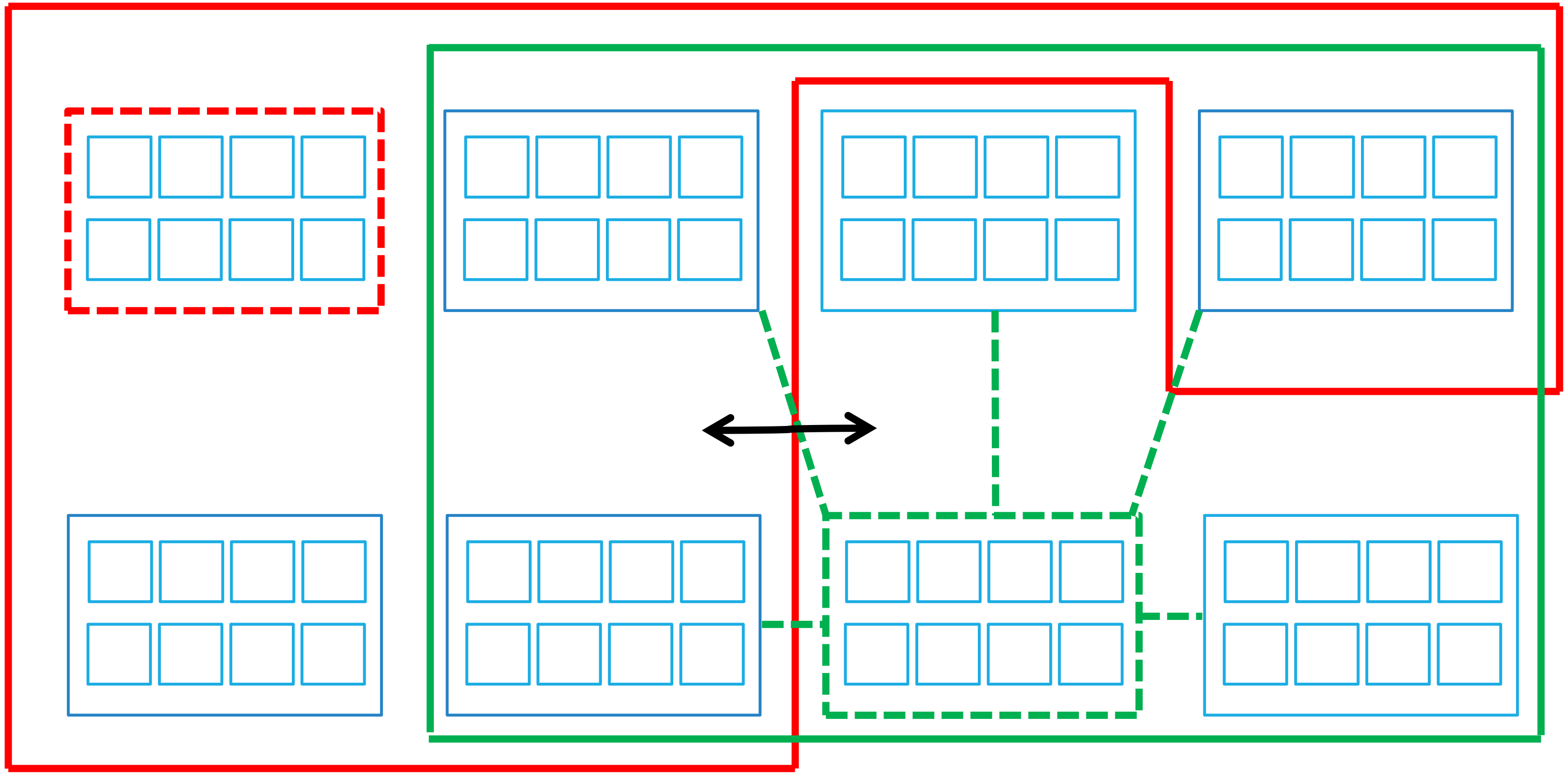

At the 4th level, the **first group of directly connected CPUs** balances load with **the other groups of directly connected CPUs**

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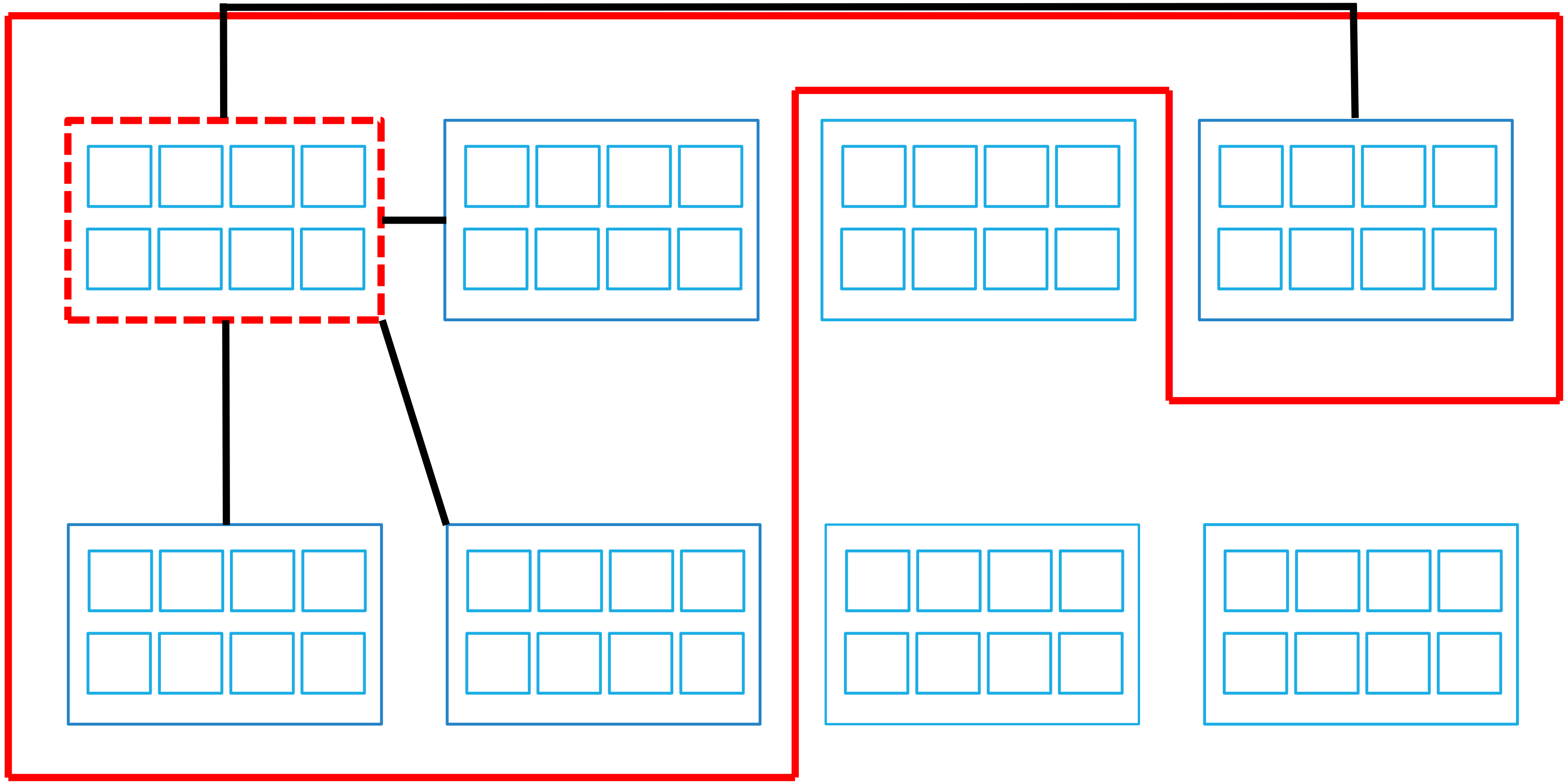

**Groups of CPUs built by:**

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

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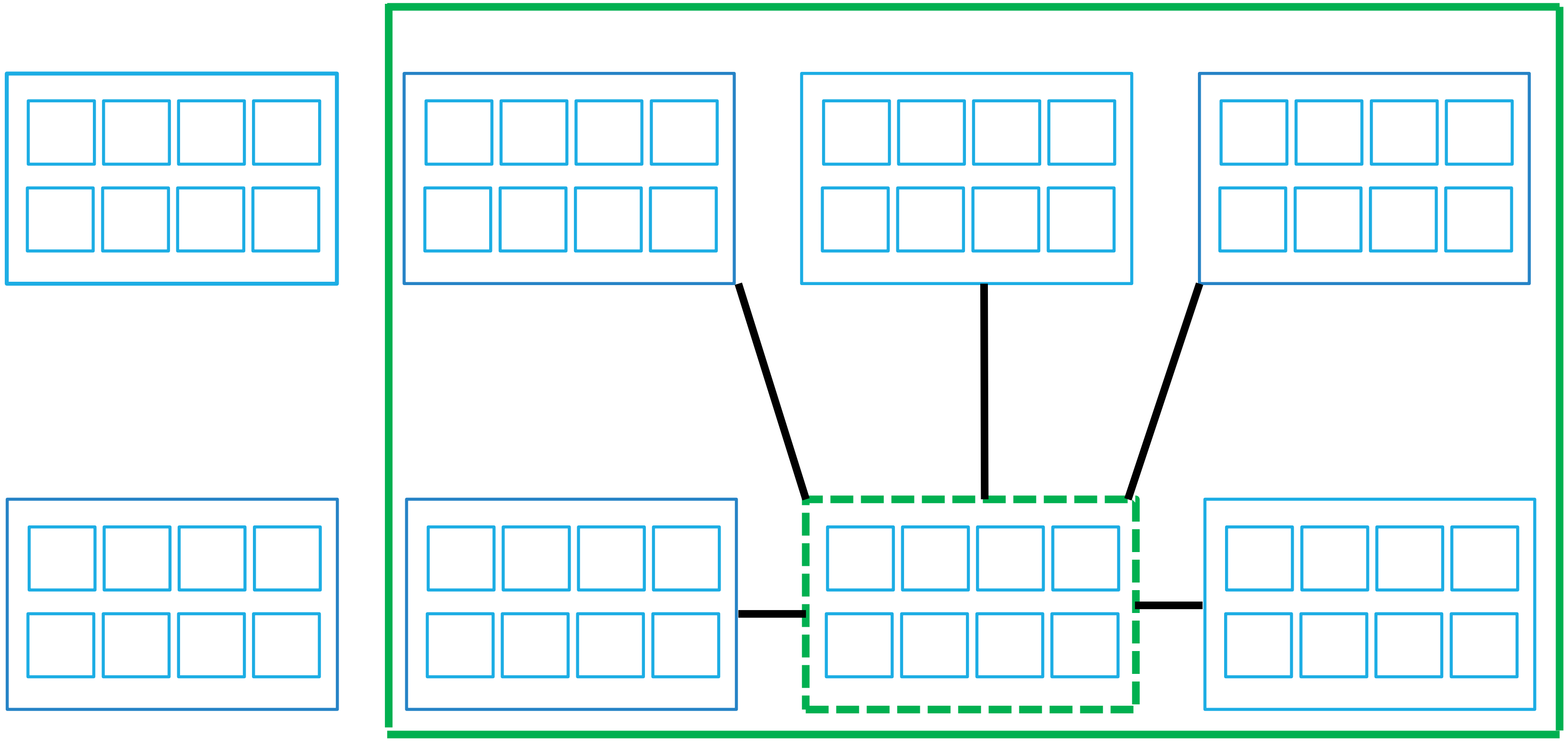

**Groups of CPUs built by:**

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

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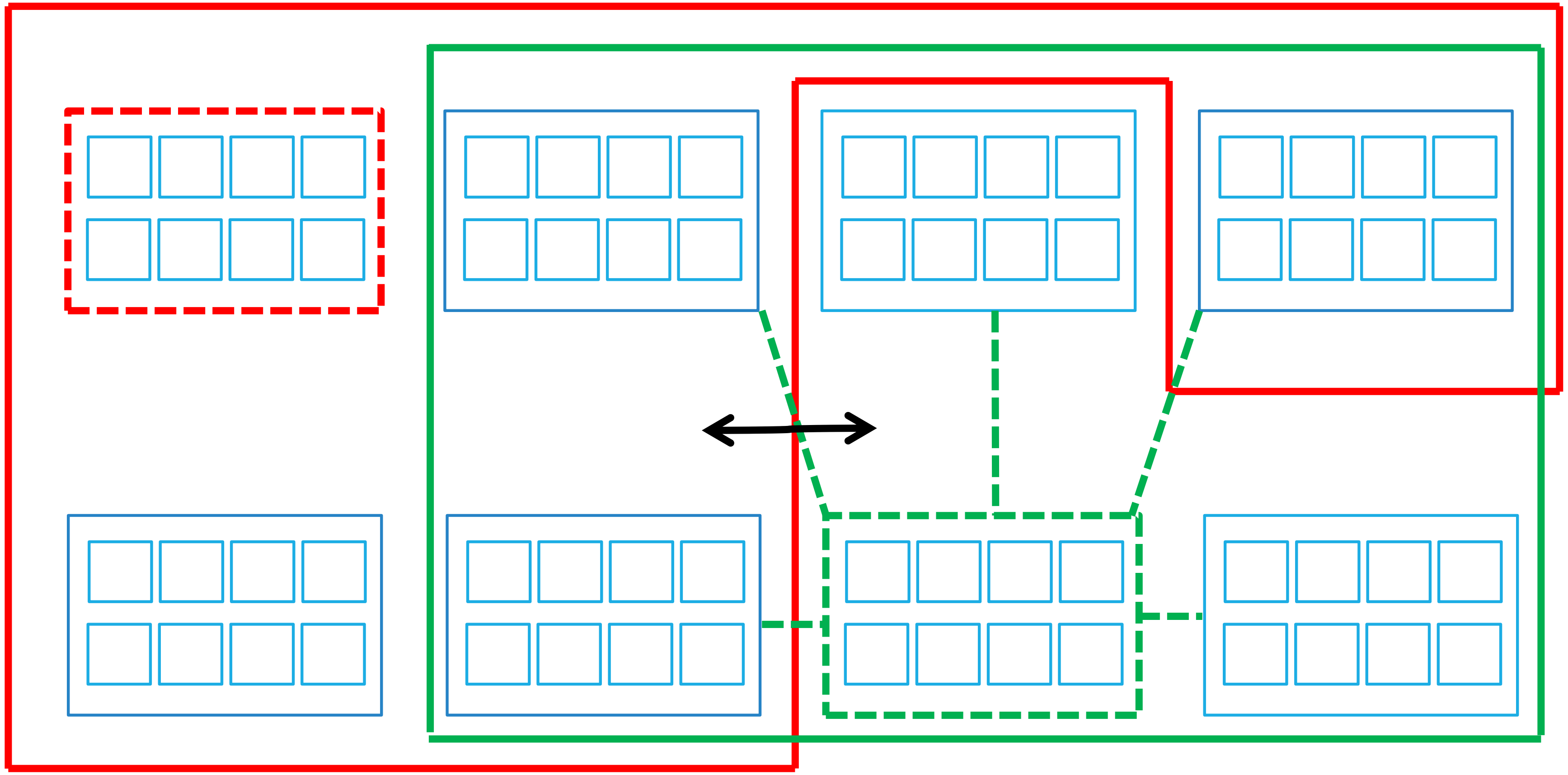

And then stop, **because all CPUs are in a group**

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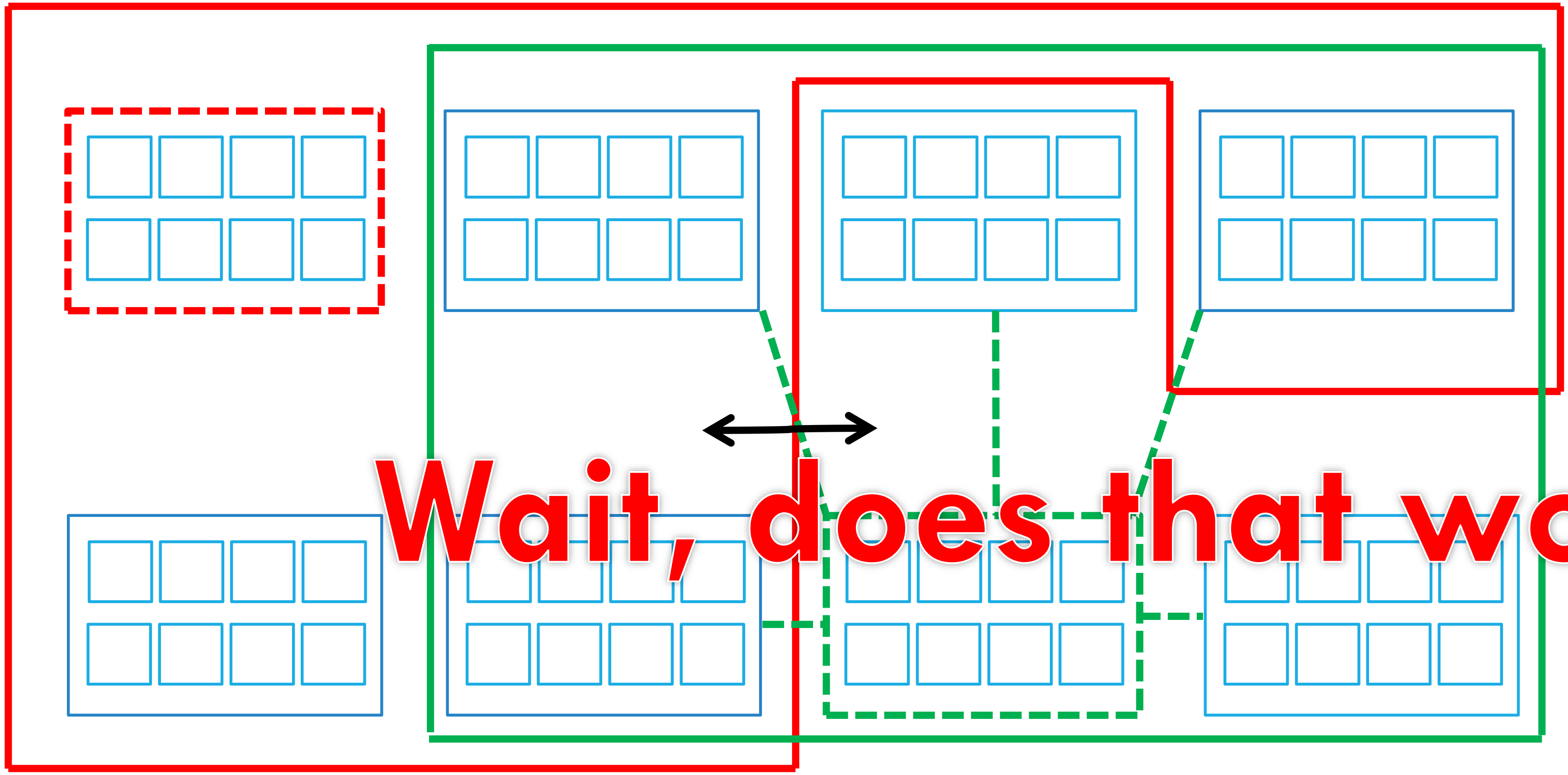

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**Wait, does that work?**

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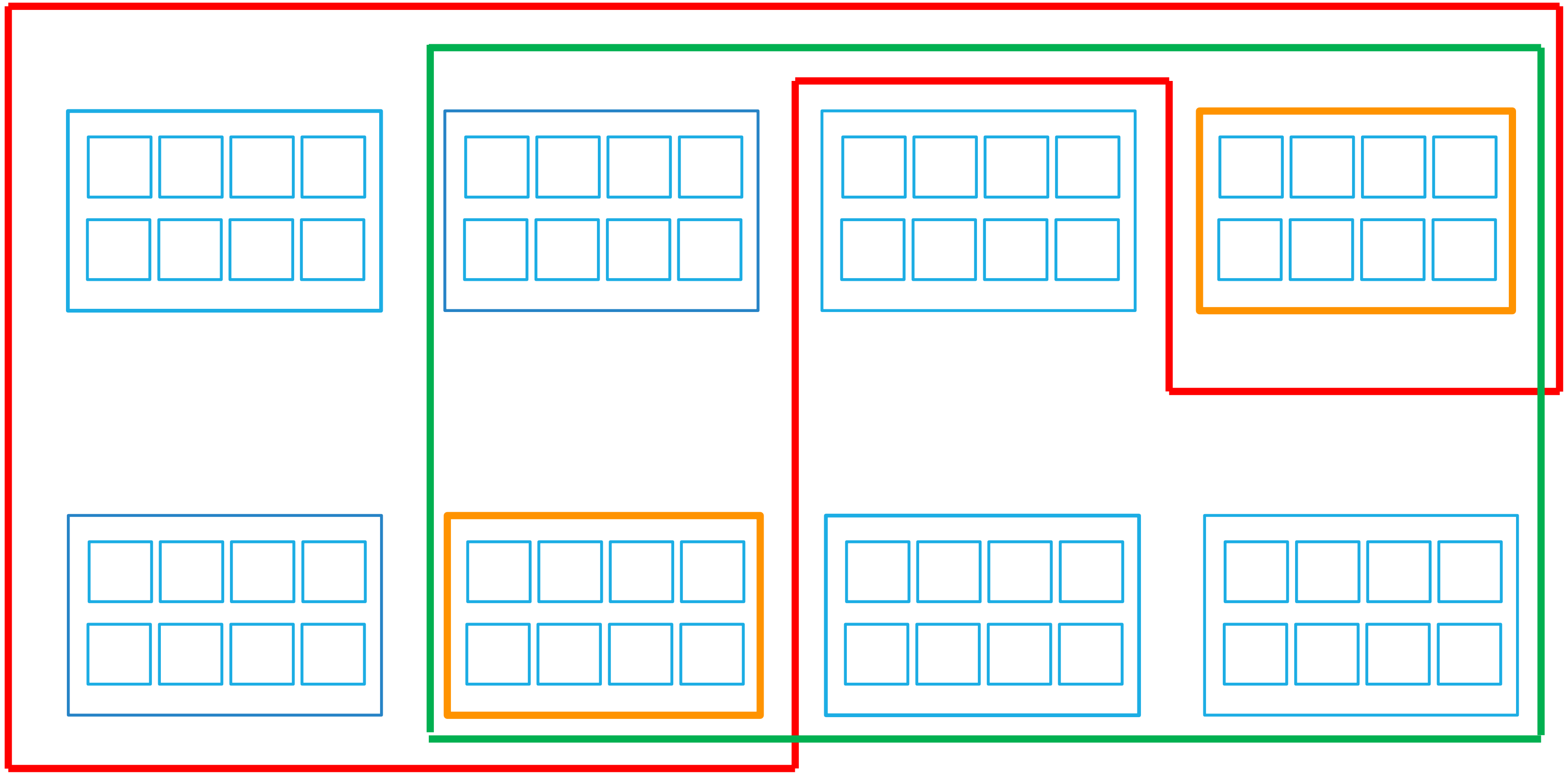

Suppose we taskset an application on **these two nodes,** two hops apart

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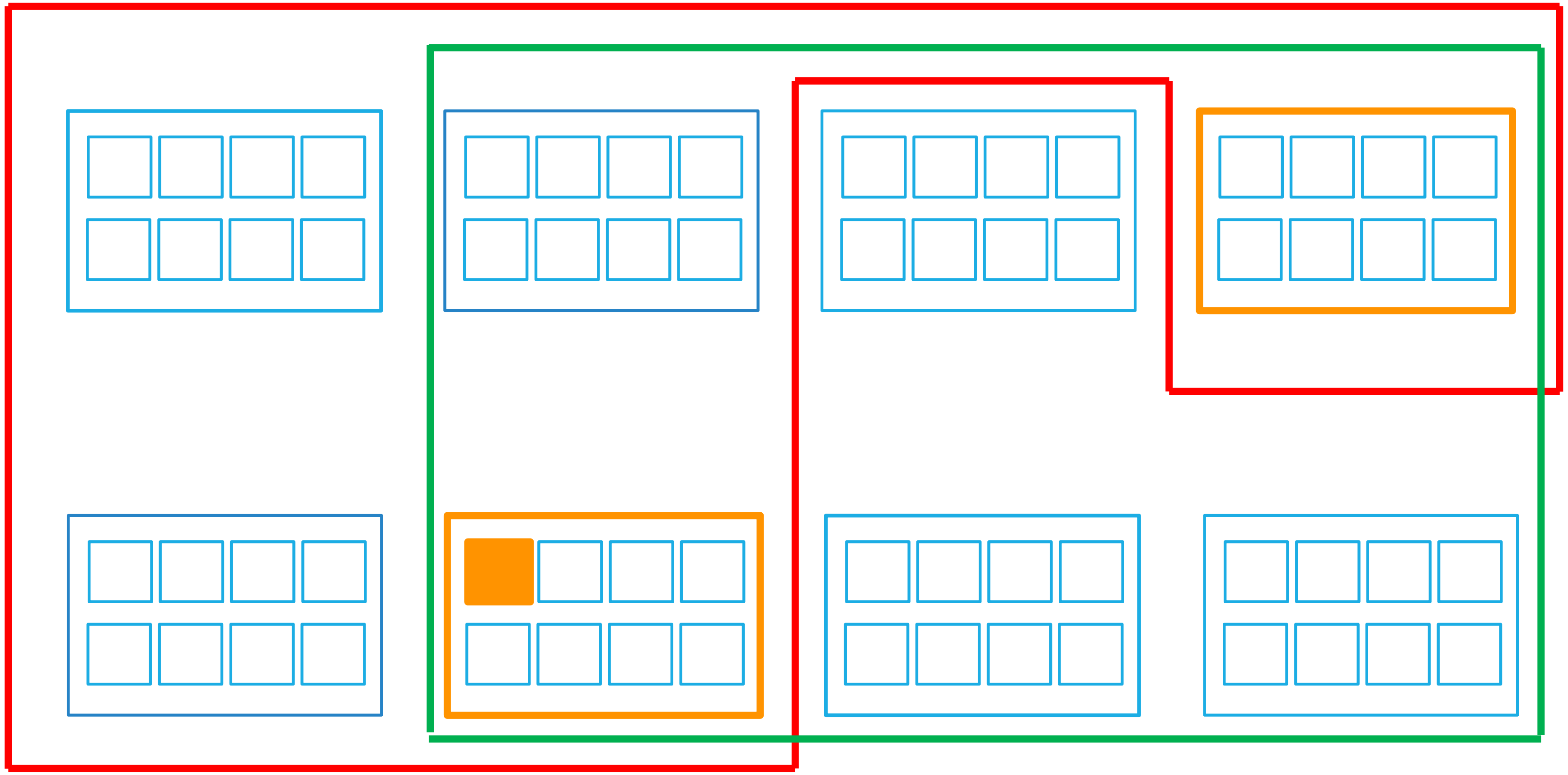

And threads are created **on this core**

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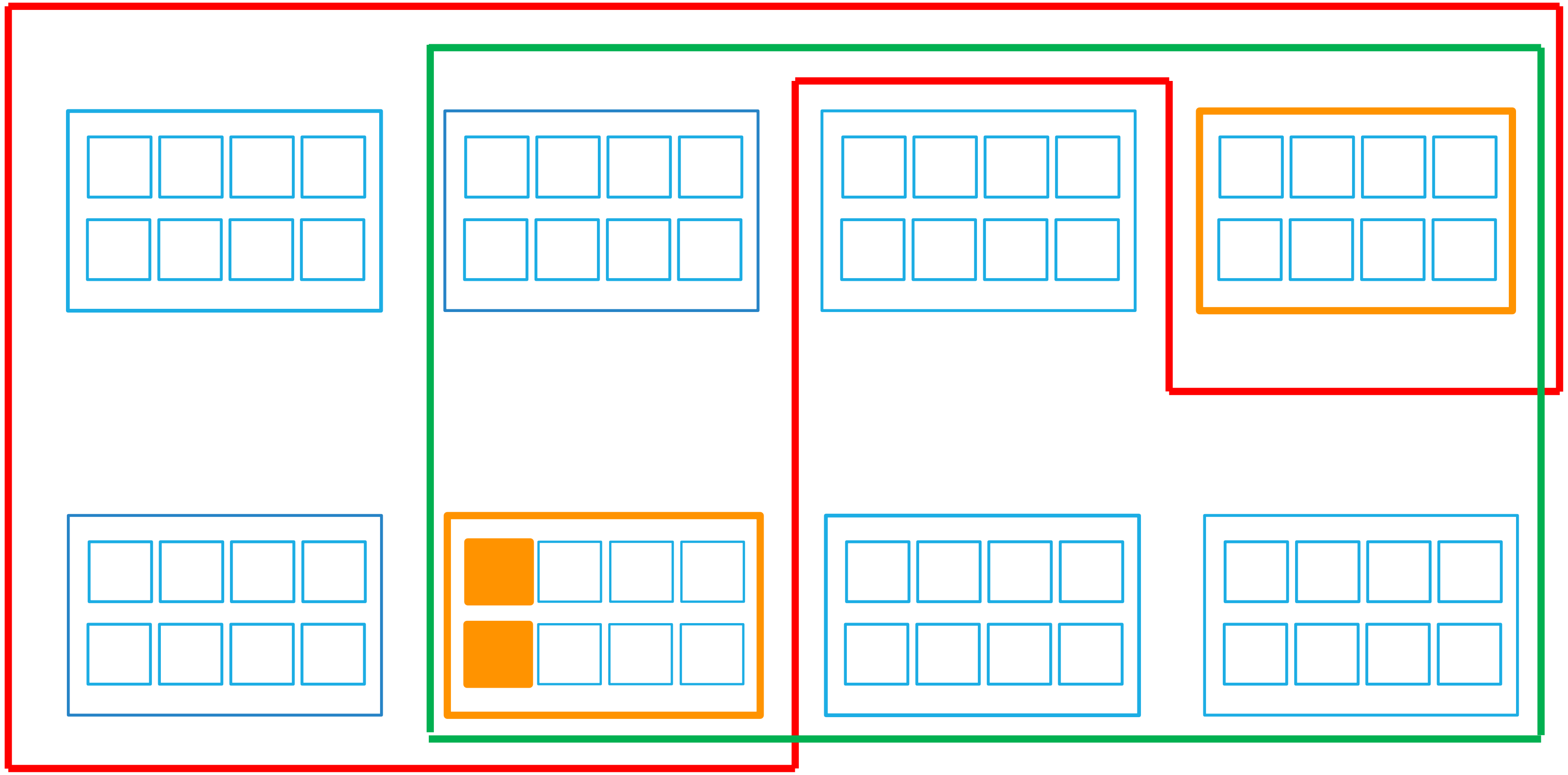

Load gets correctly balanced **on the pair of cores**

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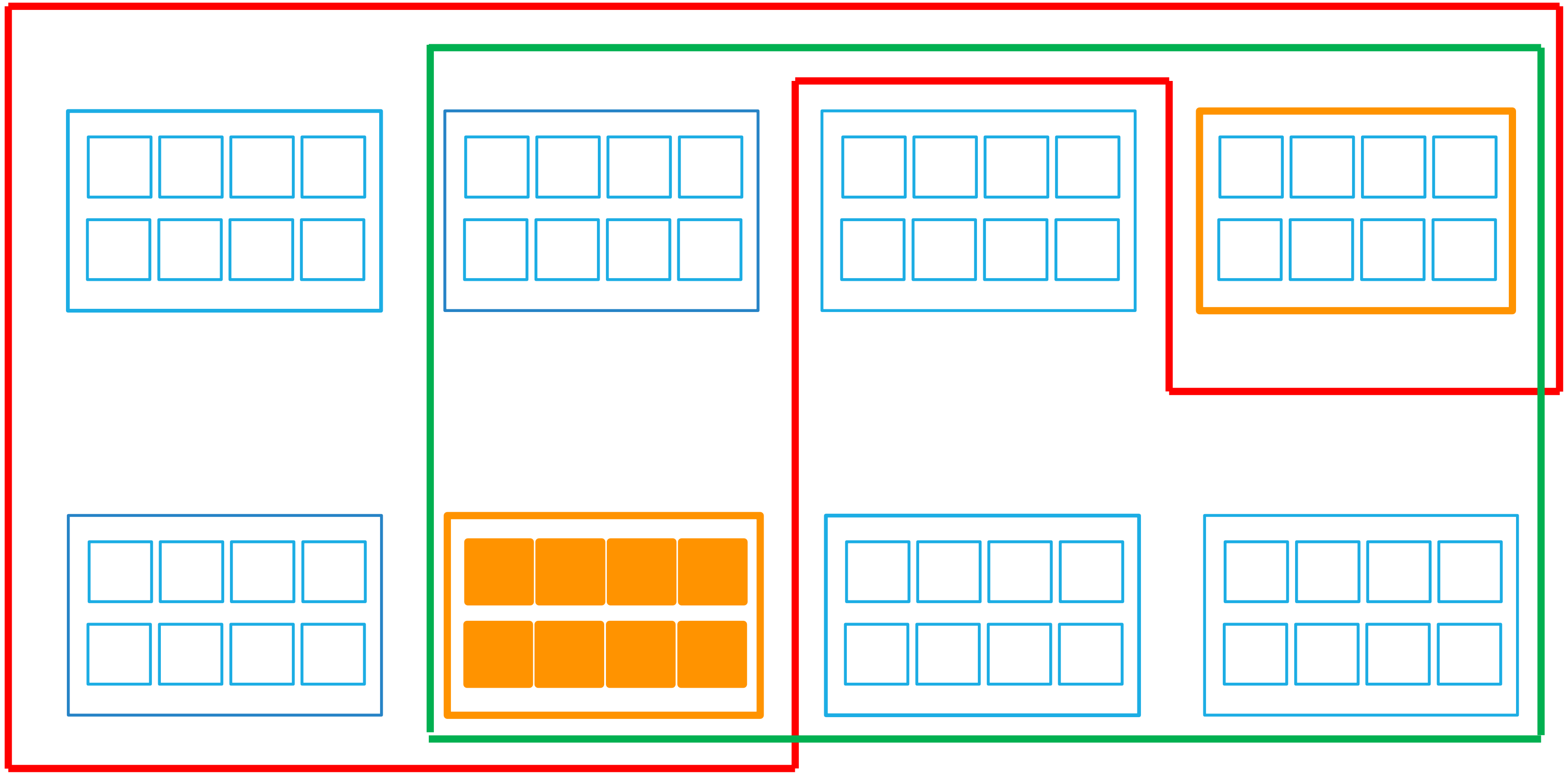

Load gets correctly balanced **on the CPU** (8 threads)

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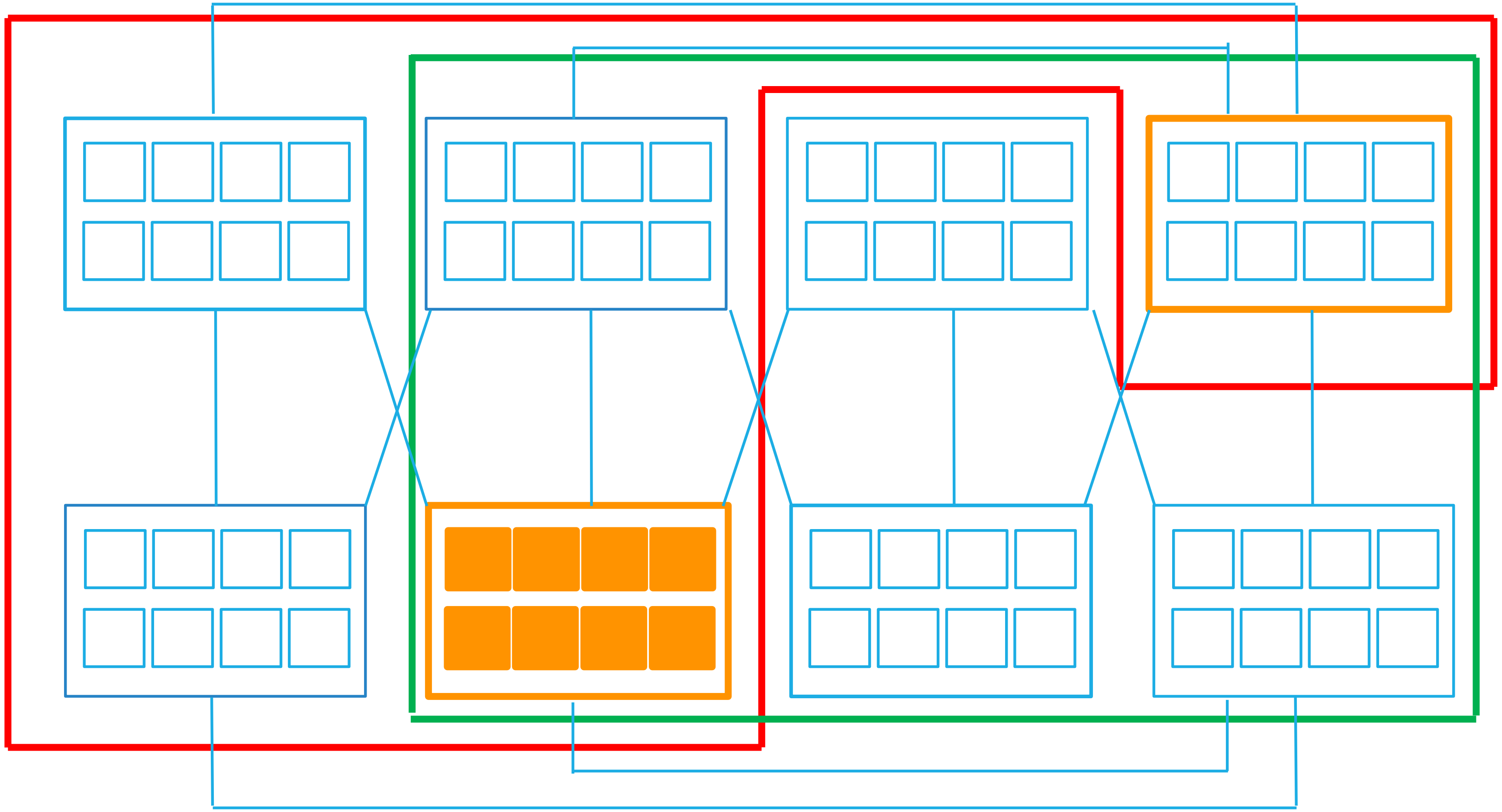

No stealing at level 3, because nodes not directly connected (1 hop apart)

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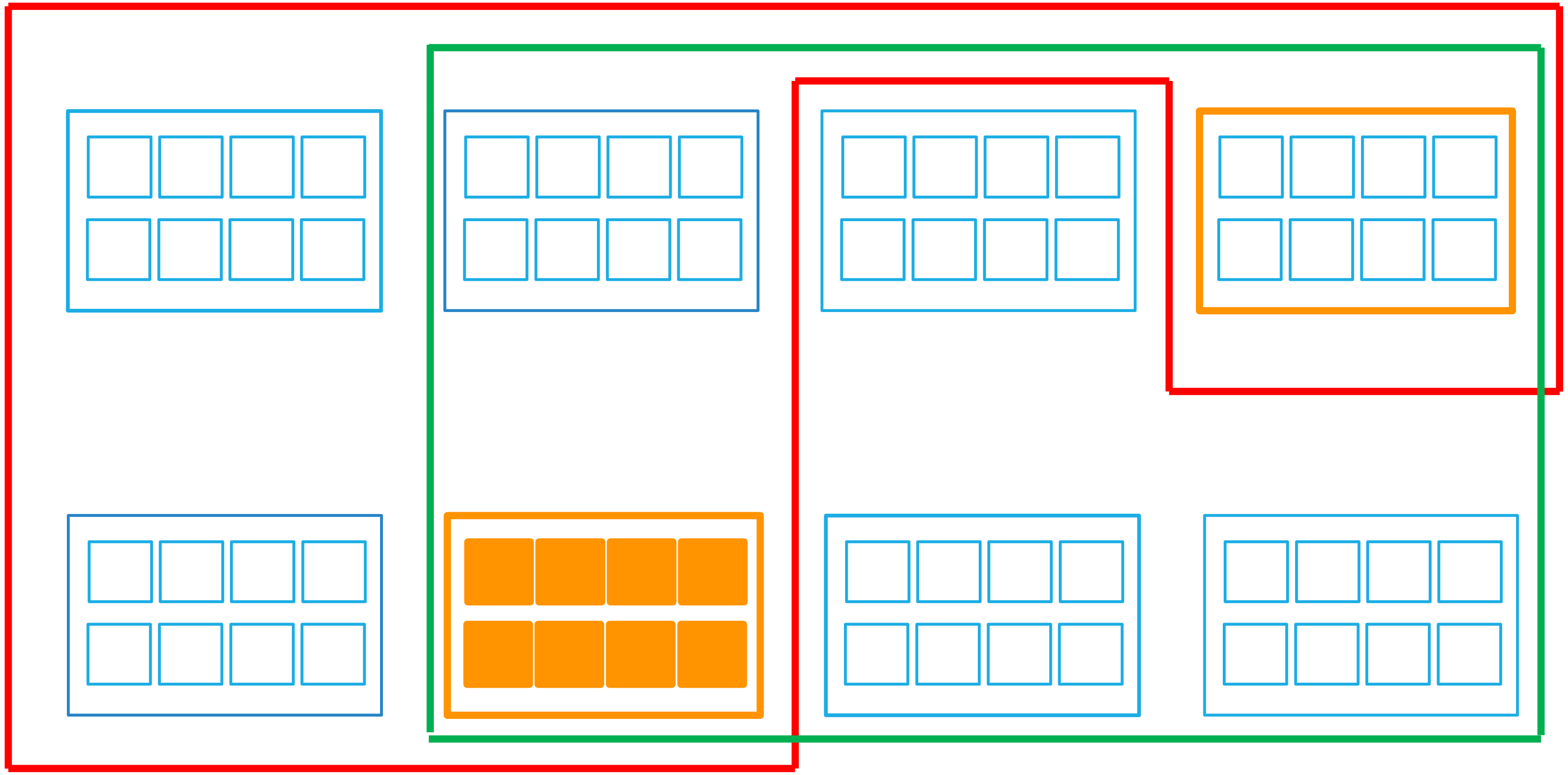

At level 4, stealing between the red and green groups…

**Overloaded node in both groups!**

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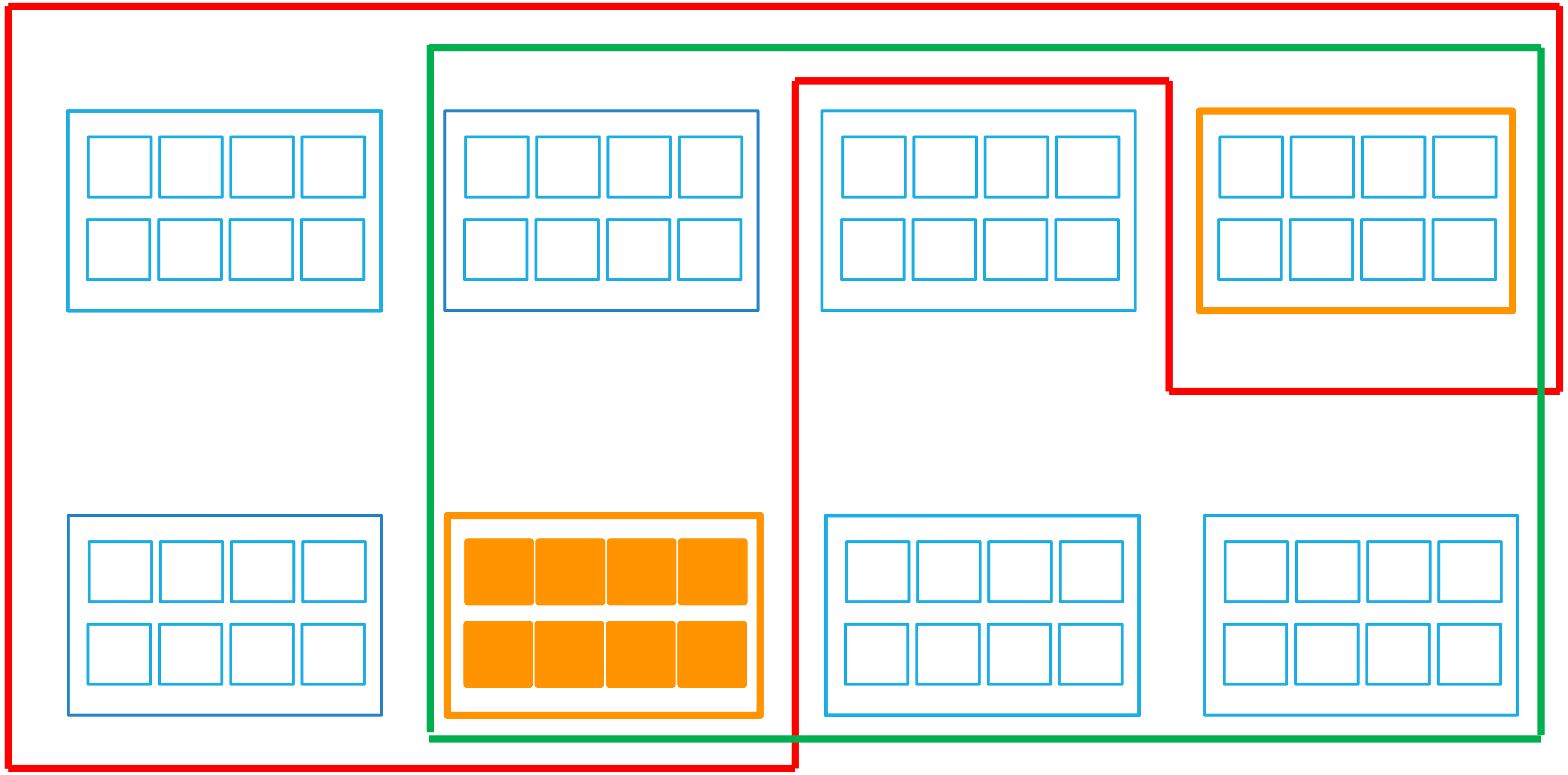

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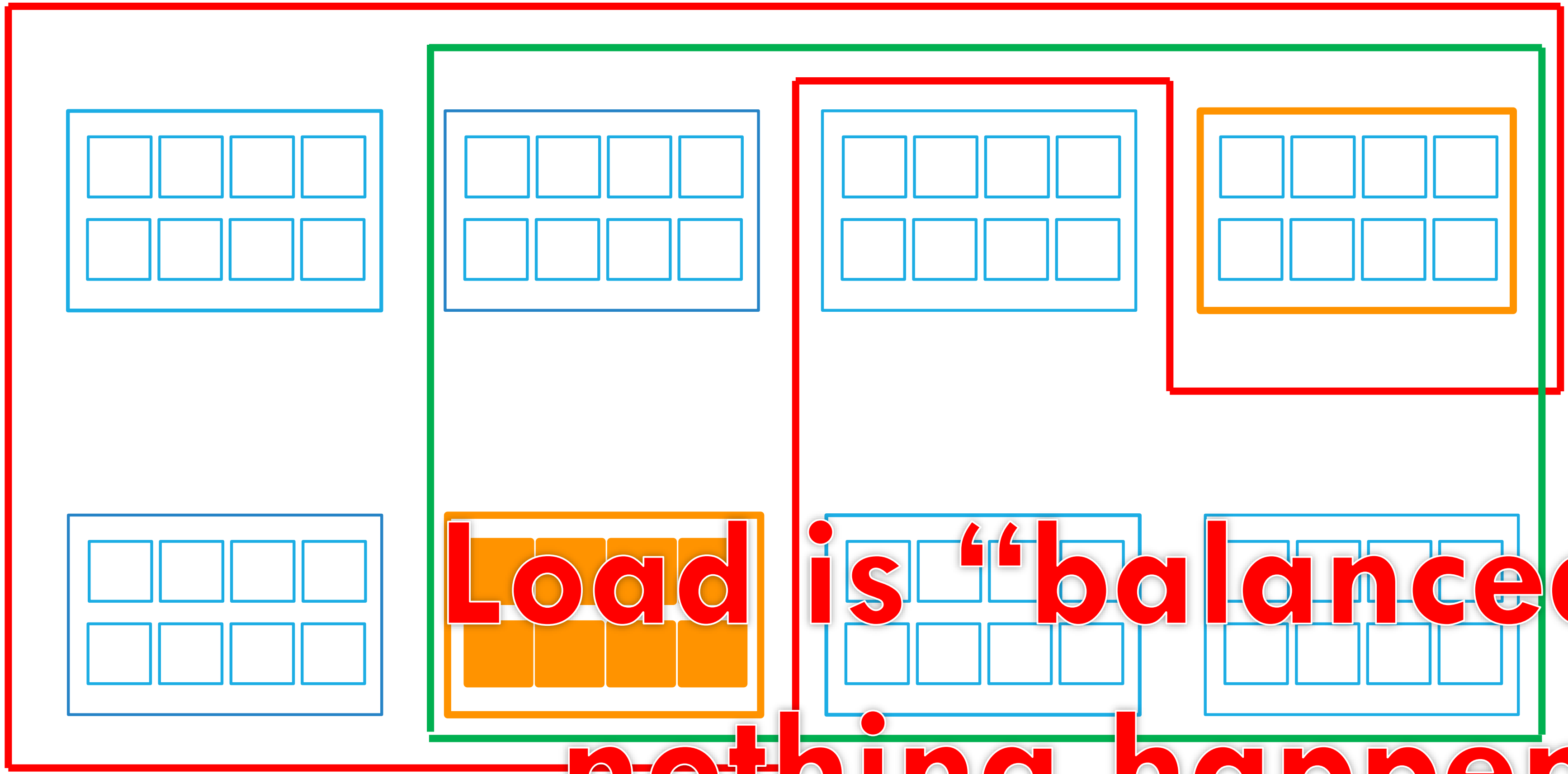

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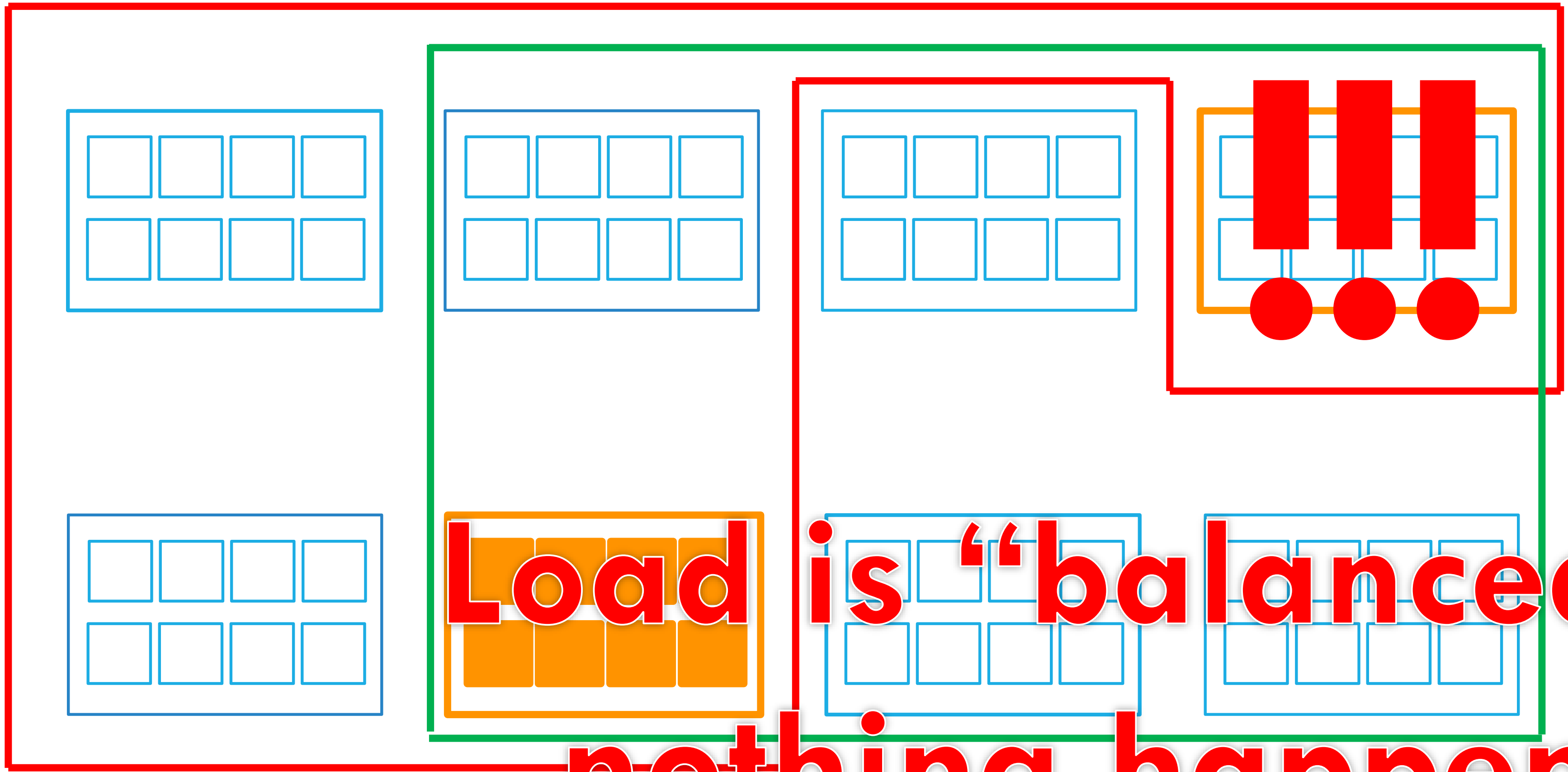

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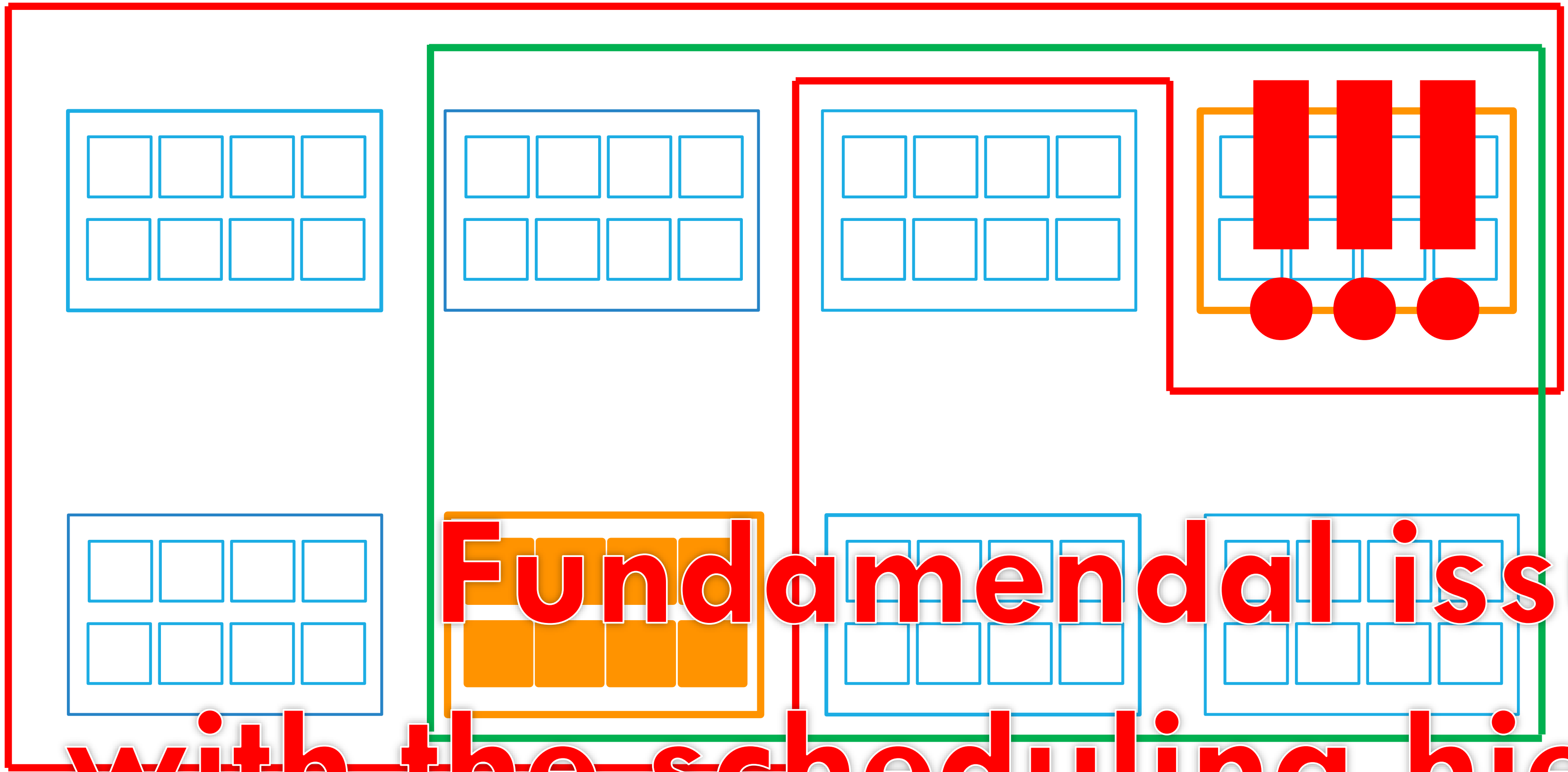

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Fundamendal issue
with the scheduling hierarchy !

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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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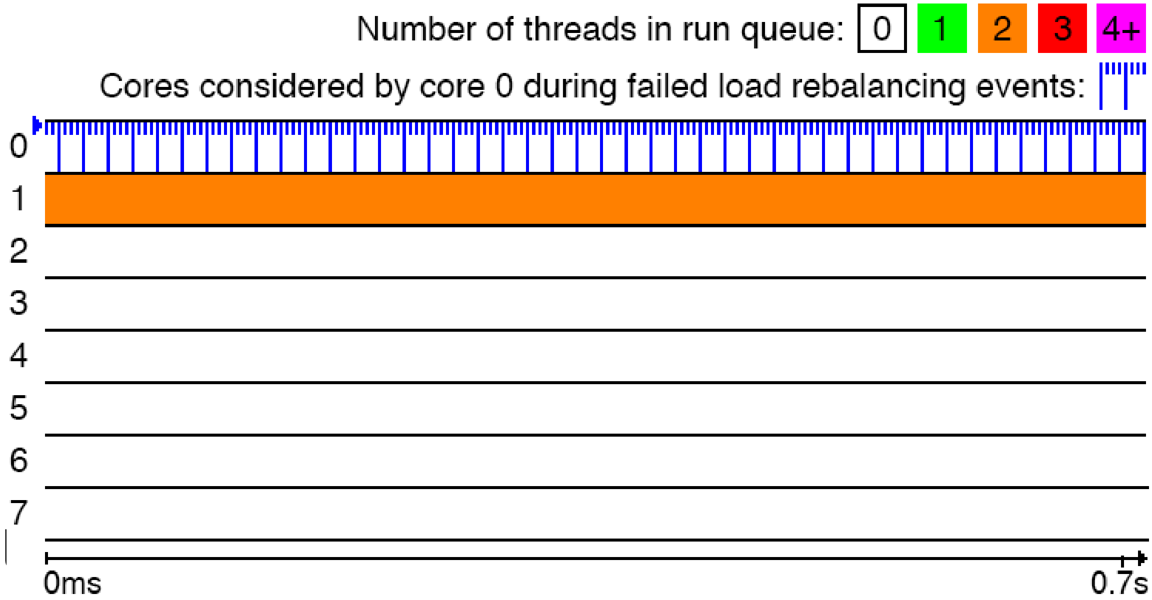

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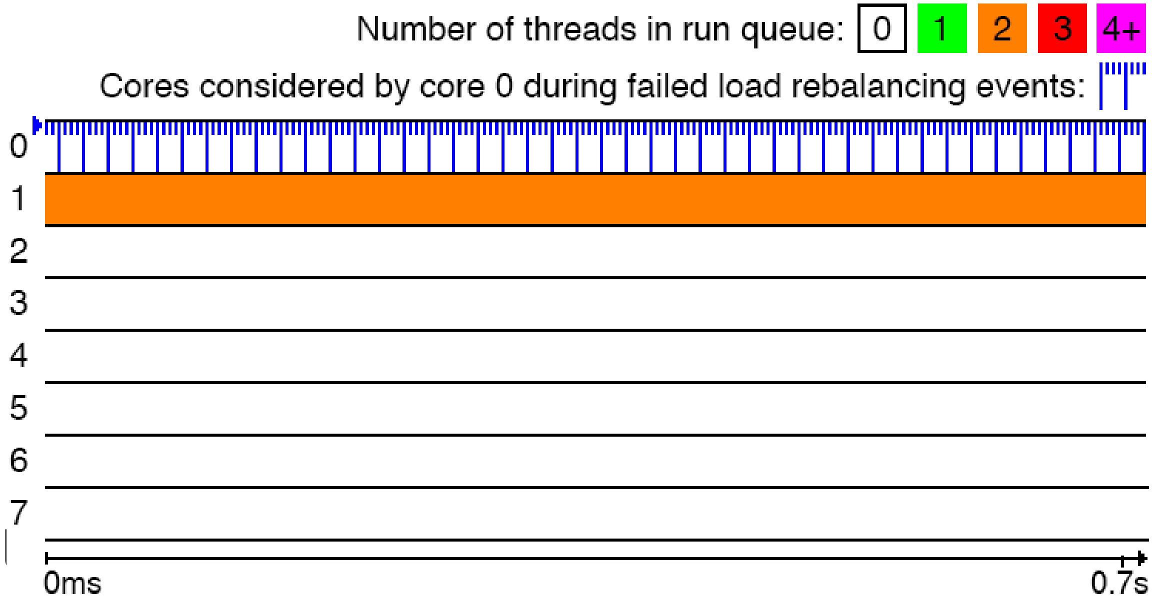
| CG | 134 | 5.4 | 25x |
| EP | 72 | 18 | 4x |
| LU | 2196 | 16 | 137x |



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**Wait, does that work?**

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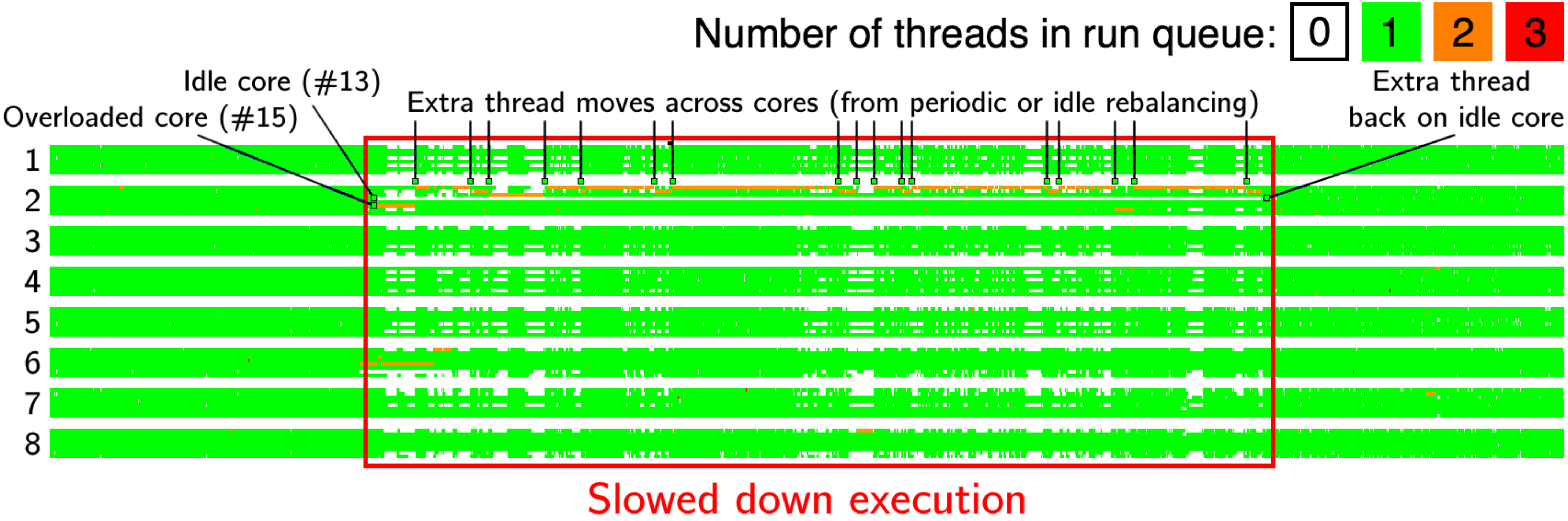


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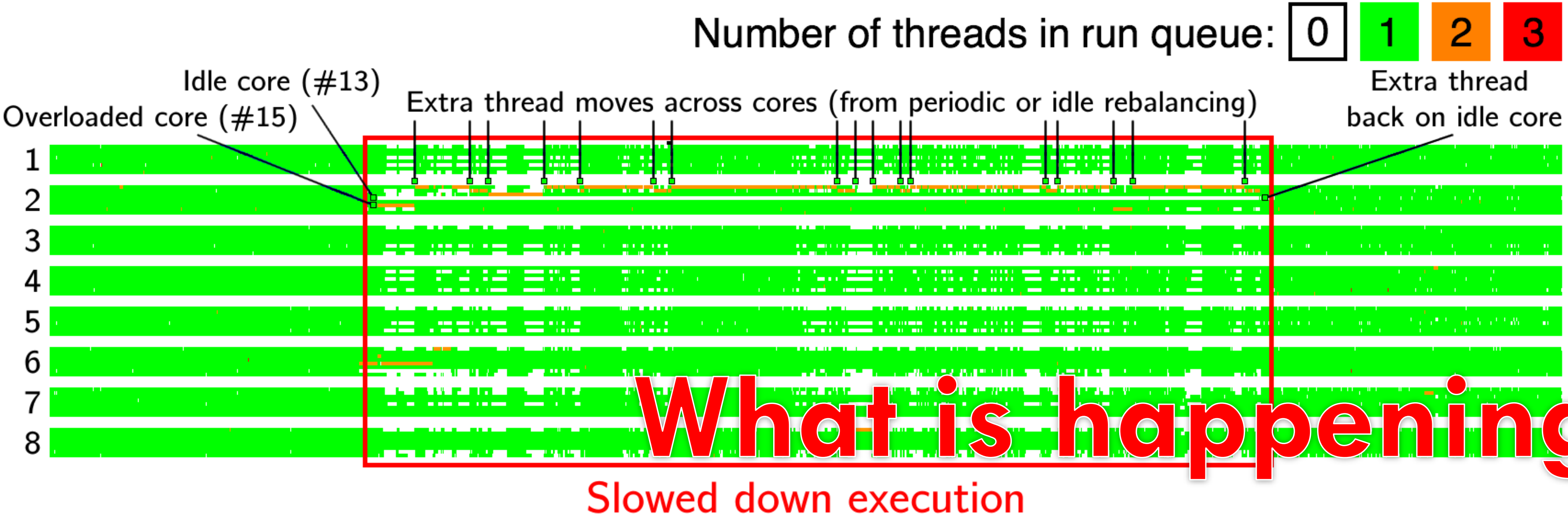


## What is happening?

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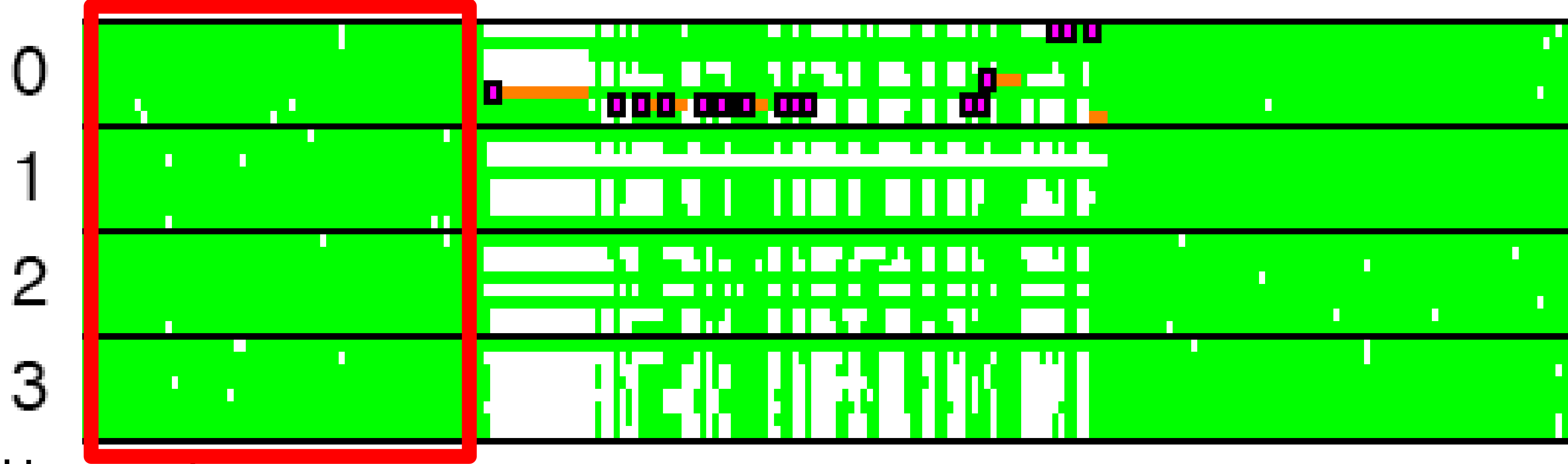
# BUG 4/4

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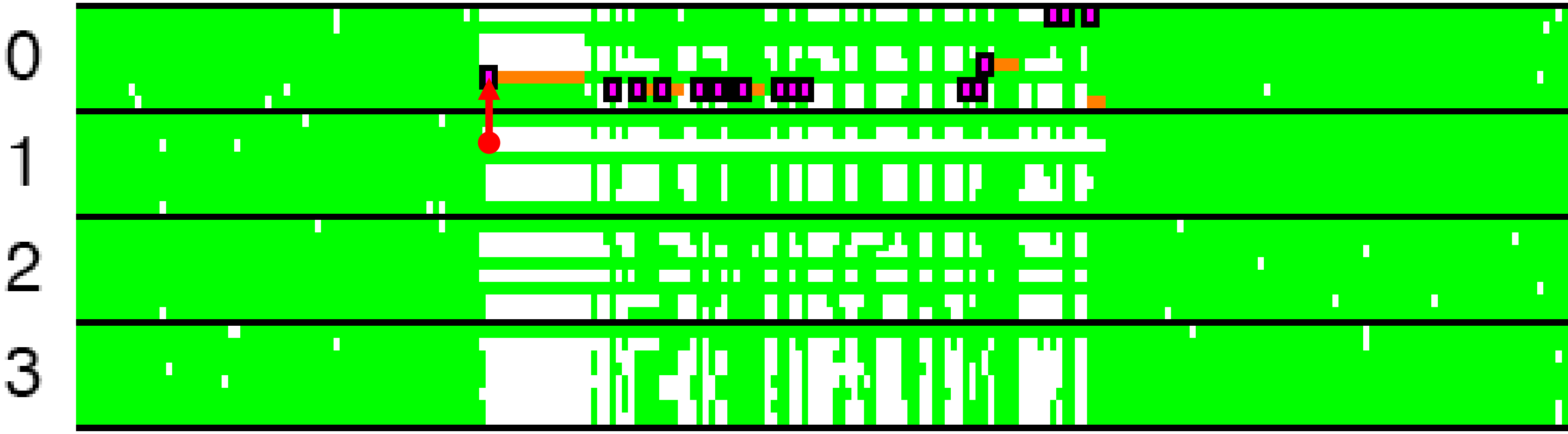


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- **"Solution":** wake up on core idle for the longest time (not great for energy)

# BUG 4/4


| 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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**Wait, does anything work at all? ☺**

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- **Model checking, formal proofs**
  - Complex, parallel code: so far, nobody knows how to do it...

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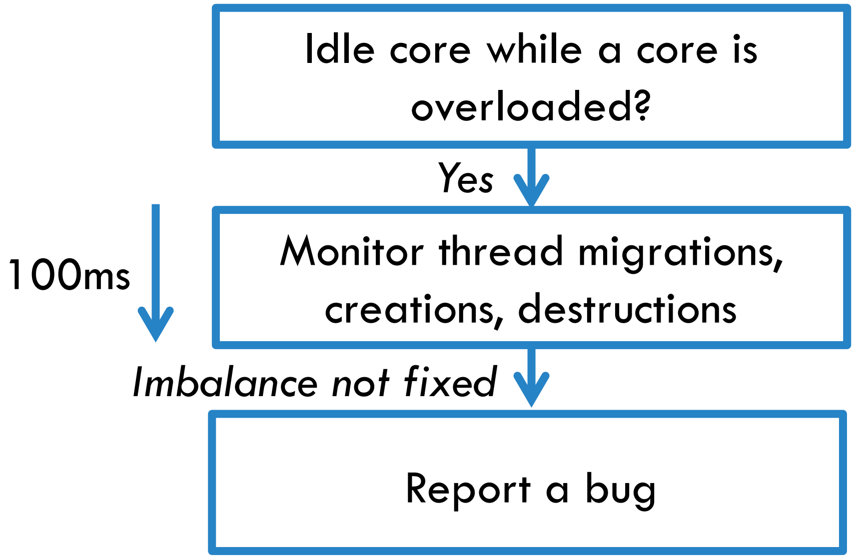


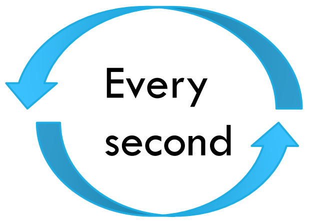

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*Imbalance not fixed*

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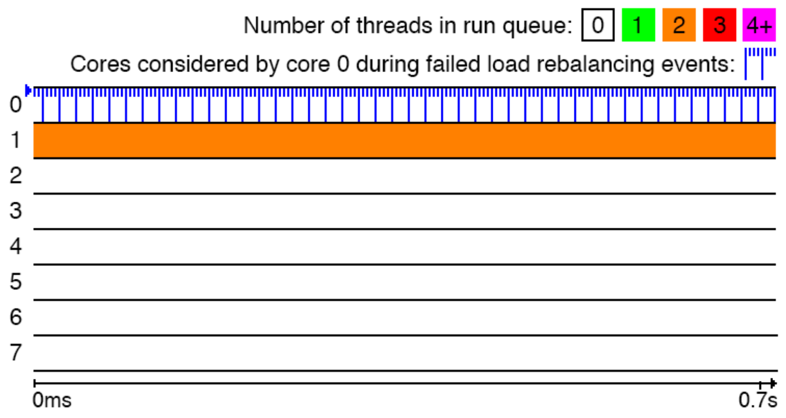


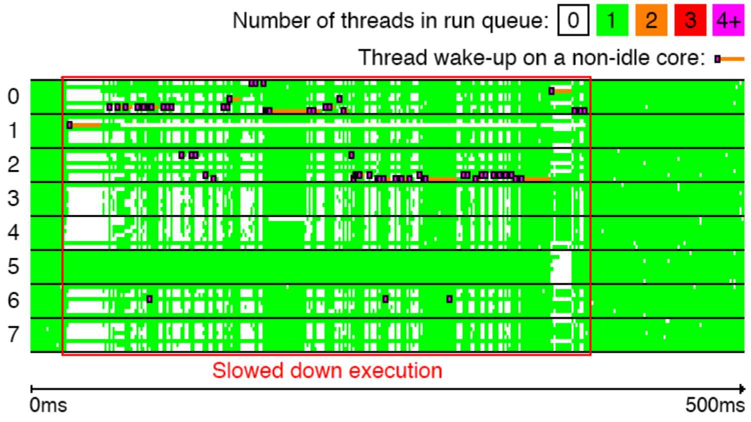


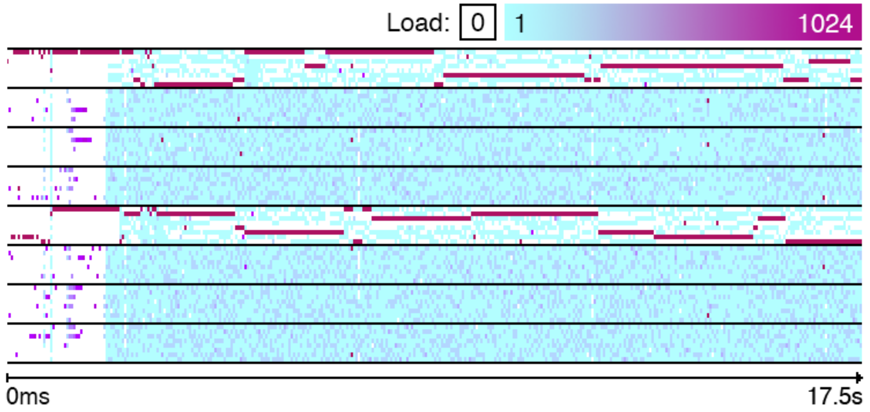

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**Your turn!**