

# THE LINUX SCHEDULER: A DECADE OF WASTED CORES

Jean-Pierre Lozi  
[jplozi@unice.fr](mailto:jplozi@unice.fr)



Baptiste Lepers  
[baptiste.lepers@epfl.ch](mailto:baptiste.lepers@epfl.ch)



Fabien Gaud  
[me@fabiengaud.net](mailto:me@fabiengaud.net)

The COHO logo, with the word 'COHO' in large red letters and 'DATA' in smaller grey letters below it.

Alexandra Fedorova  
[sasha@ece.ubc.ca](mailto:sasha@ece.ubc.ca)



Justin Funston  
[jfunston@ece.ubc.ca](mailto:jfunston@ece.ubc.ca)

Vivien Quéma  
[vivien.quema@imag.fr](mailto:vivien.quema@imag.fr)



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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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- **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...**
  - Intrinsic problems with the design of the scheduler?

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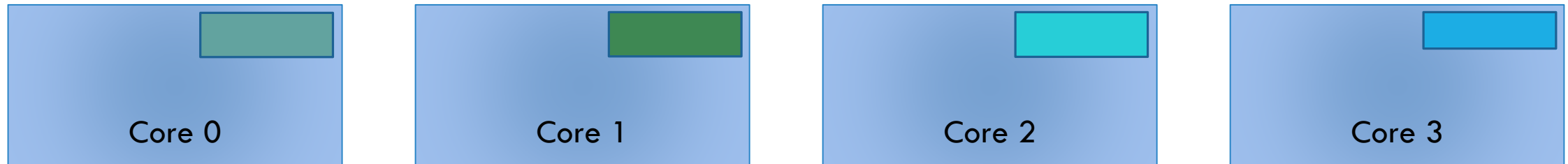
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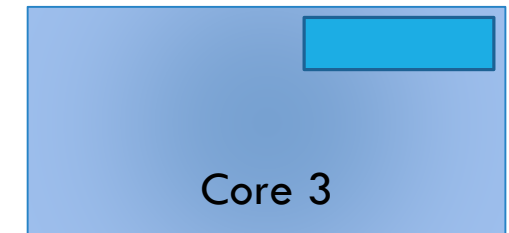
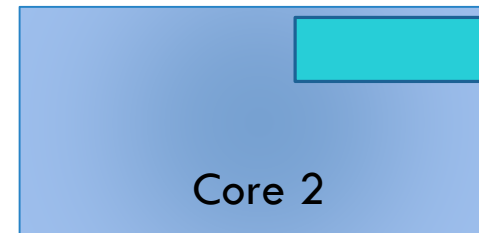
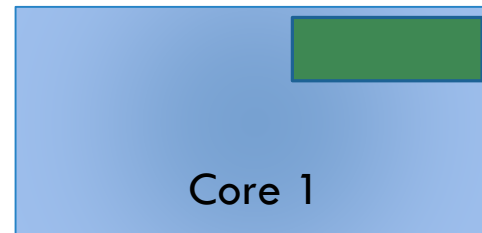
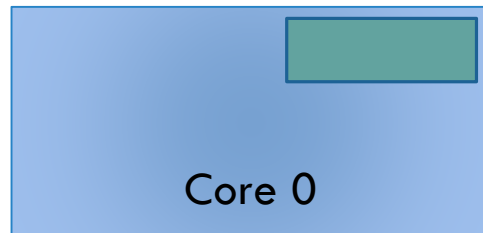
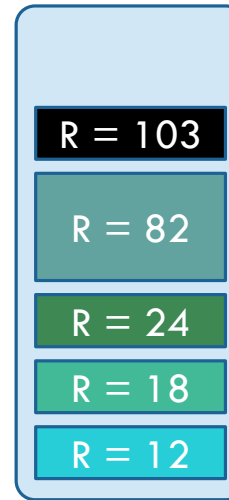
# THE COMPLETELY FAIR SCHEDULER (CFS): CONCEPT





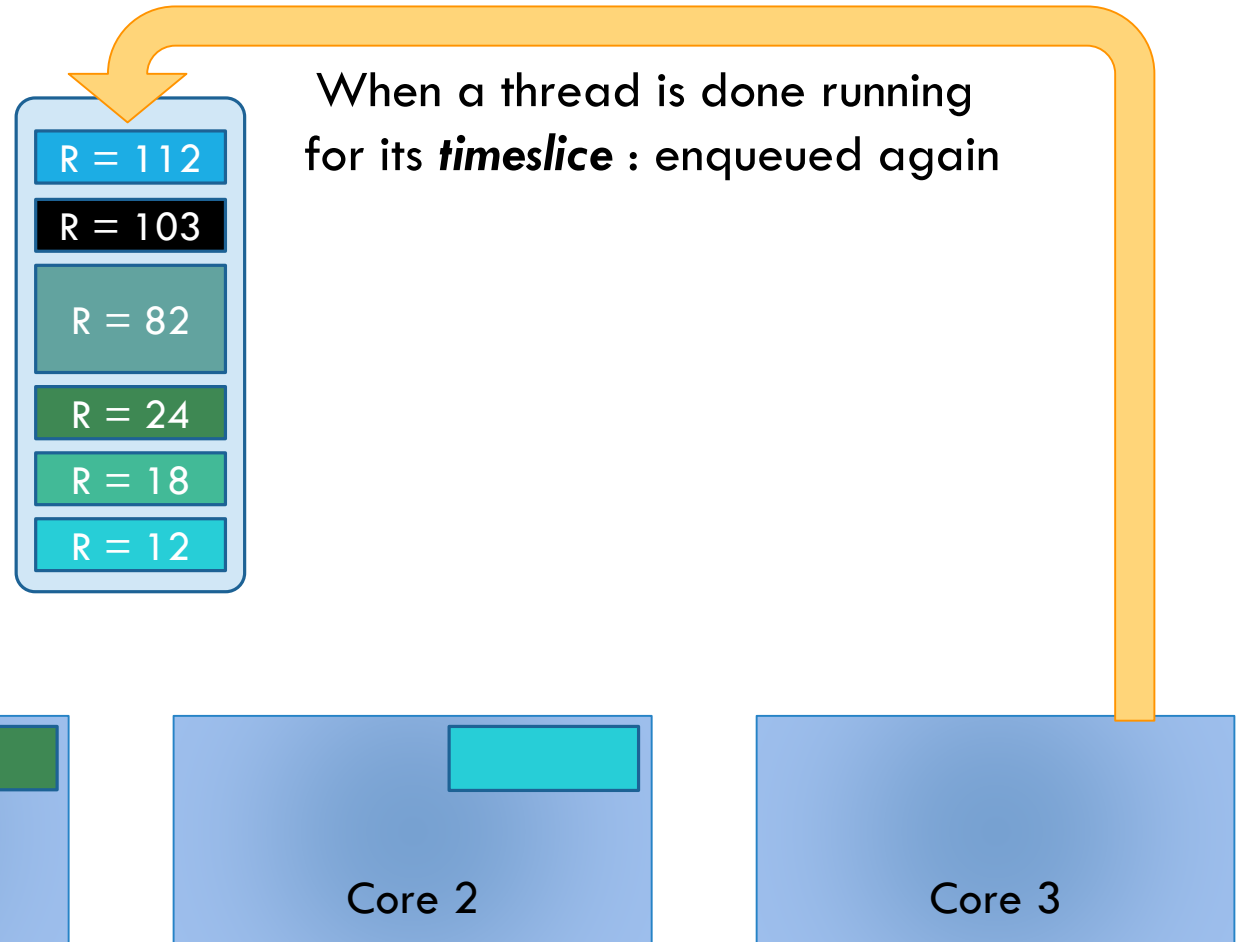
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One runqueue where threads are globally sorted by *runtime*



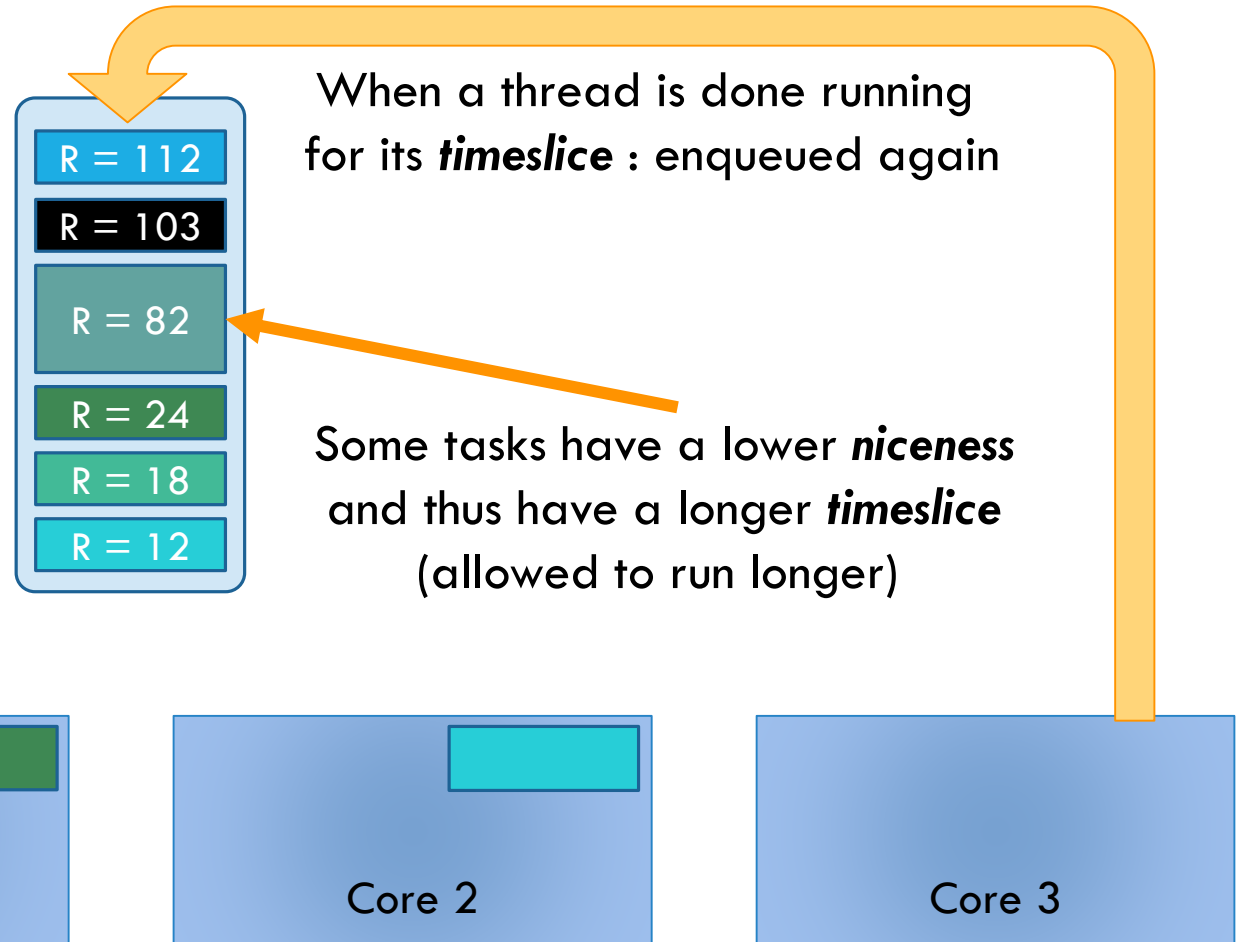
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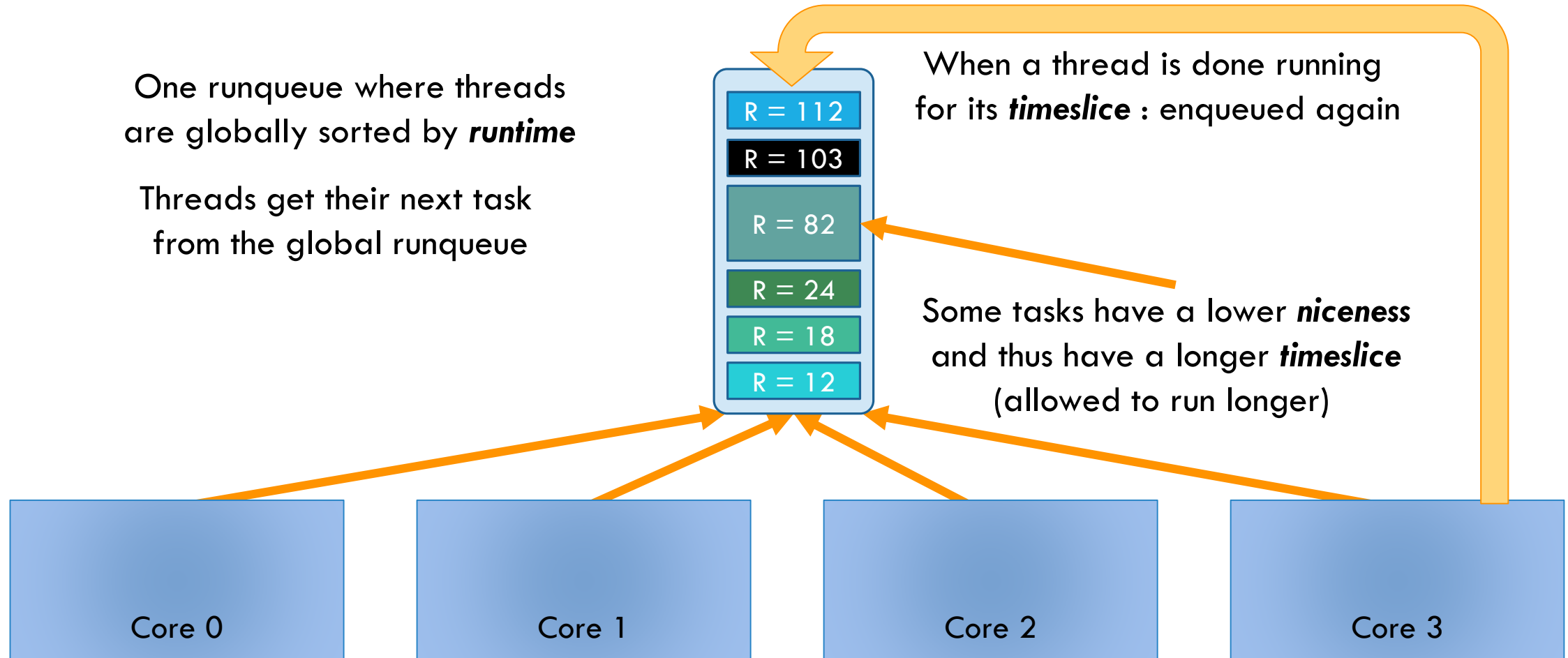
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Threads get their next task from the global runqueue

When a thread is done running for its **timeslice** : enqueued again

Some tasks have a lower **niceness** and thus have a longer **timeslice** (allowed to run longer)



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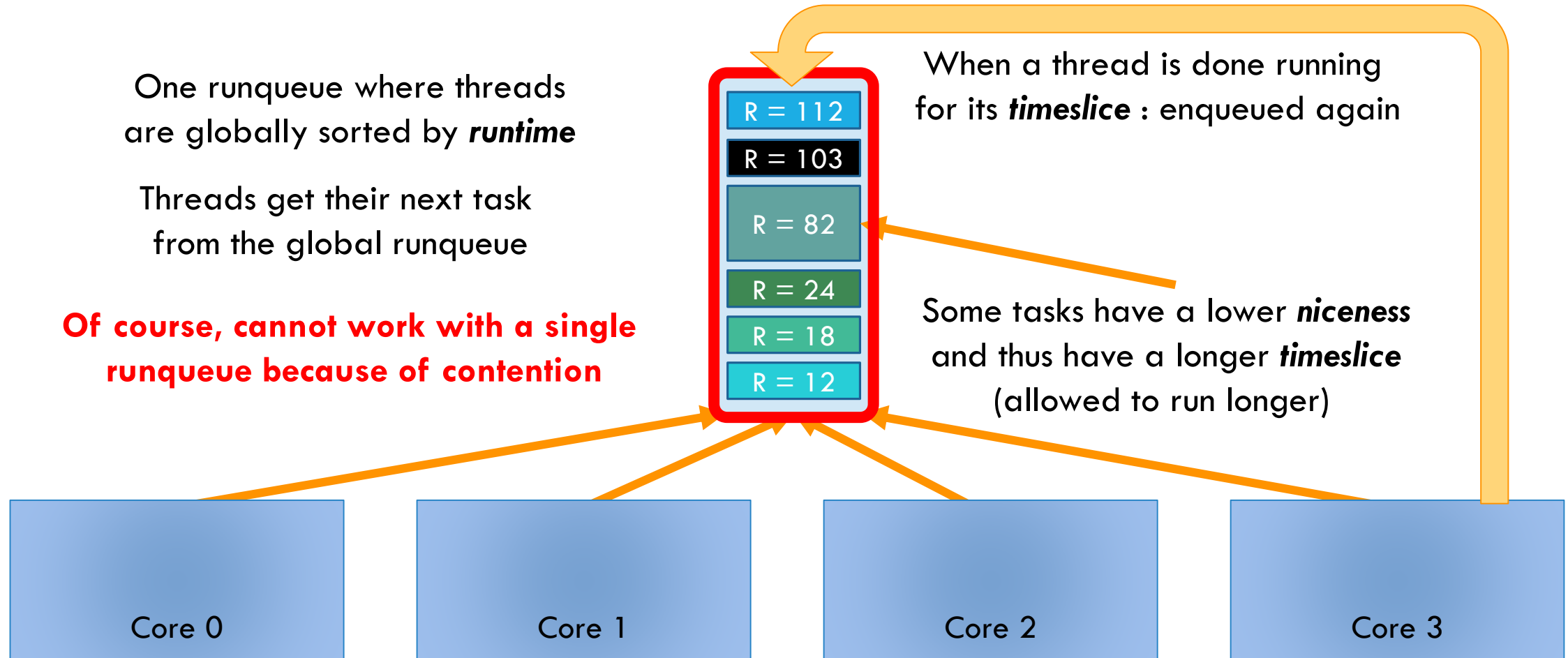
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Threads get their next task from the global runqueue

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

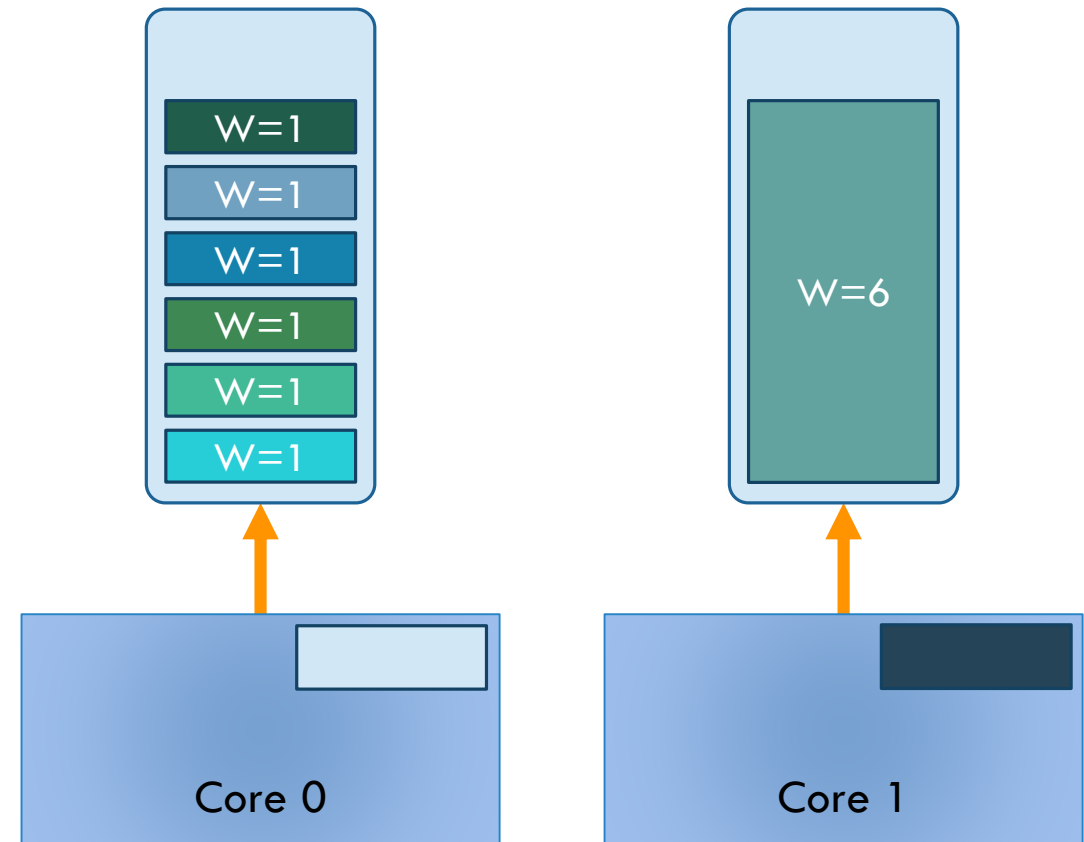
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- **One runqueue per core** to avoid contention

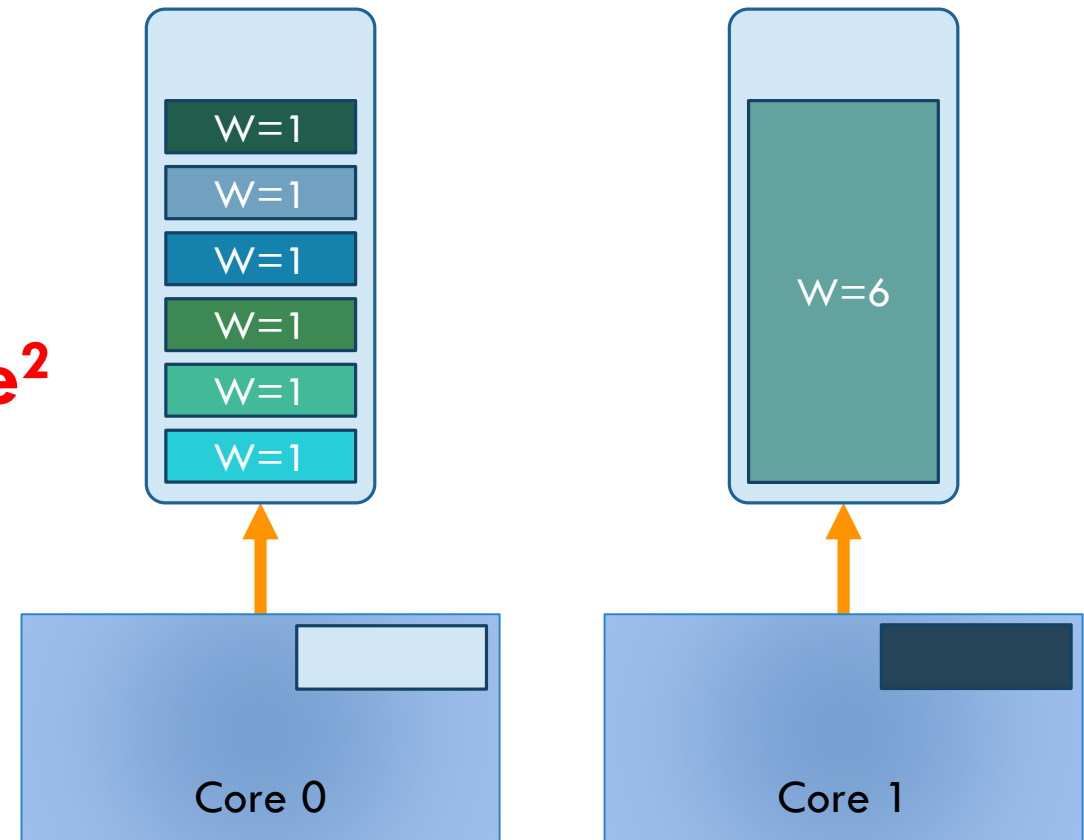


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$$\text{load(task)} = \text{weight}^1 \times \% \text{ cpu use}^2$$

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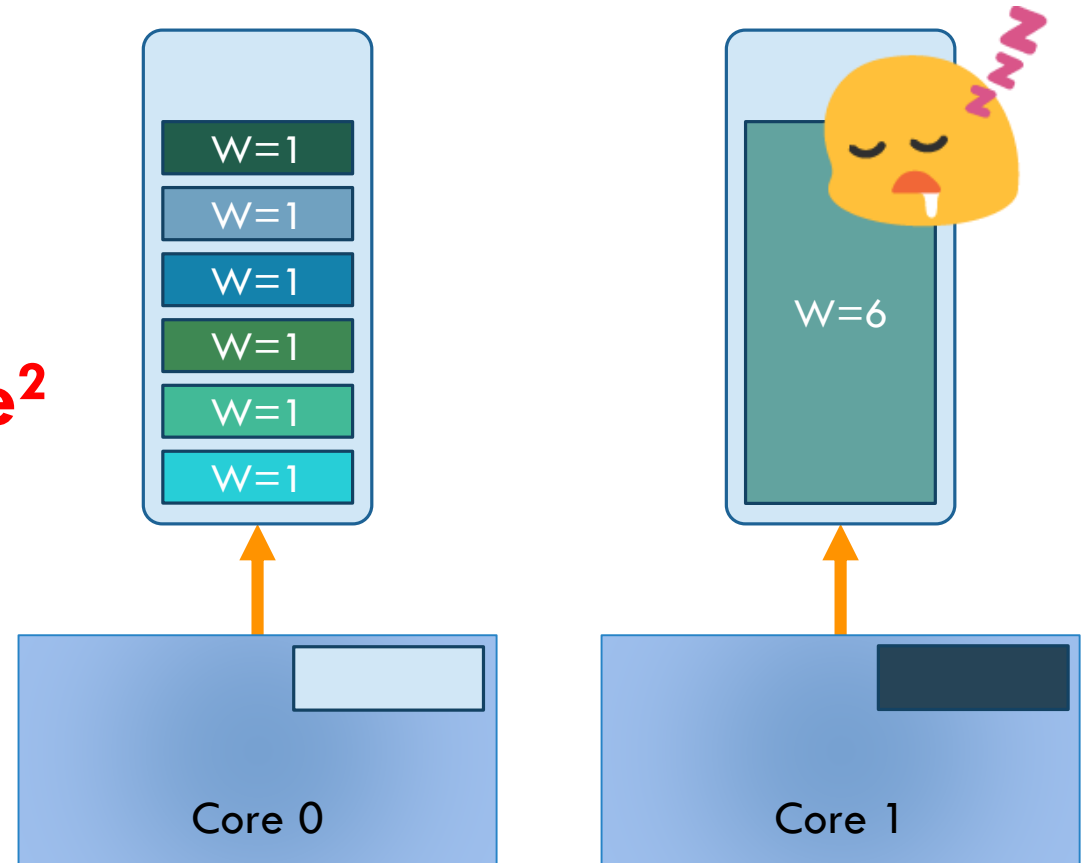
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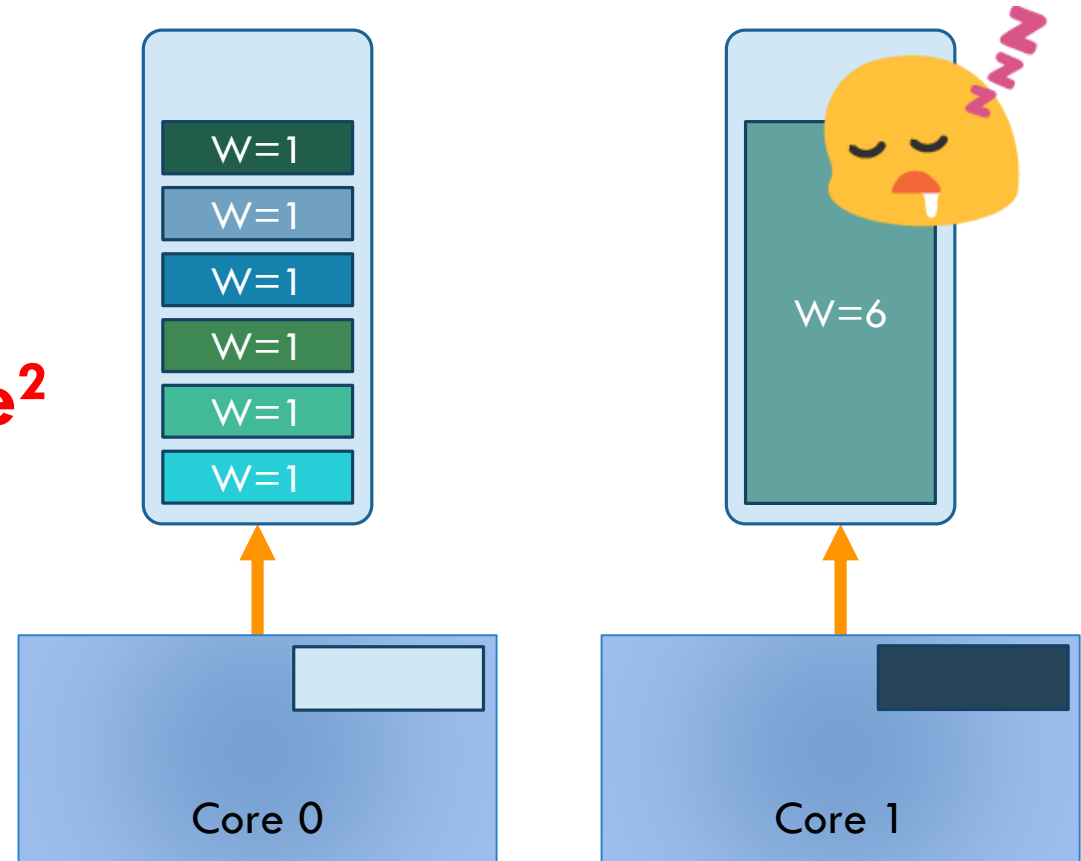
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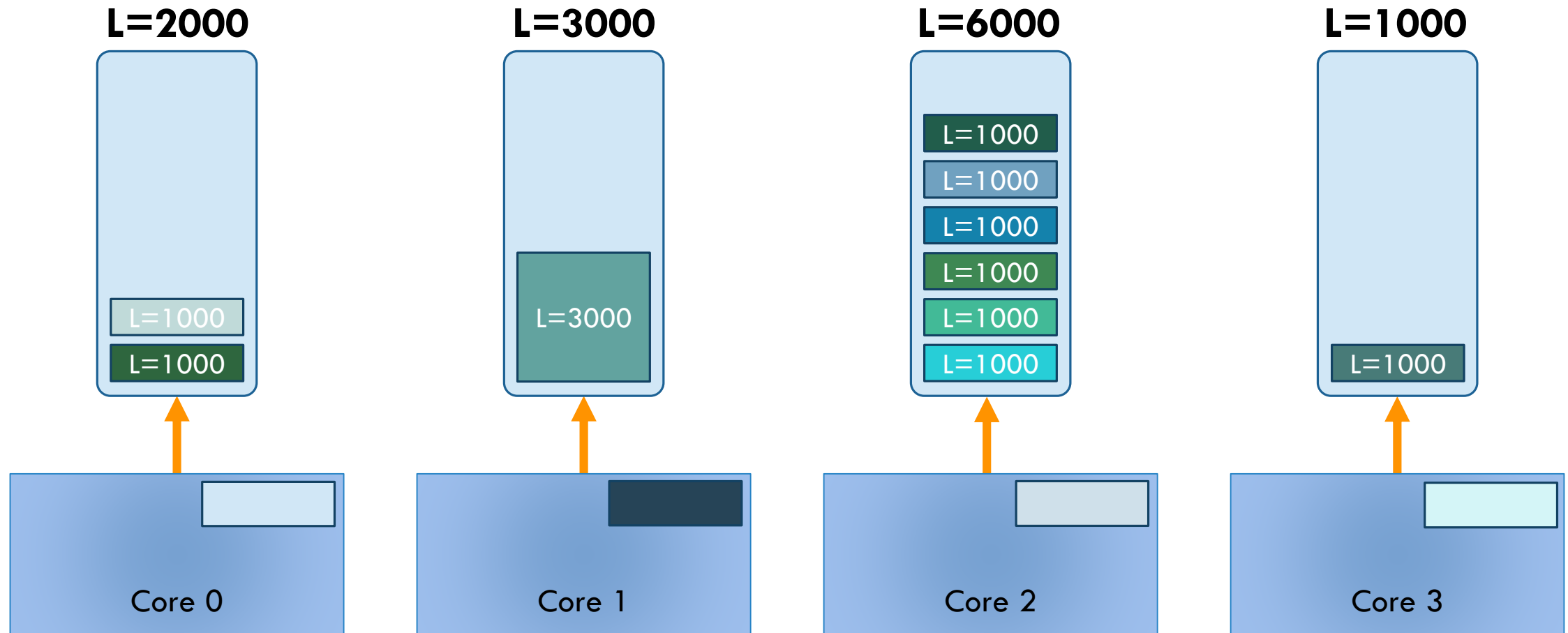
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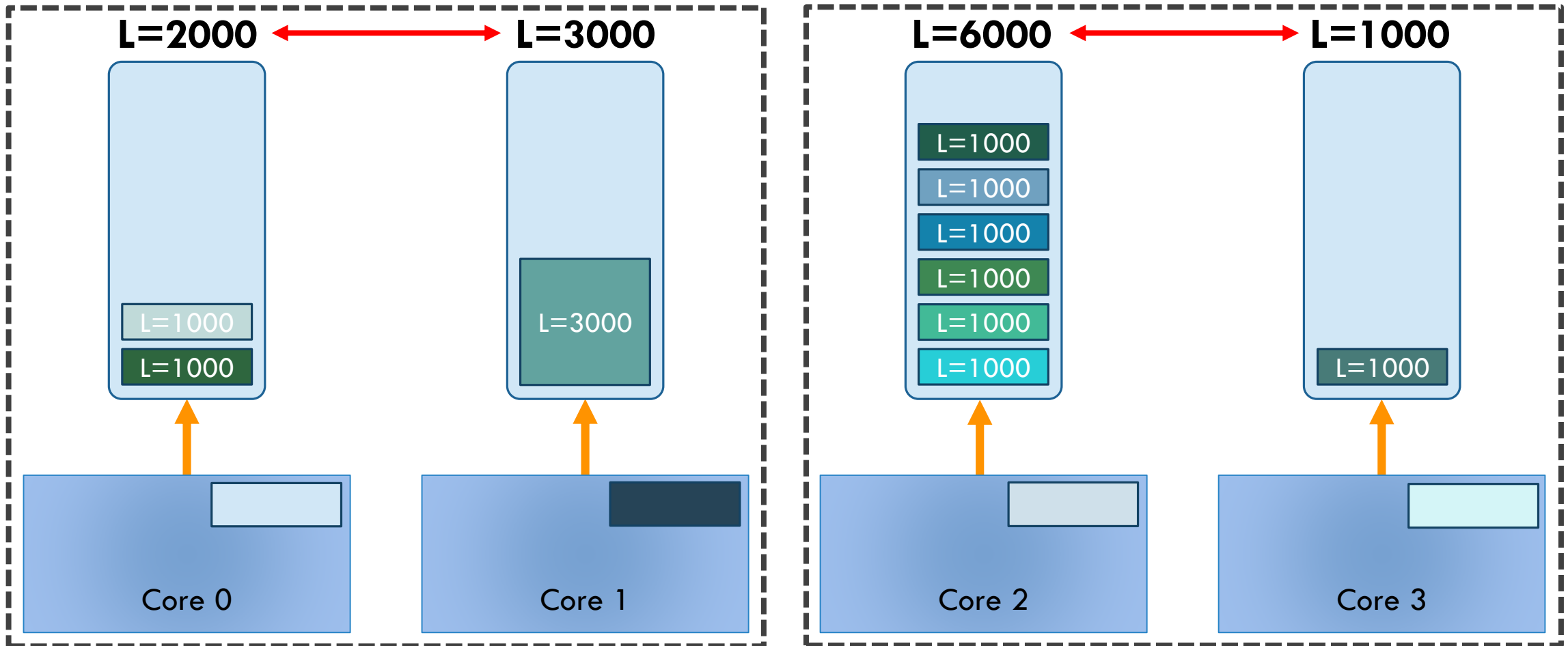
- Since there can be many cores: **hierarchical approach!**



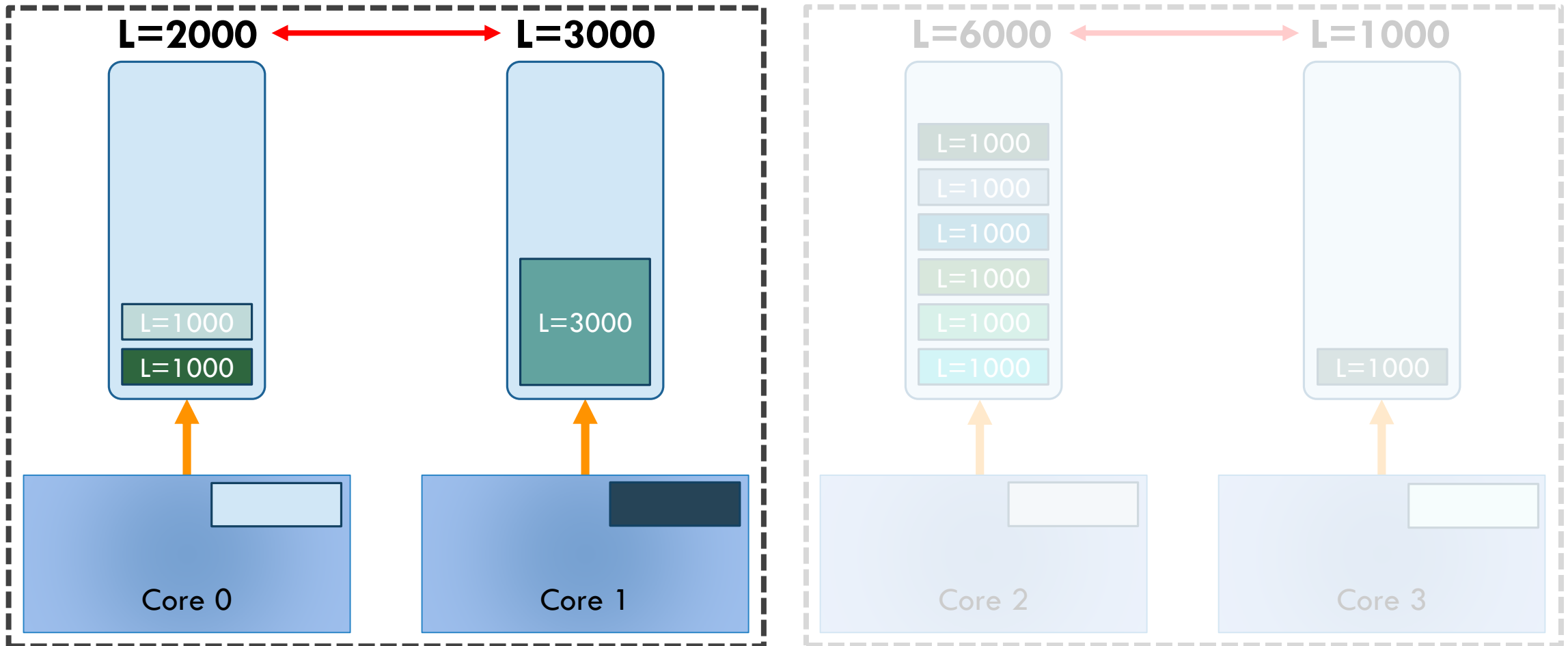
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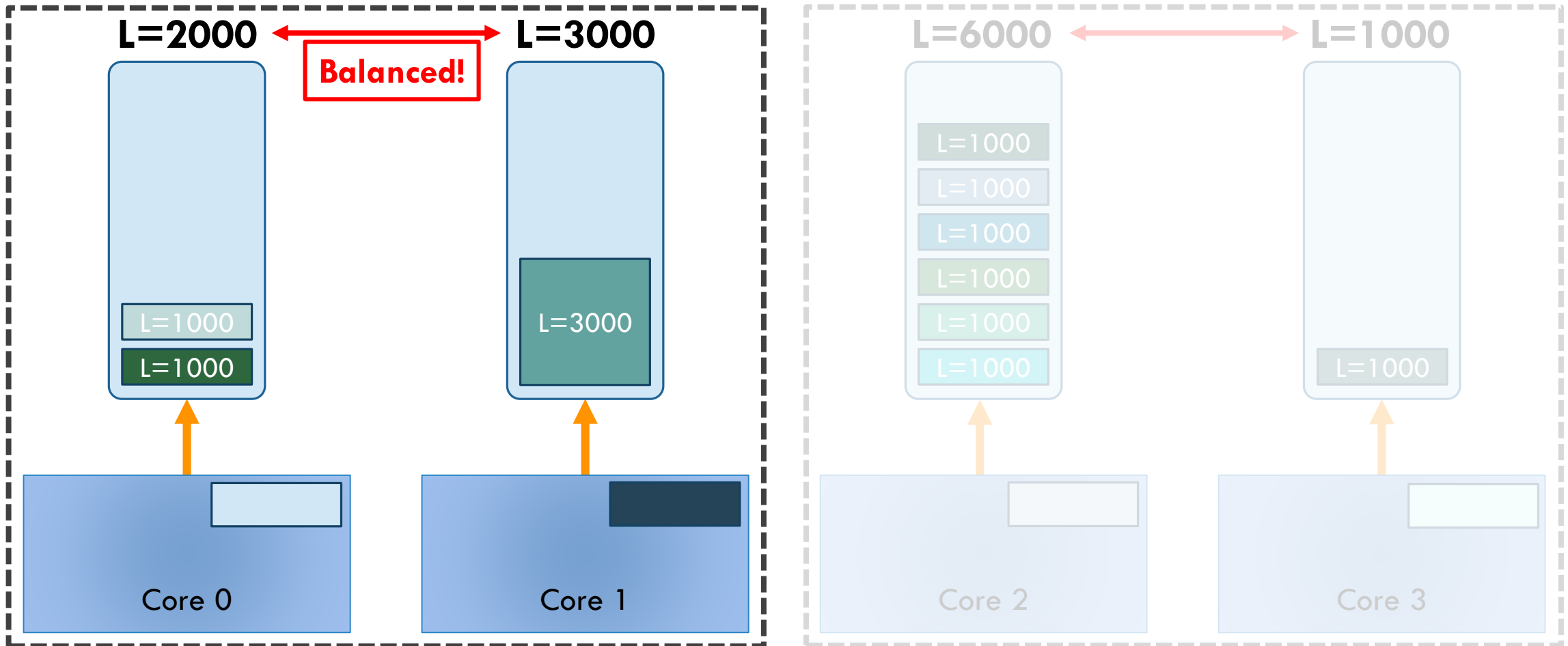
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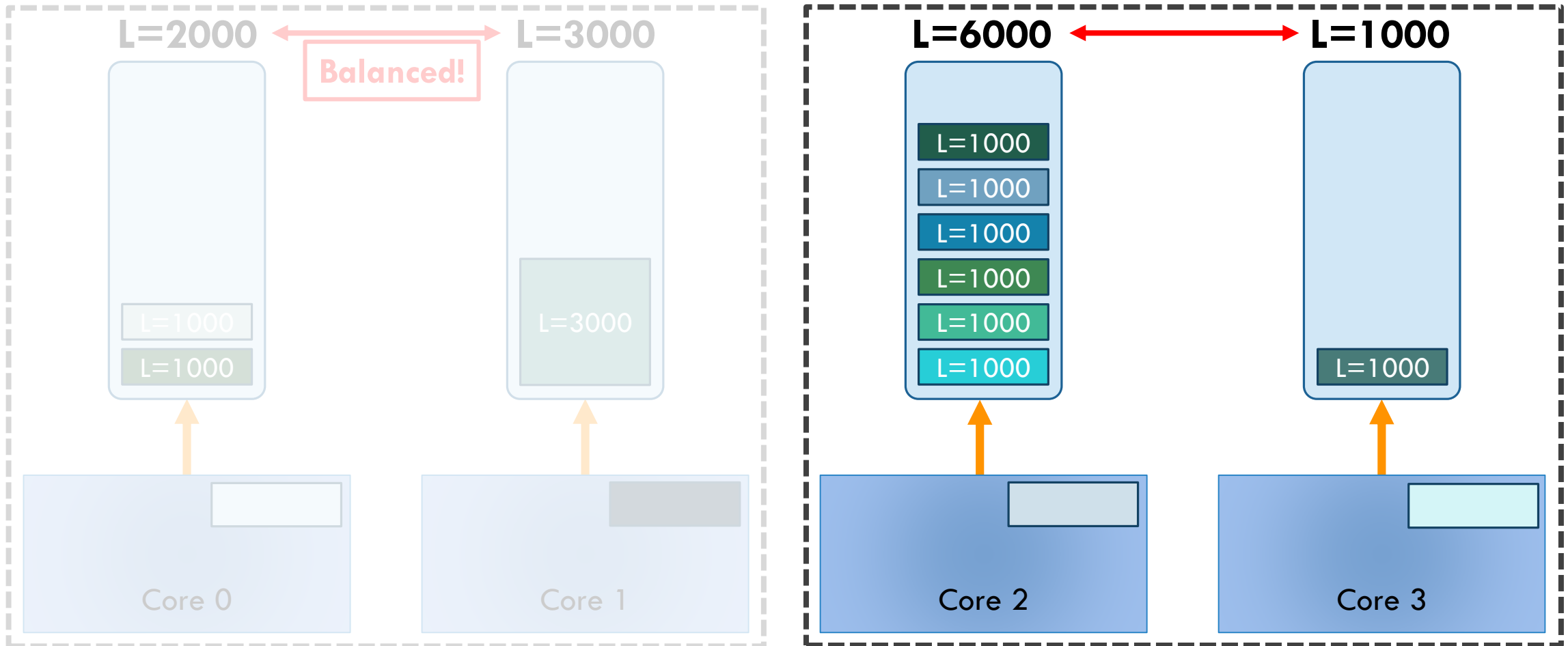
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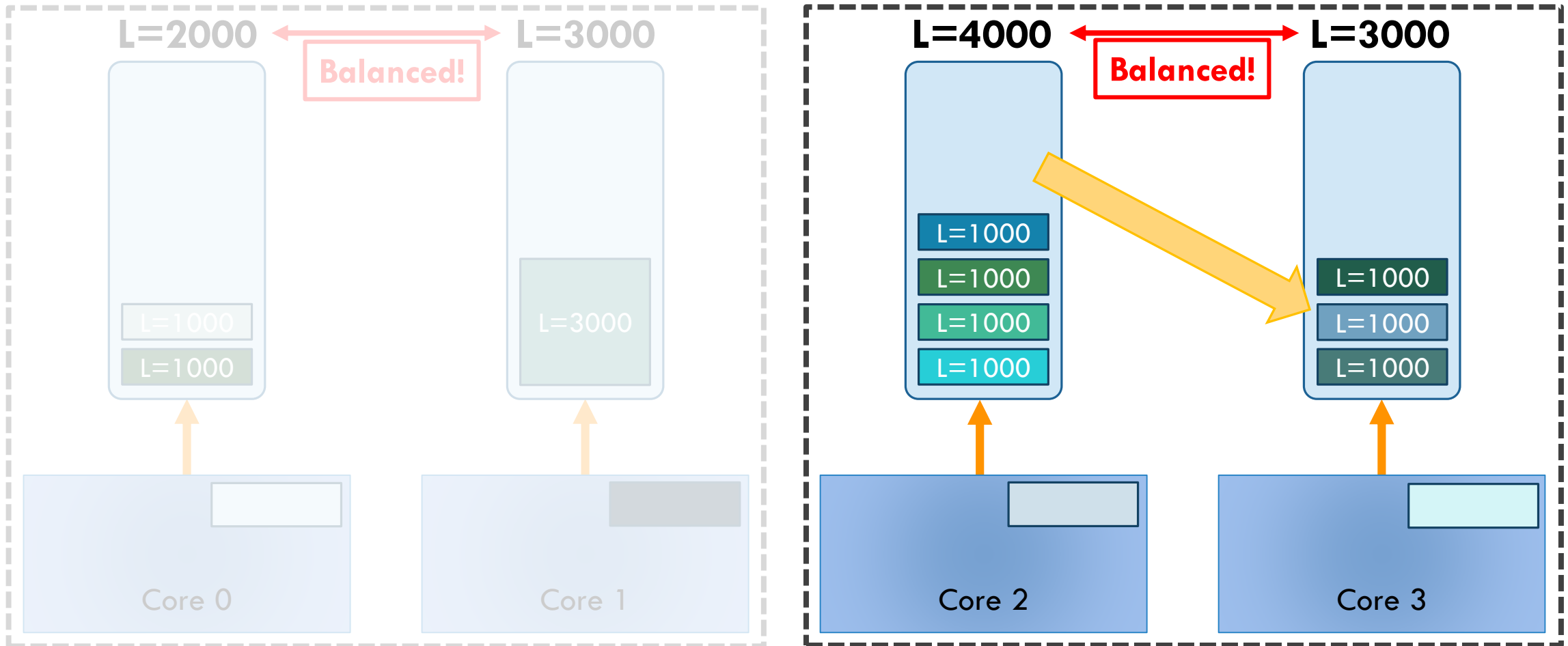


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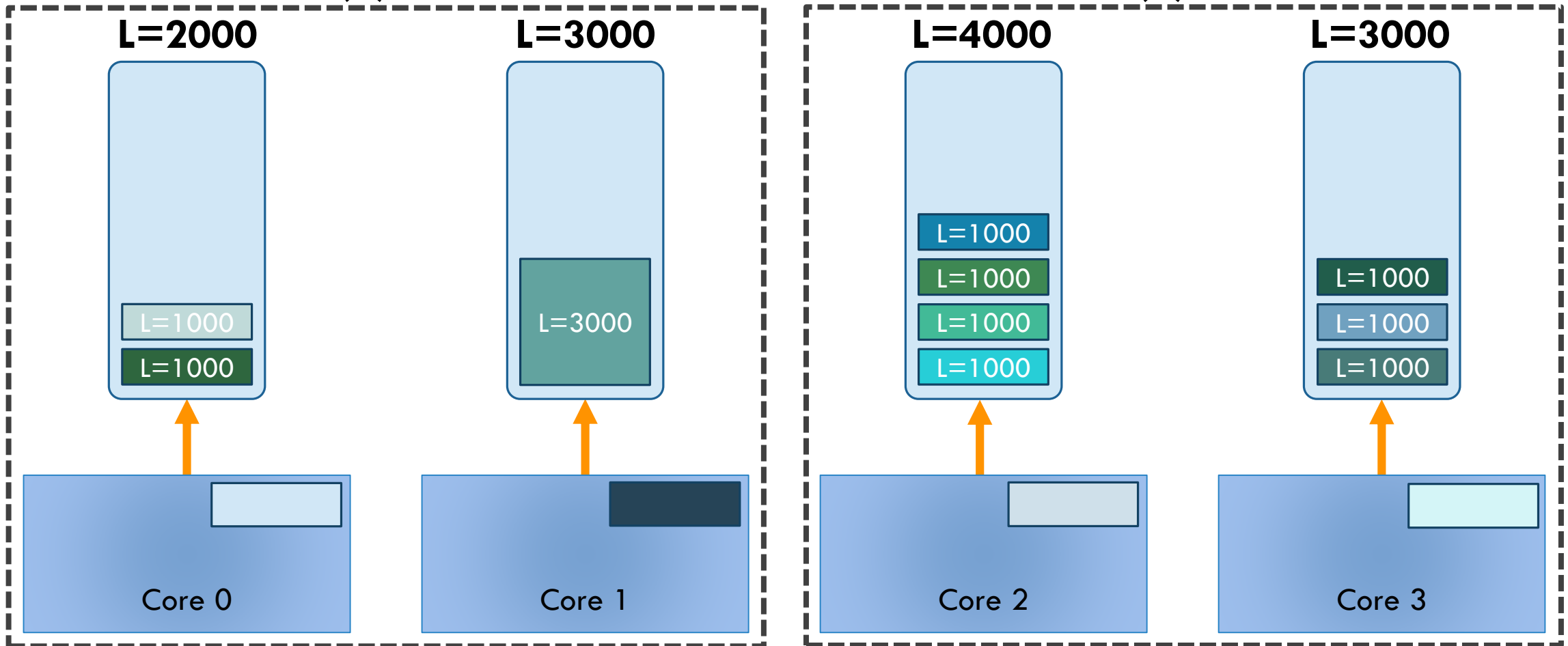
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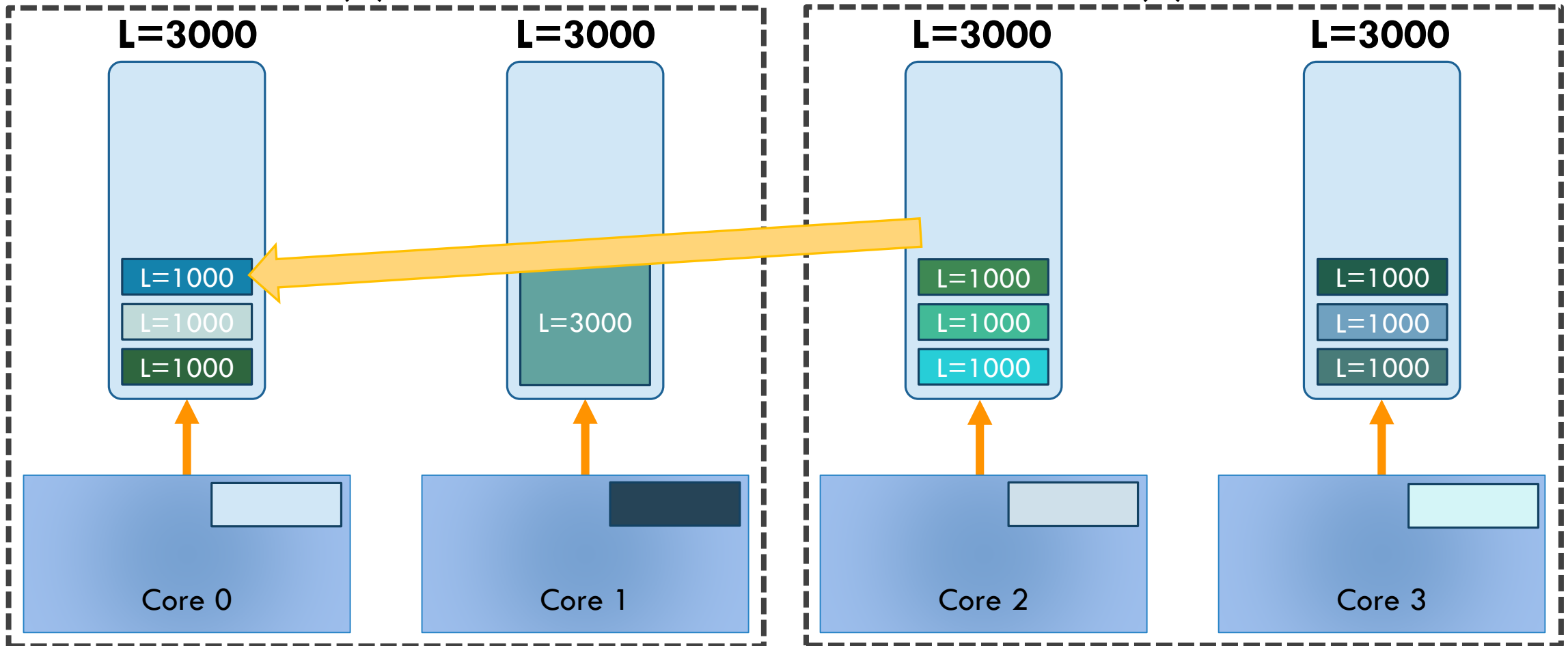




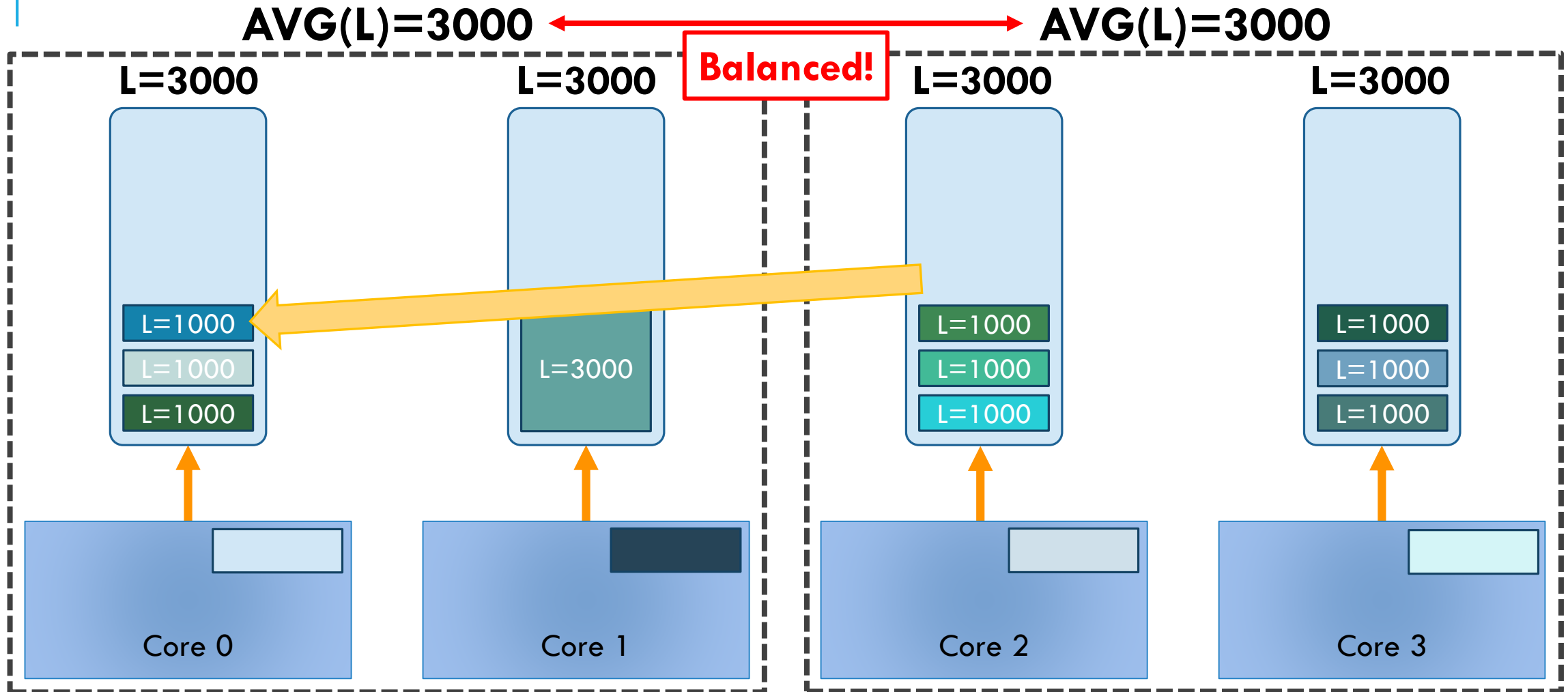
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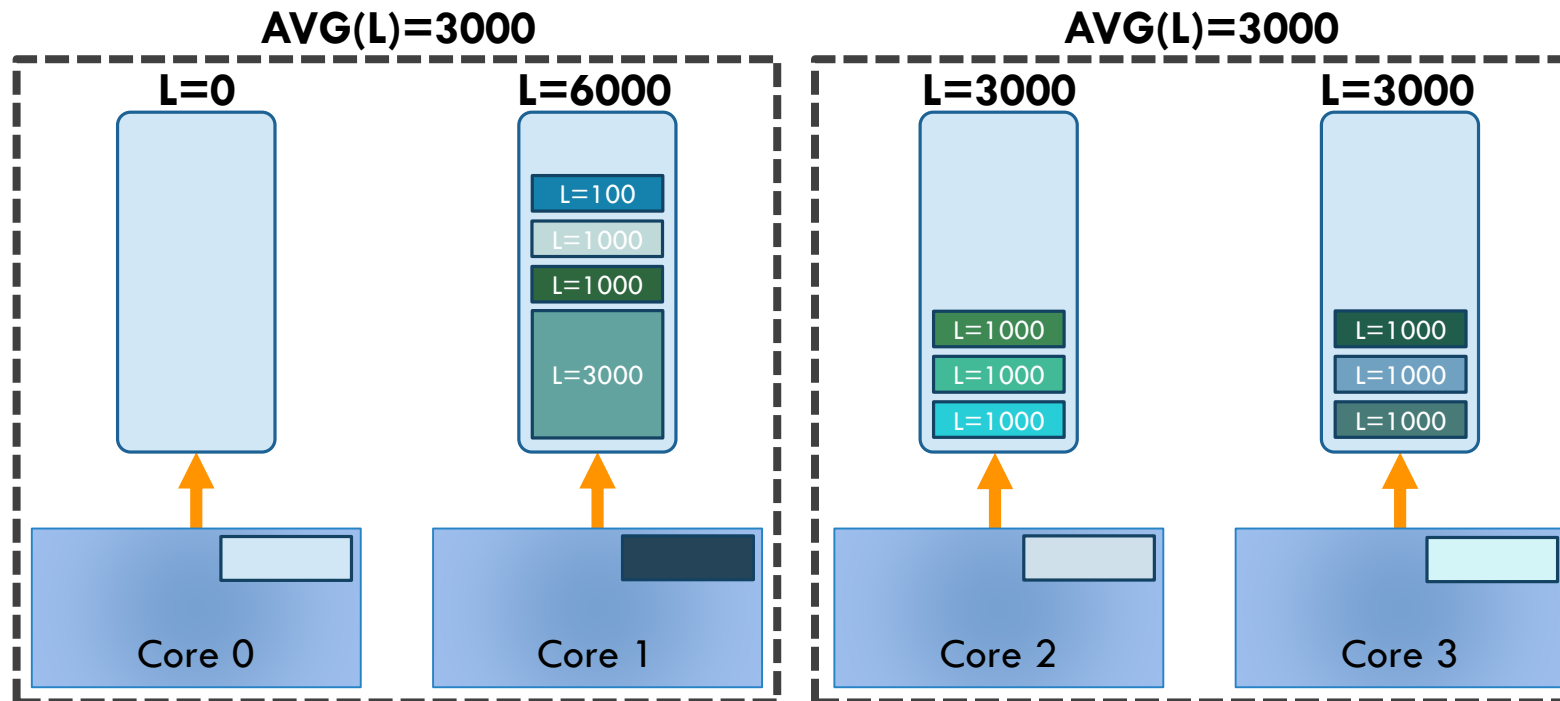
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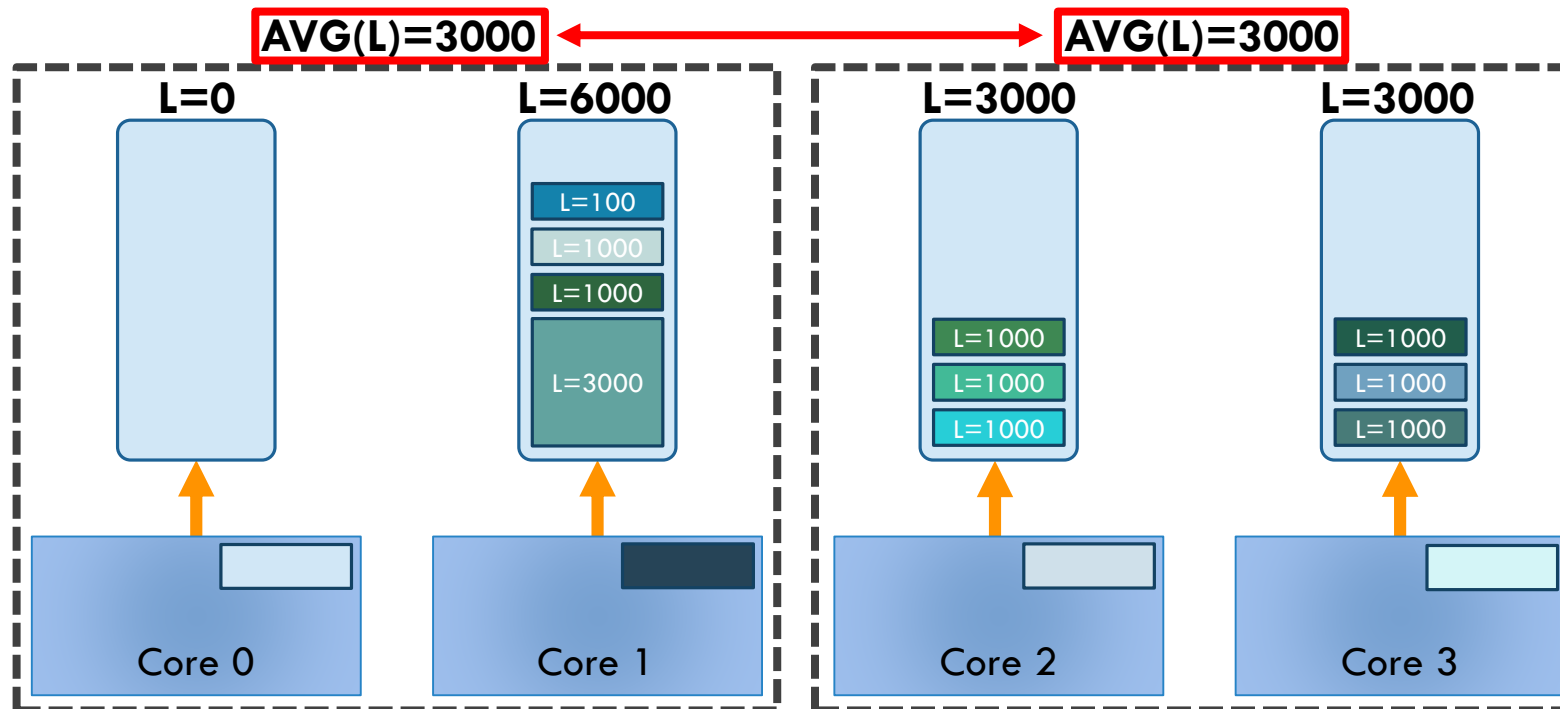
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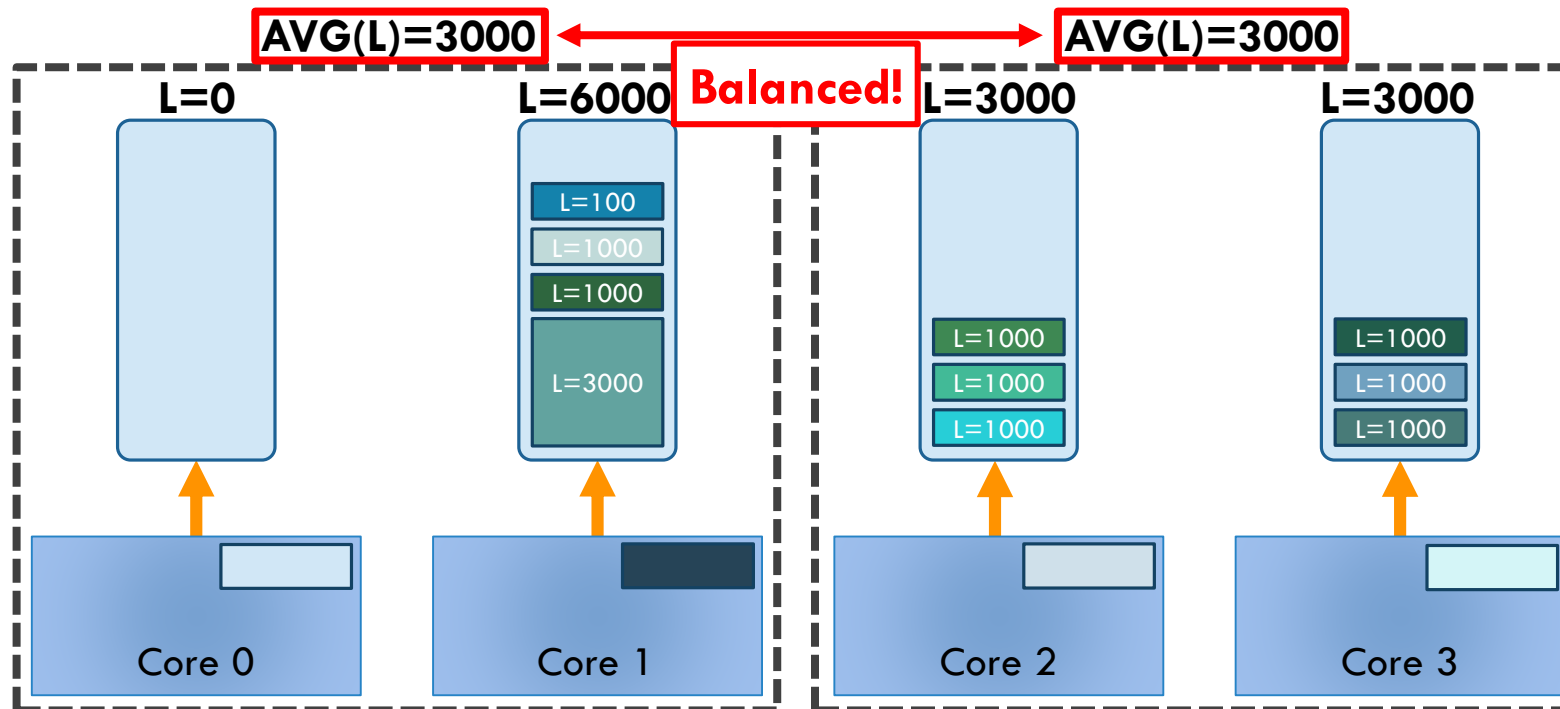
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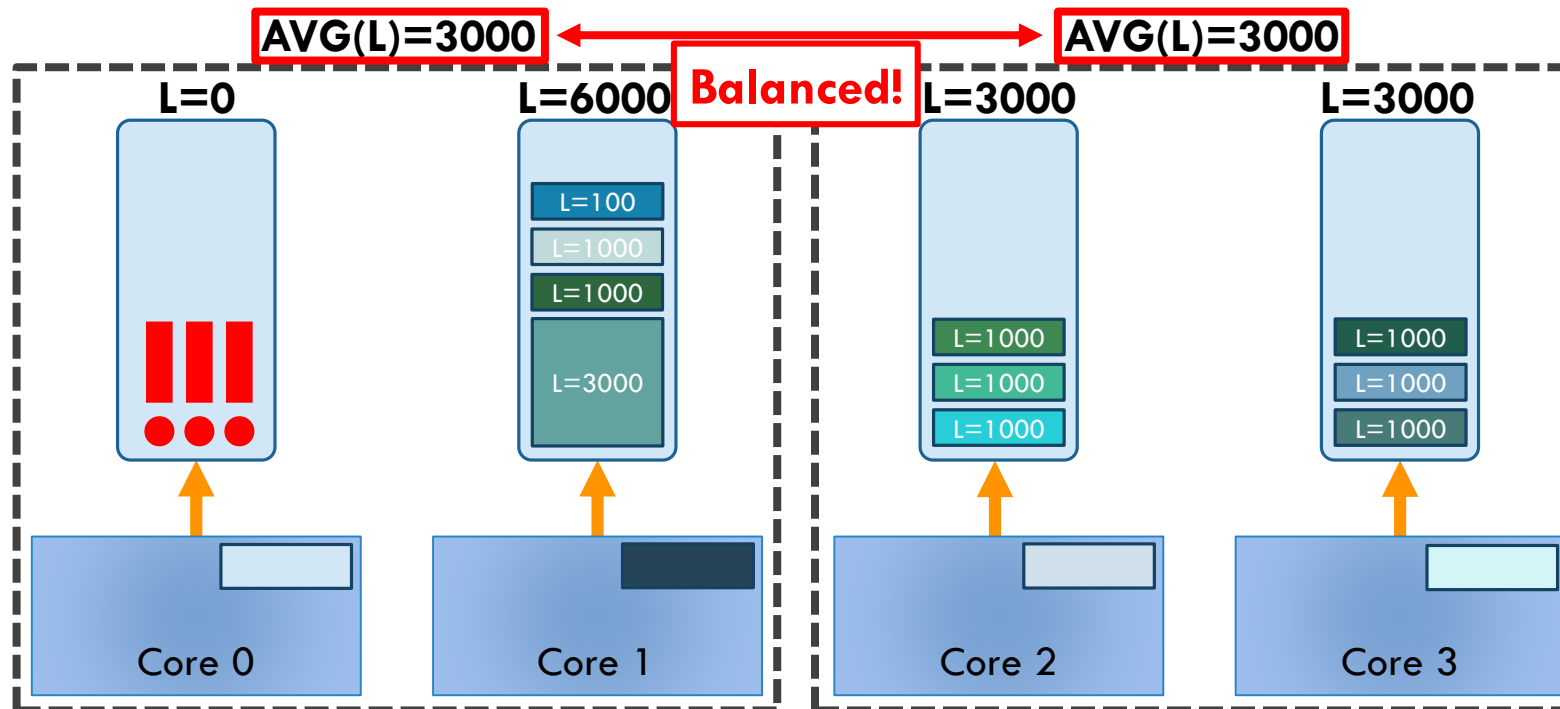
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- **Objective:** making sure that launching lots of threads from one terminal doesn't prevent other processes on the machine (potentially from other users) from running.
  - Otherwise, easy to use more resources than other users by spawning many threads...

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L=1000

L=1000

Session (tty) 2

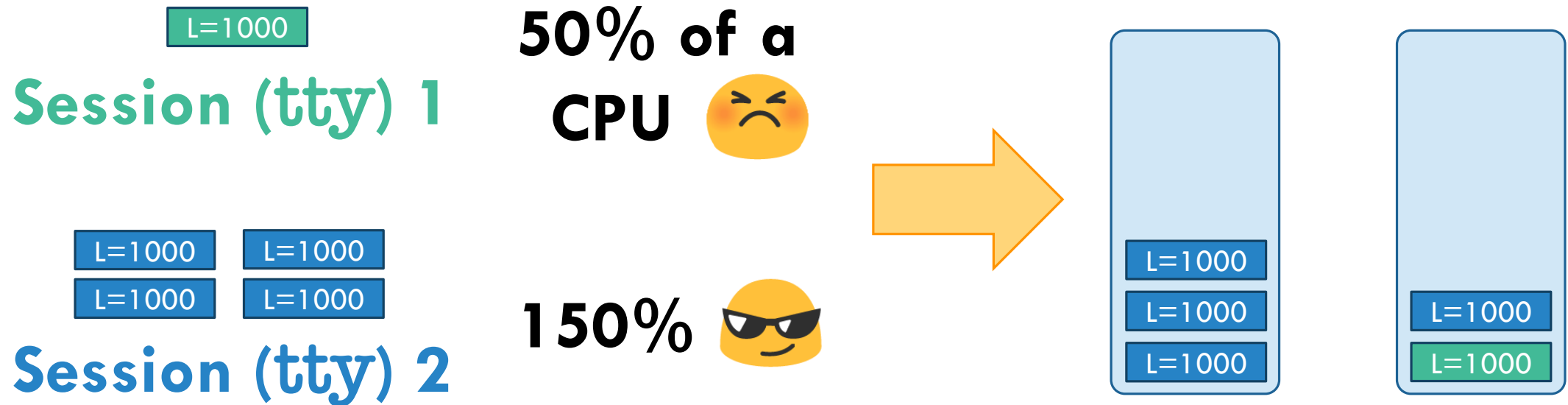
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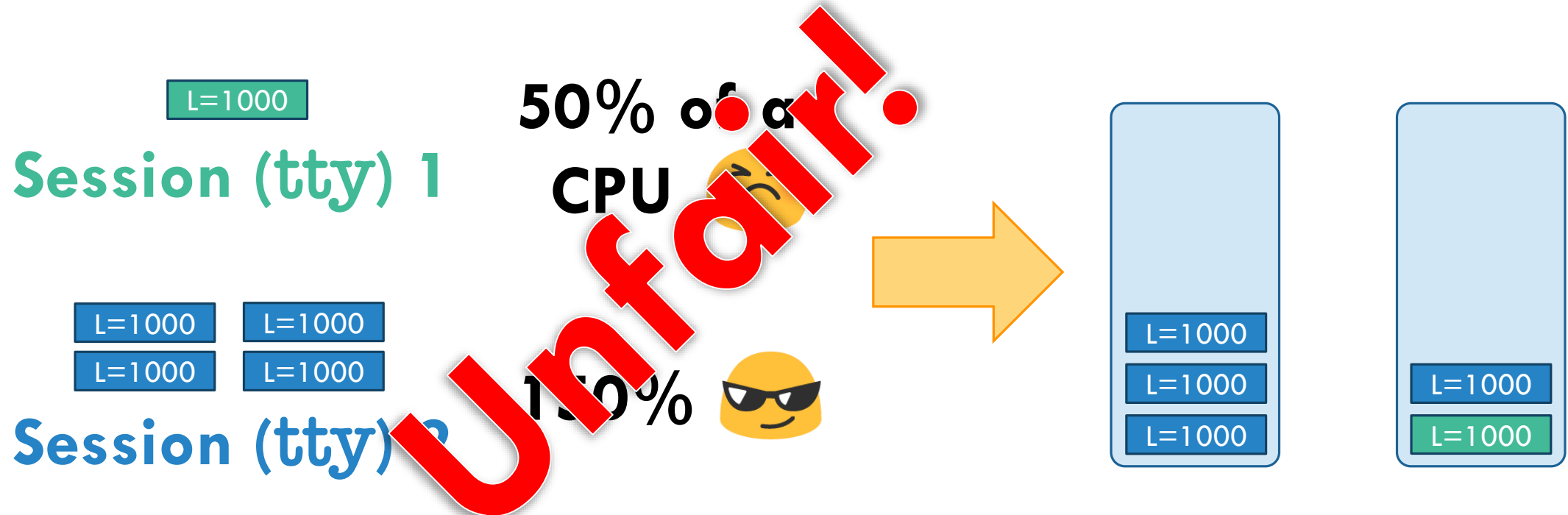
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L=250

L=250

L=250

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Session (tty) 2

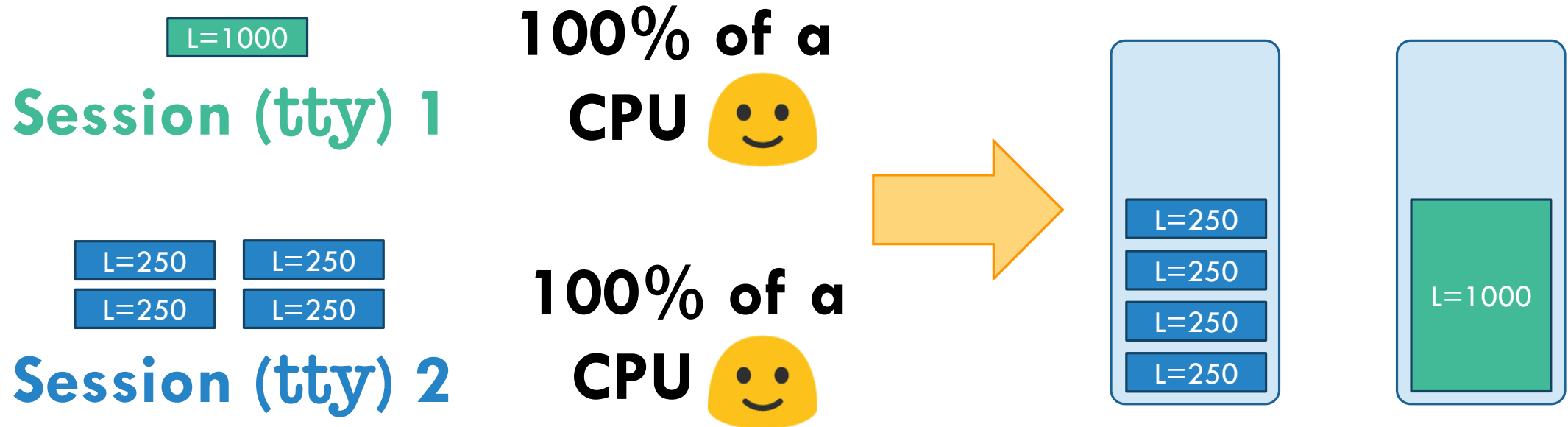
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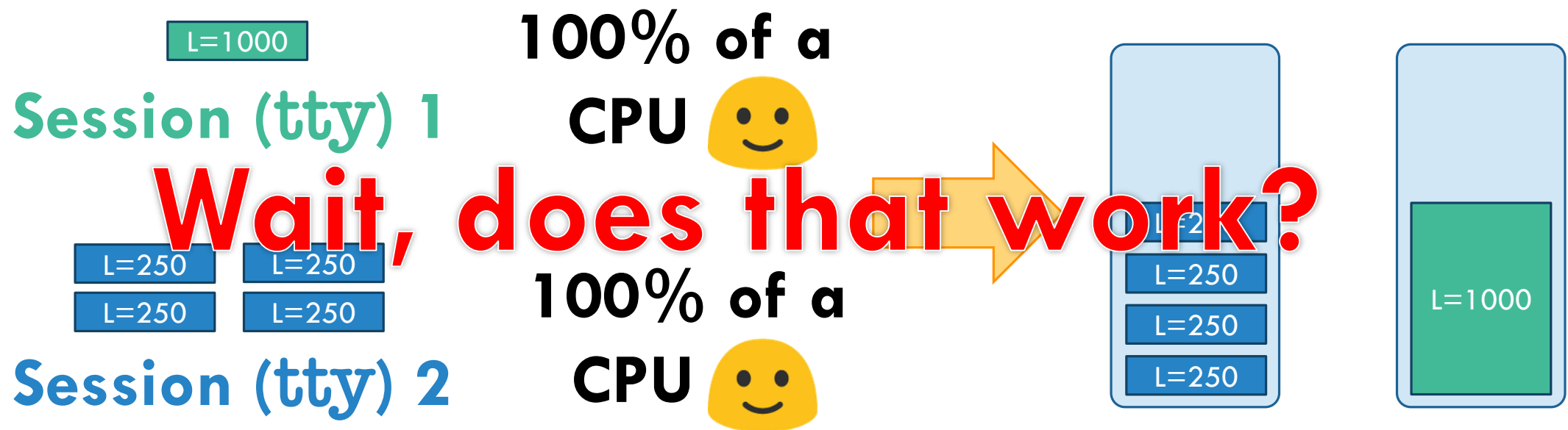
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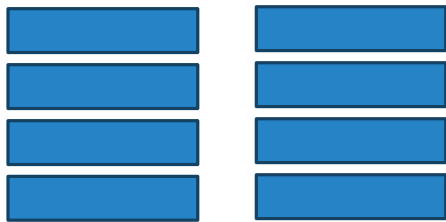
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# BUG 1/4: GROUP IMBALANCE



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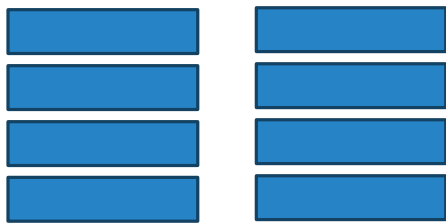
Session (tty) 2

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



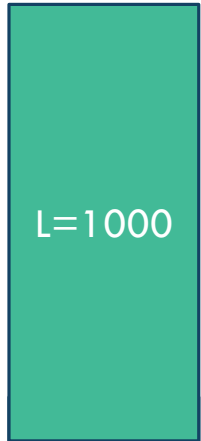
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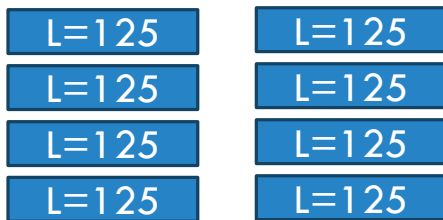
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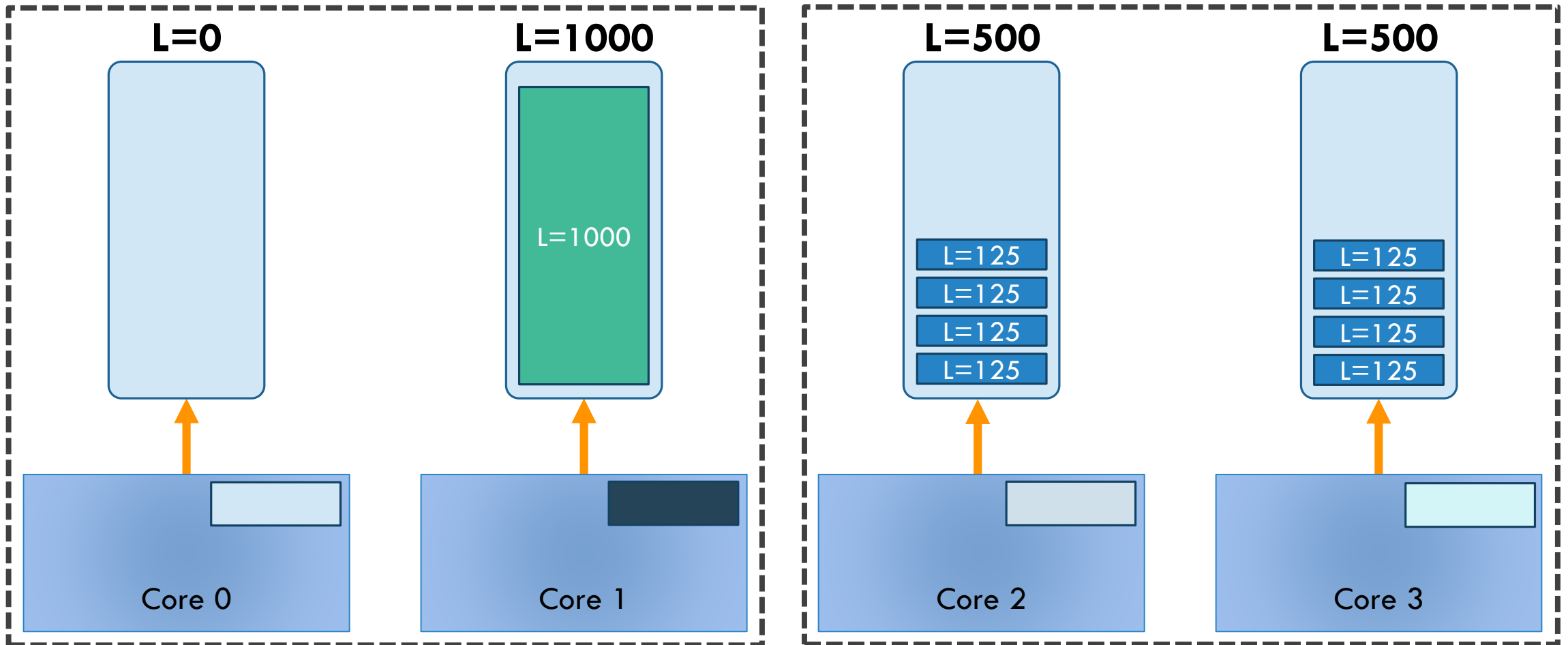


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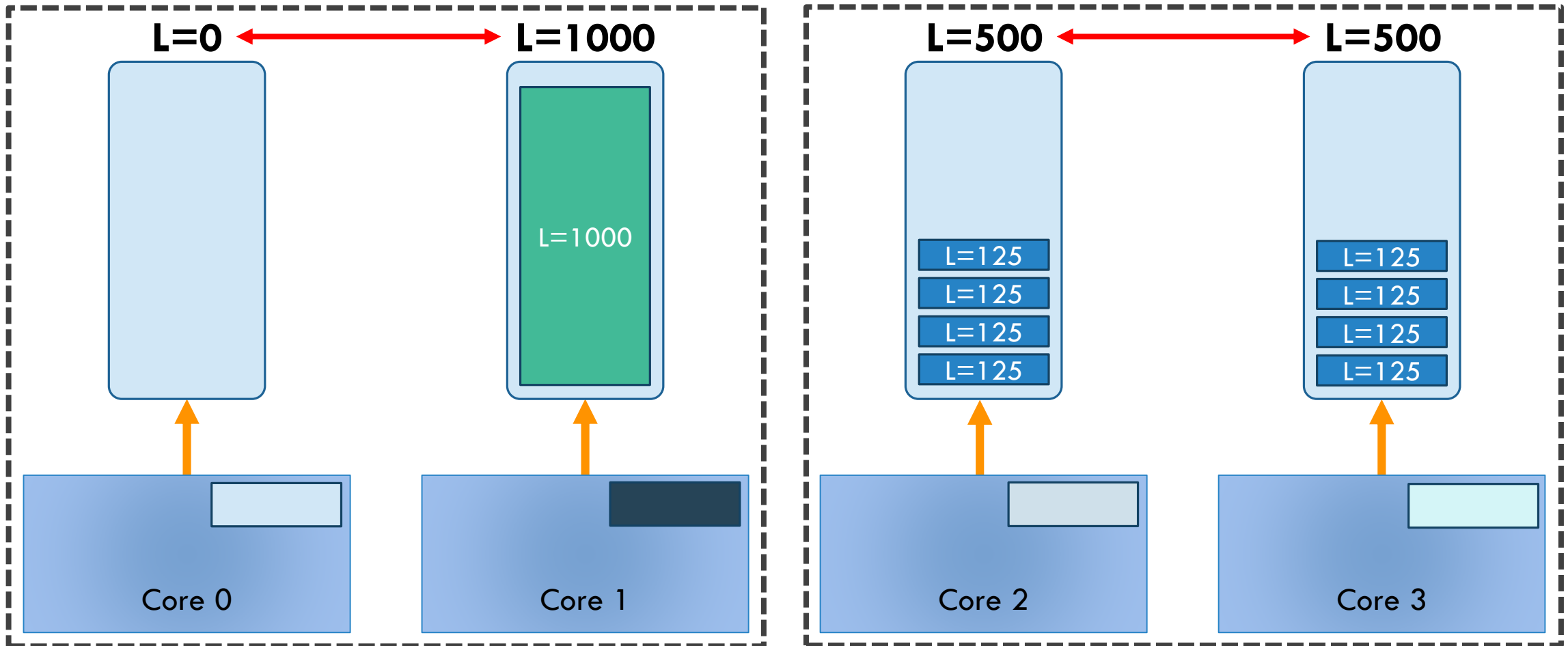
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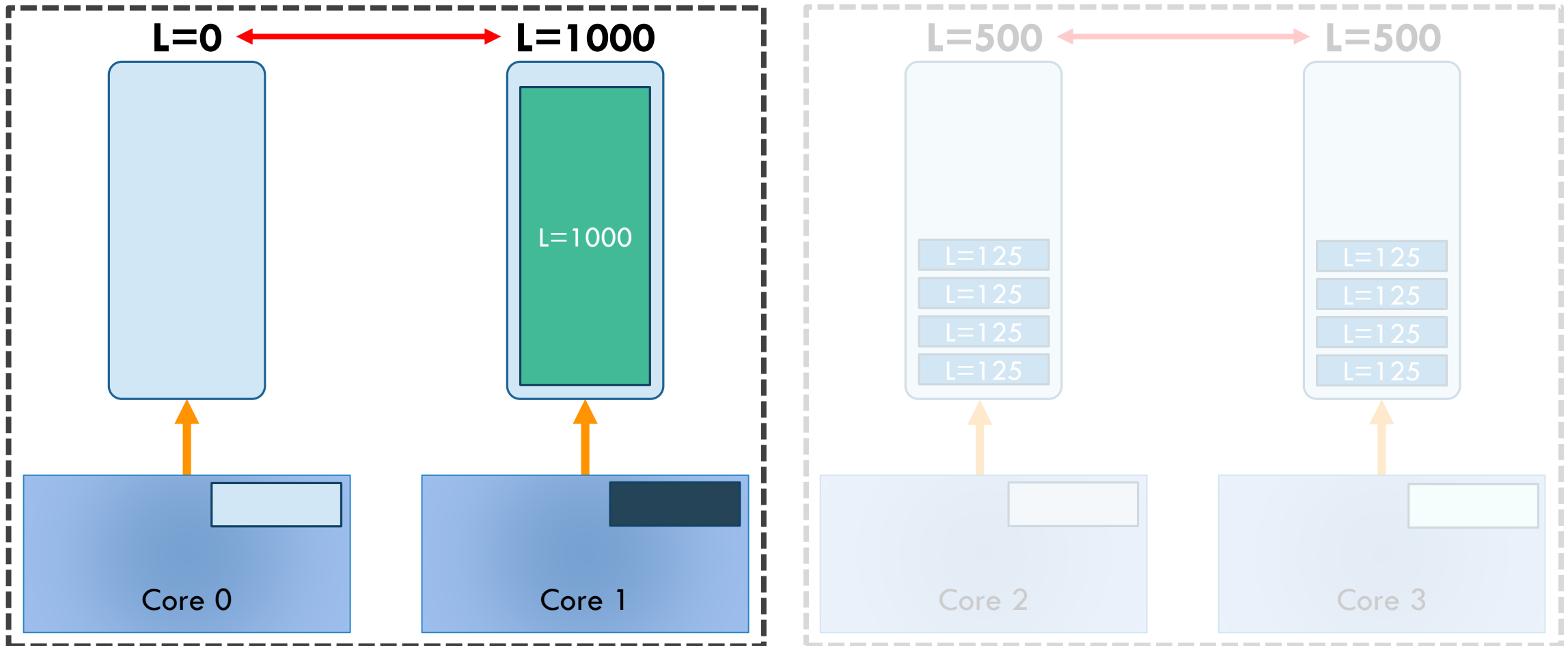
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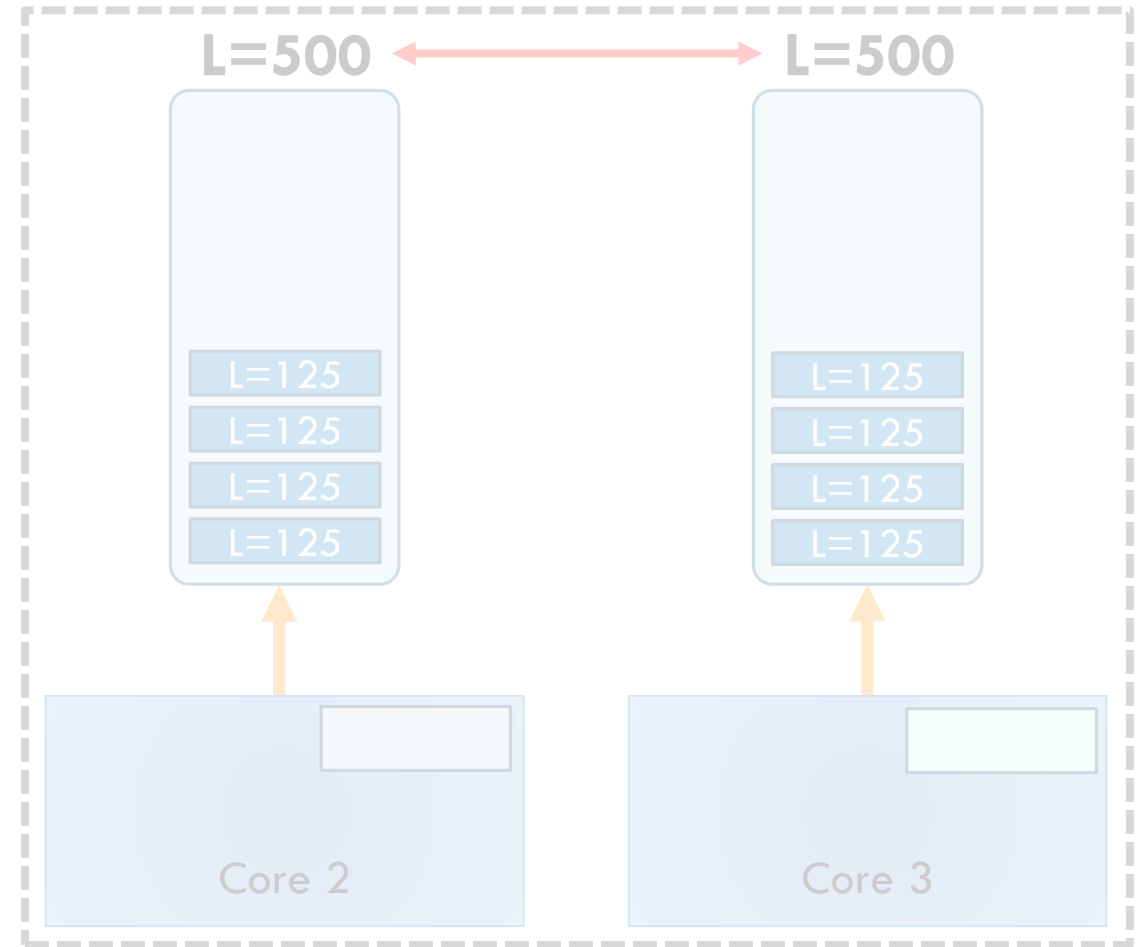
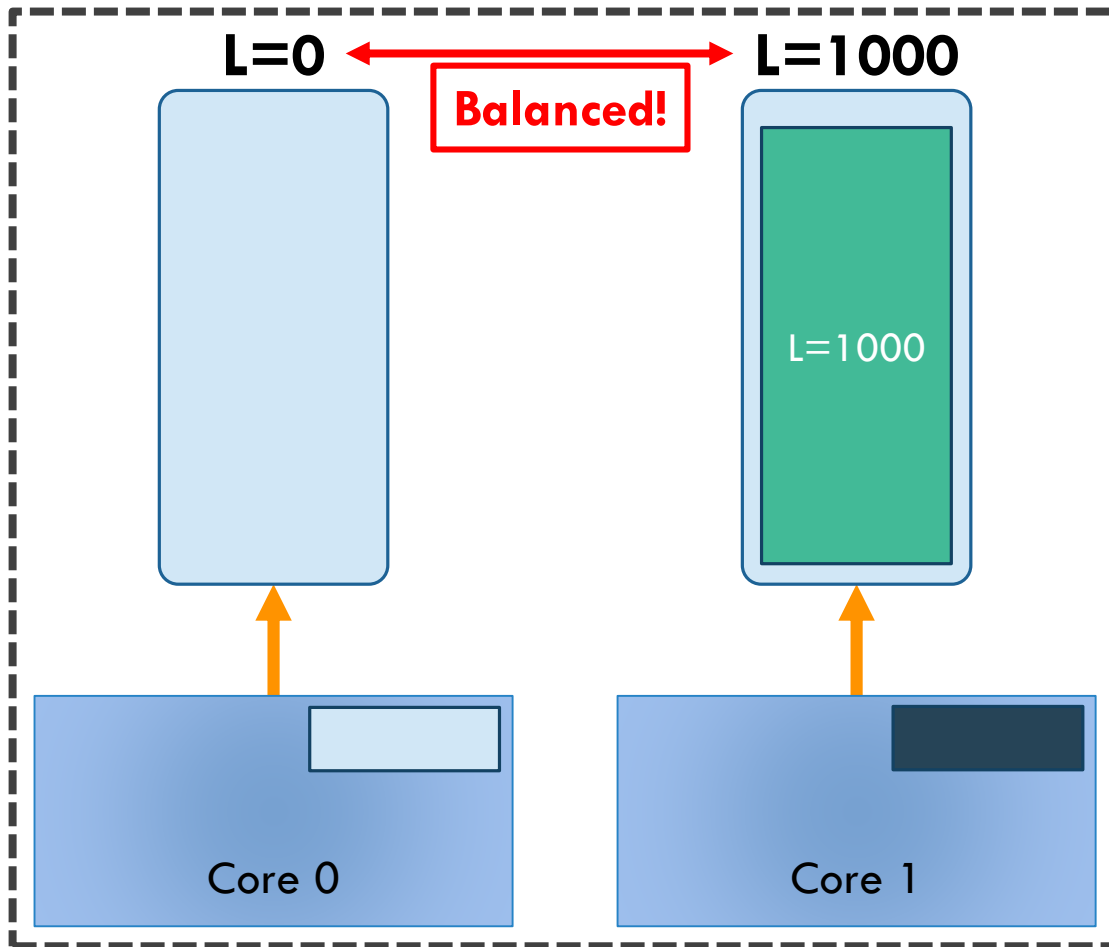
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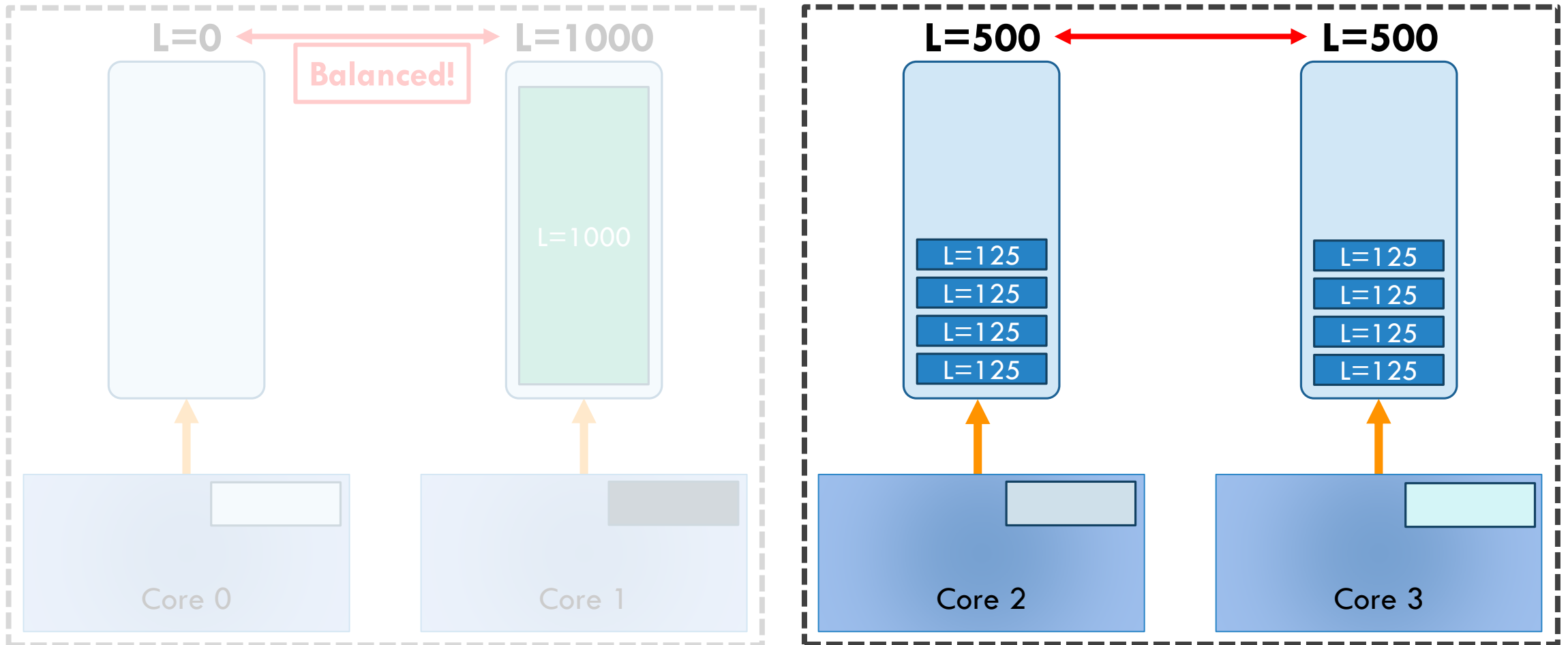
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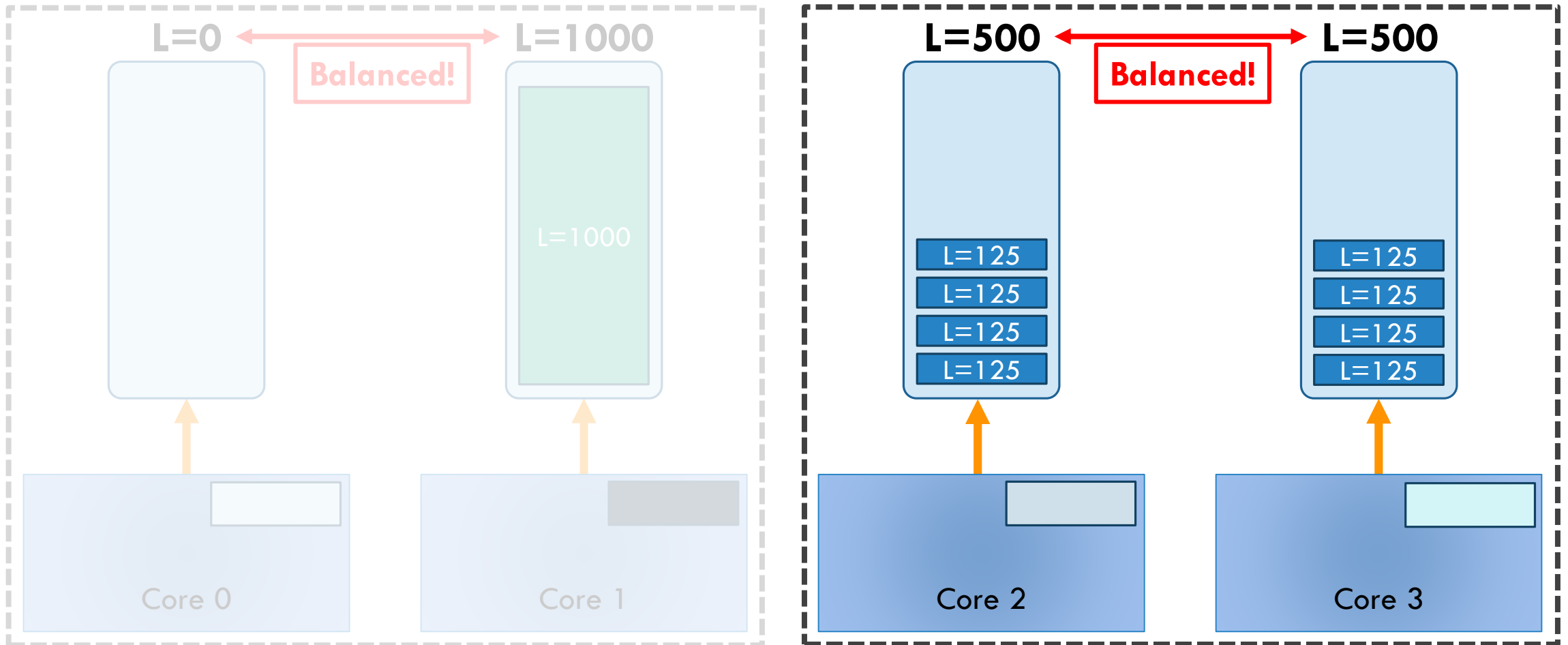
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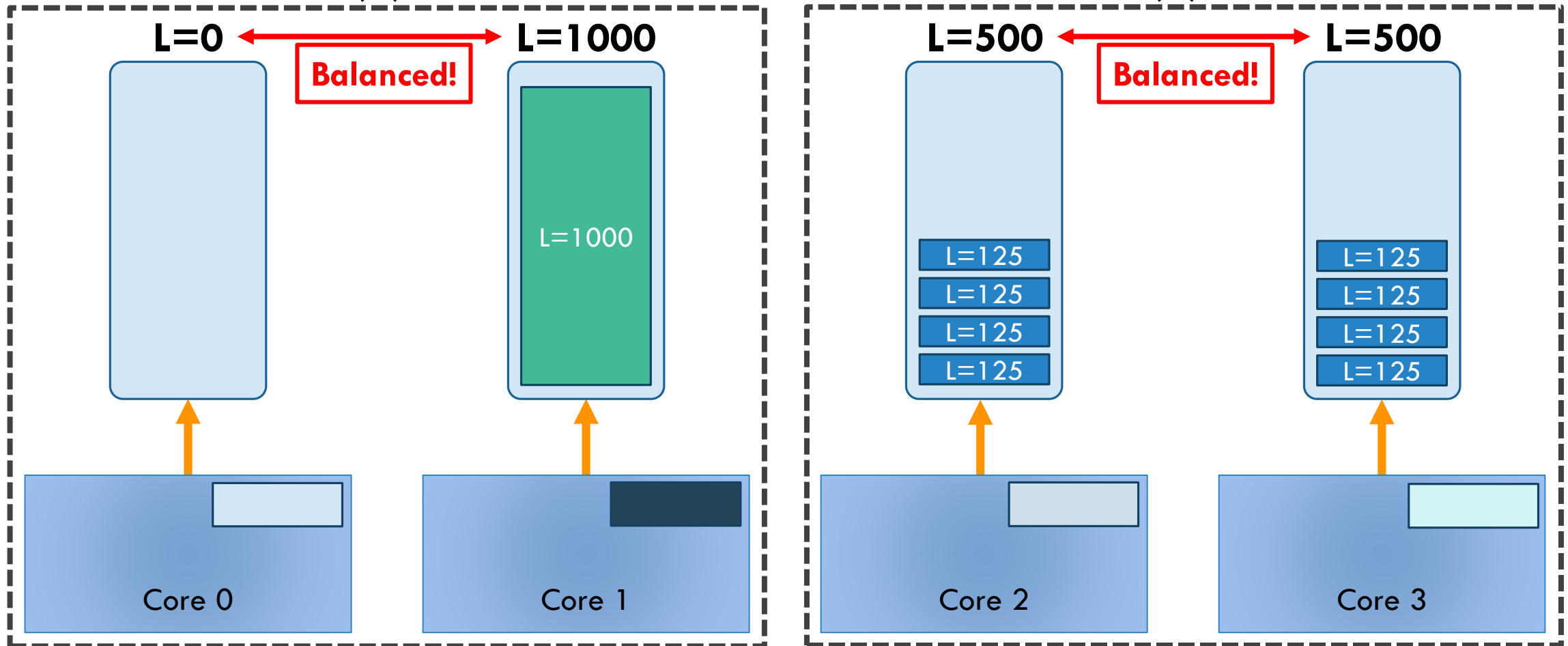
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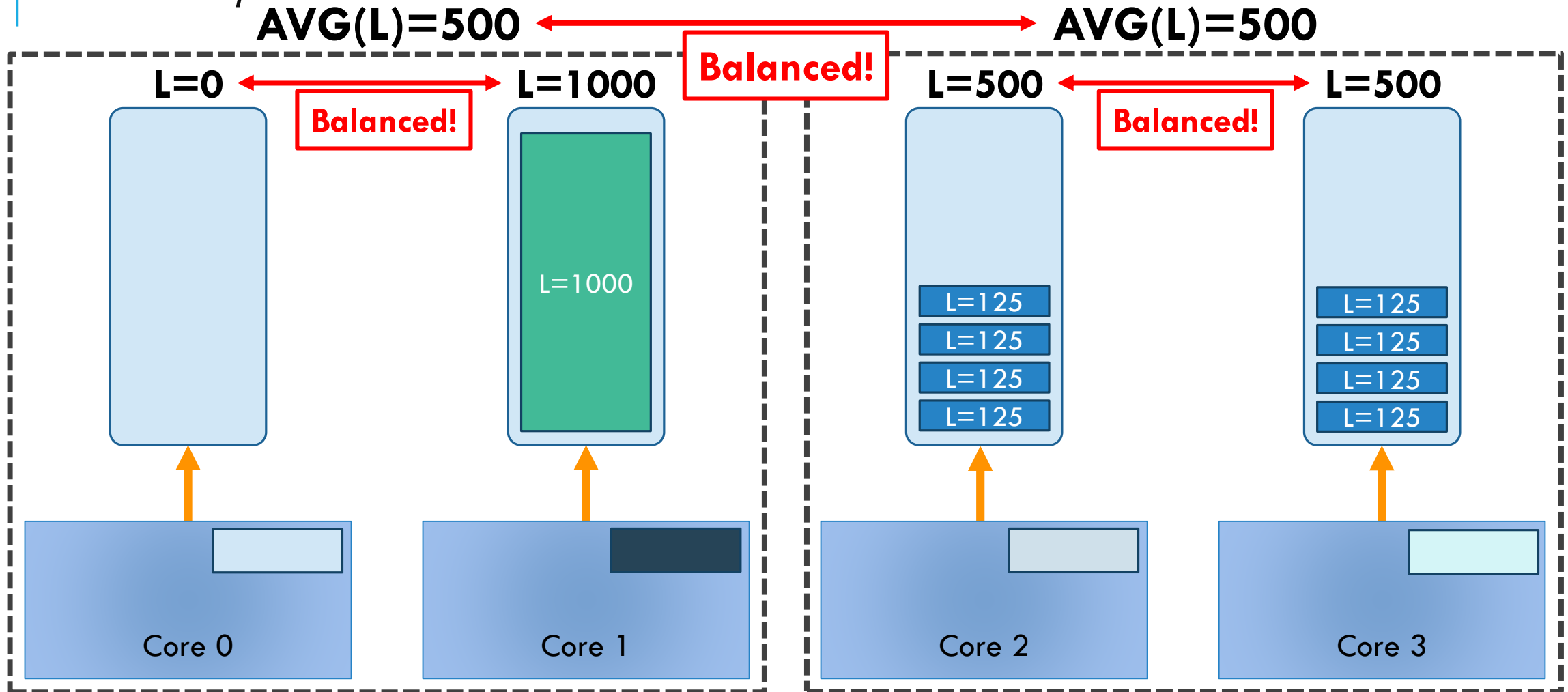
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$AVG(L)=500$

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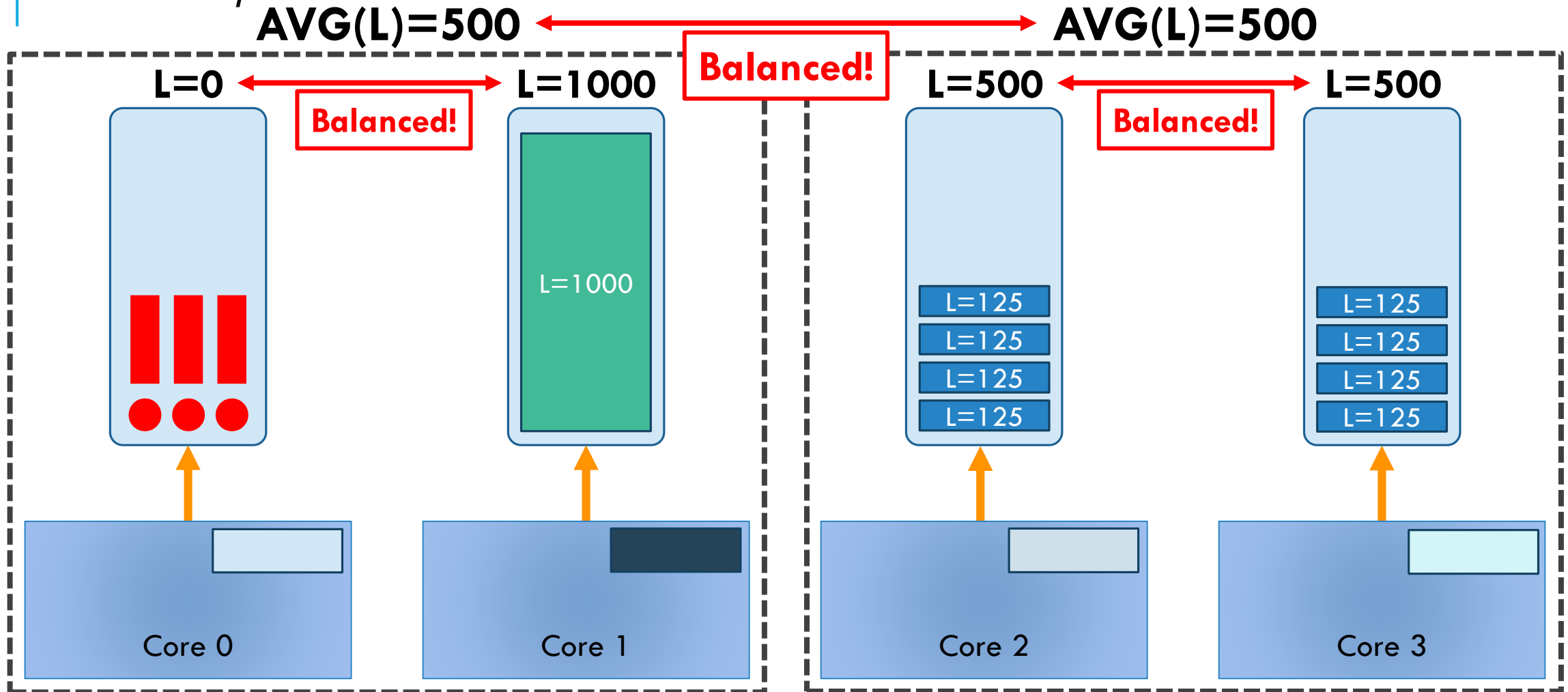


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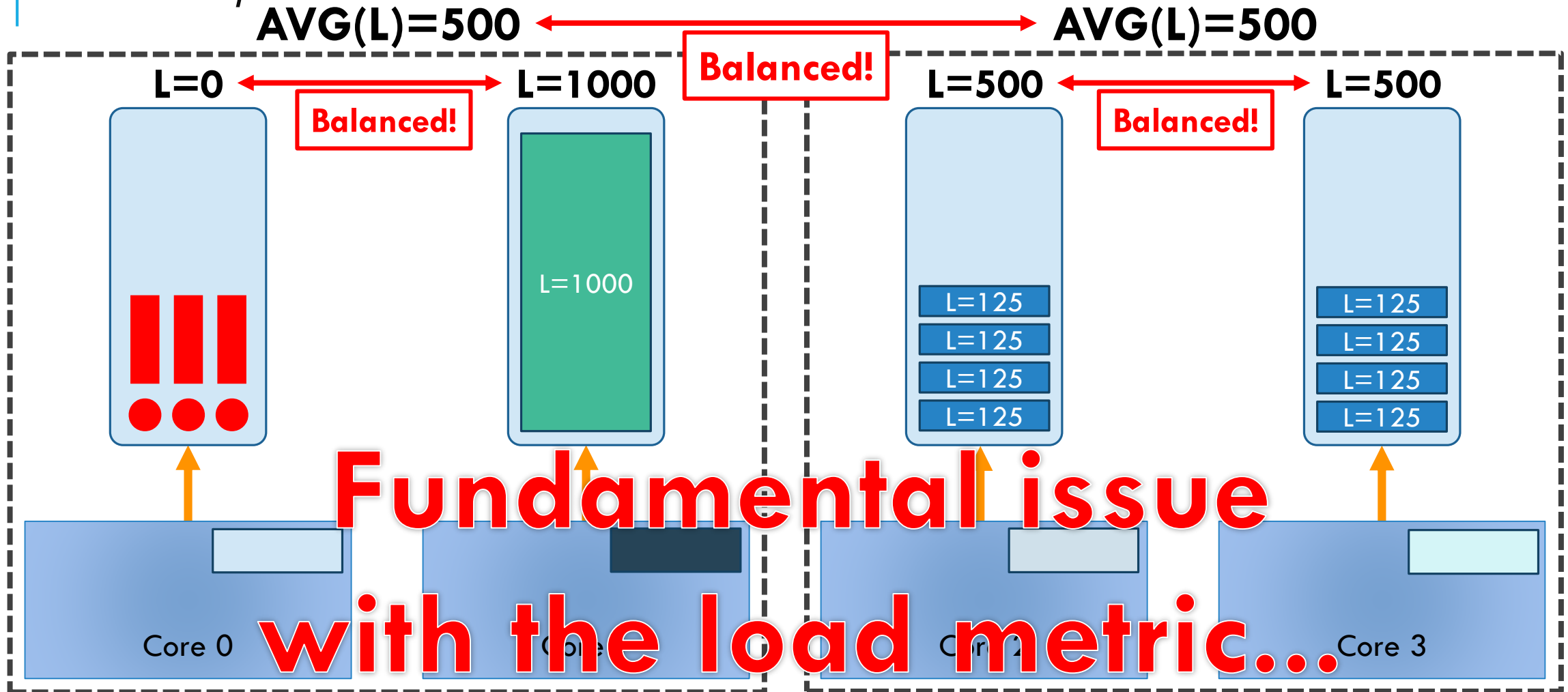




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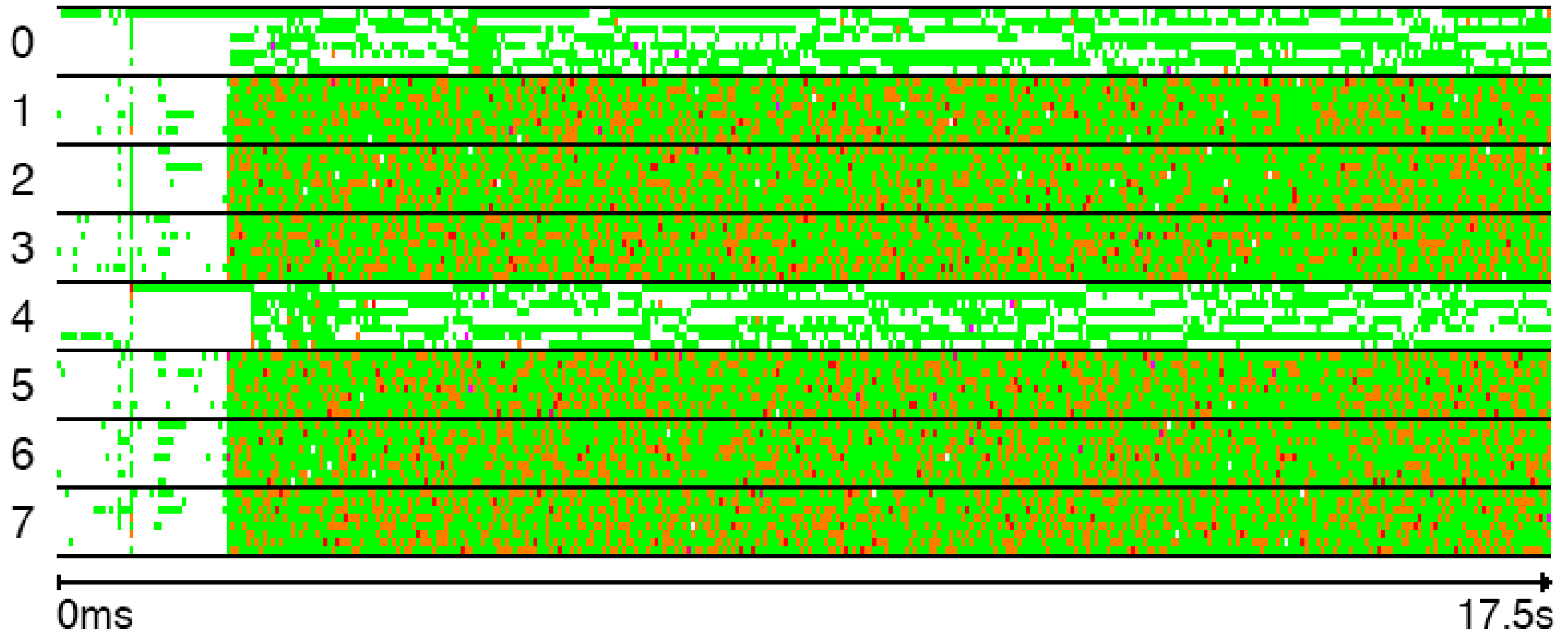
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  - Other core on pair of core idle
  - Other cores on NUMA node less busy...

Number of threads in run queue: 0 1 2 3 4+



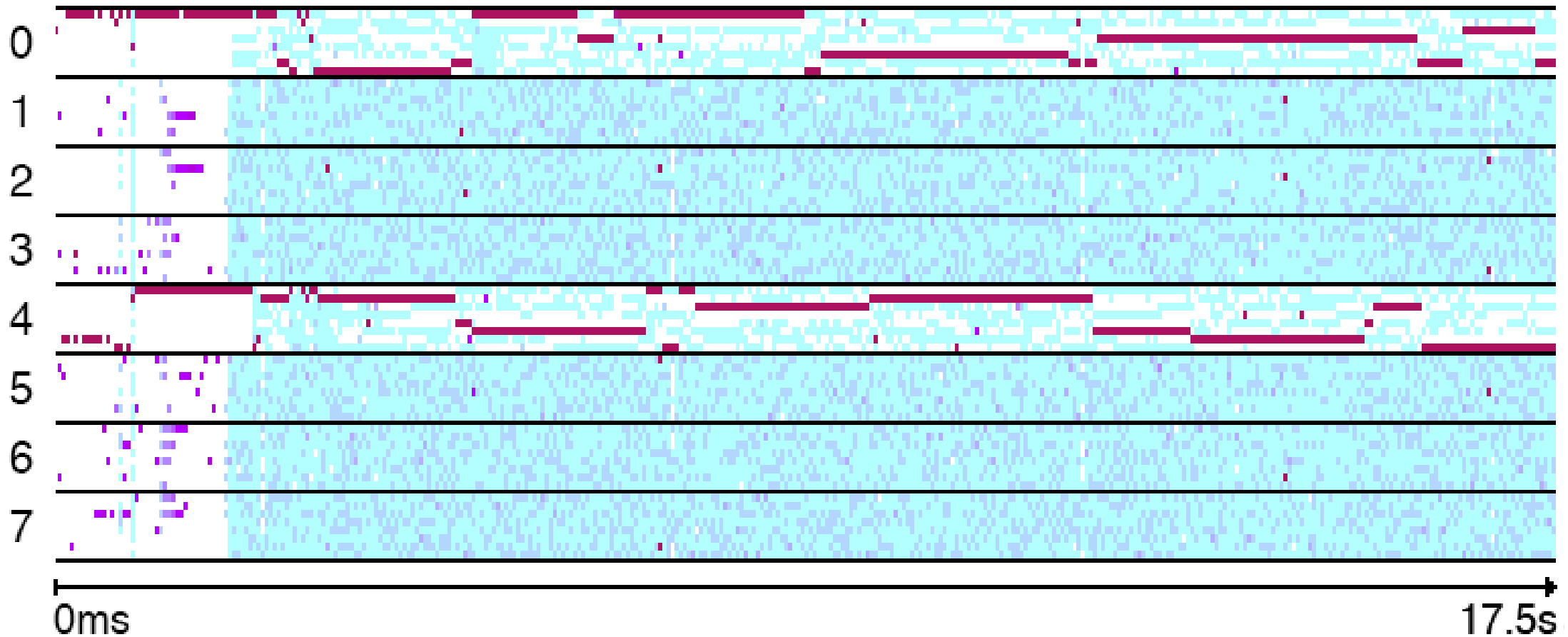
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Load:

0

1

1024

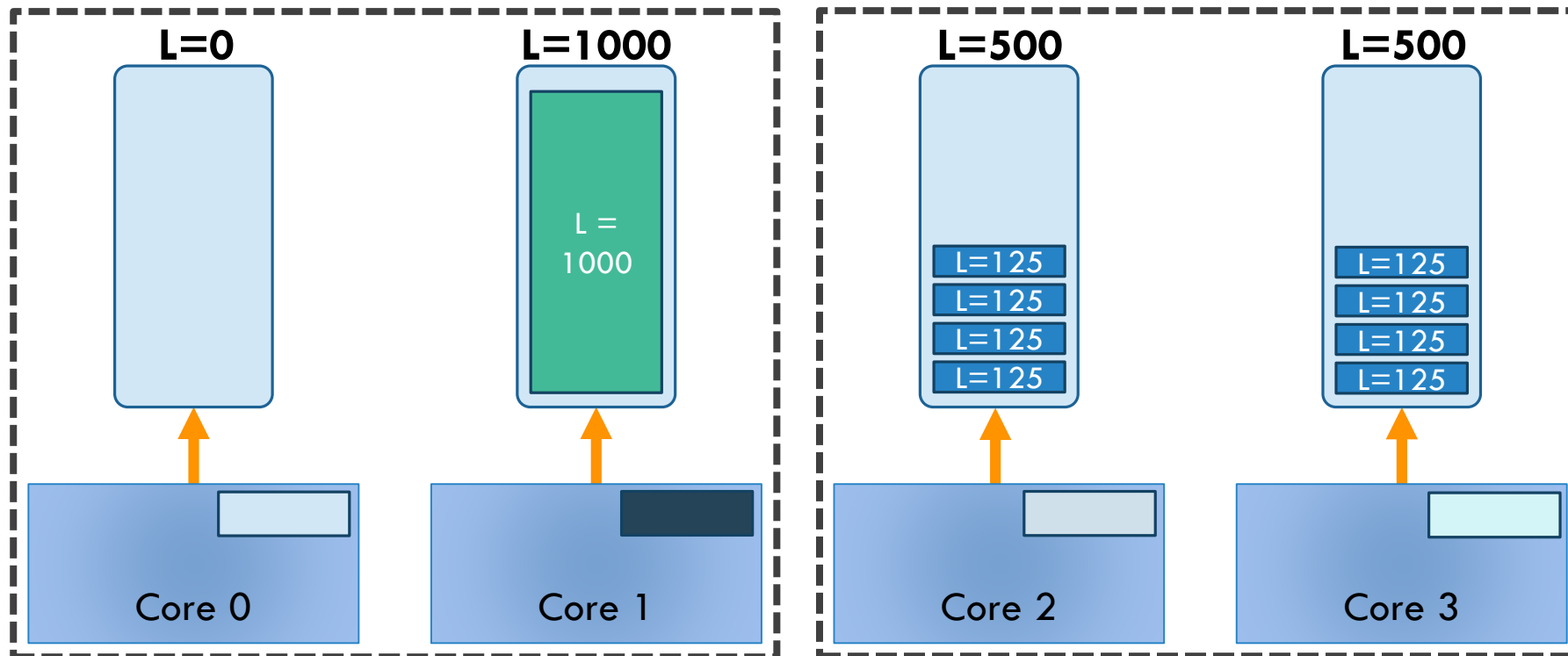


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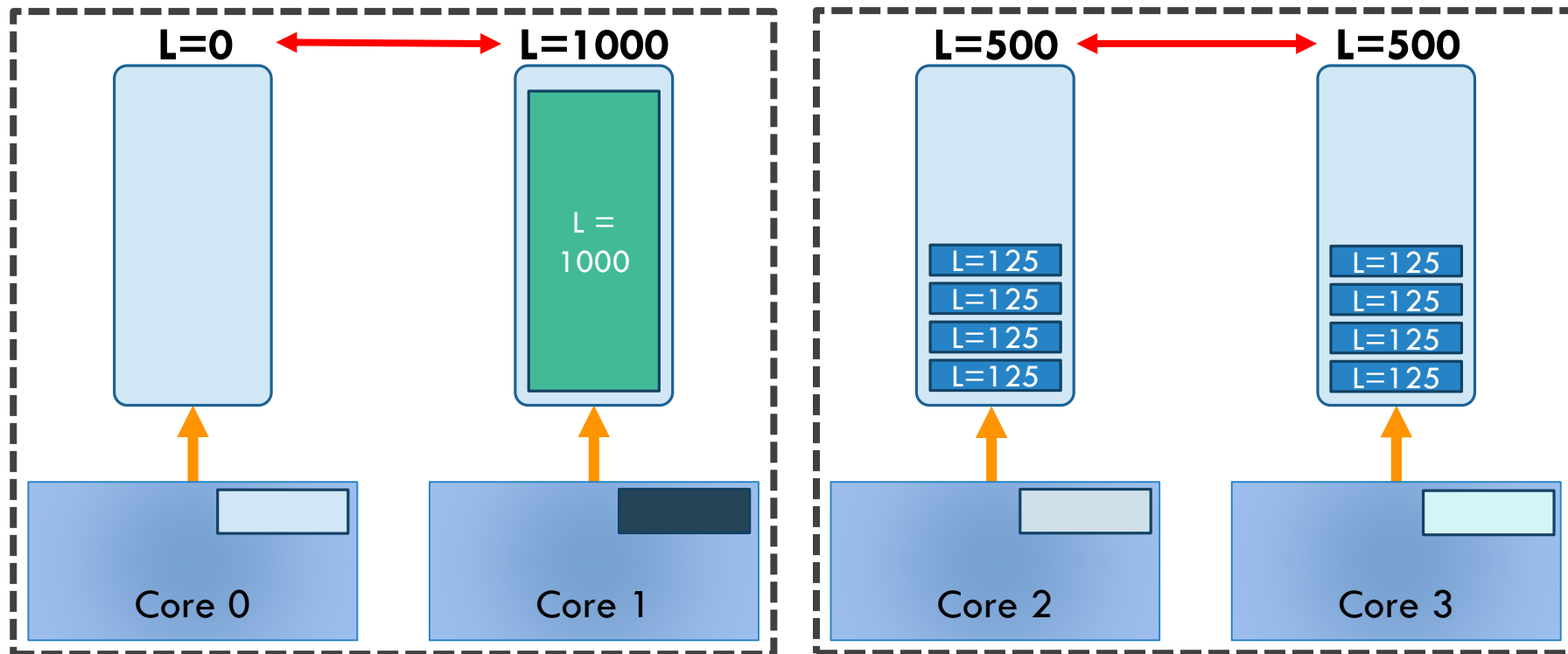
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- A simple solution: balance the *minimum* load of groups instead of the *average*



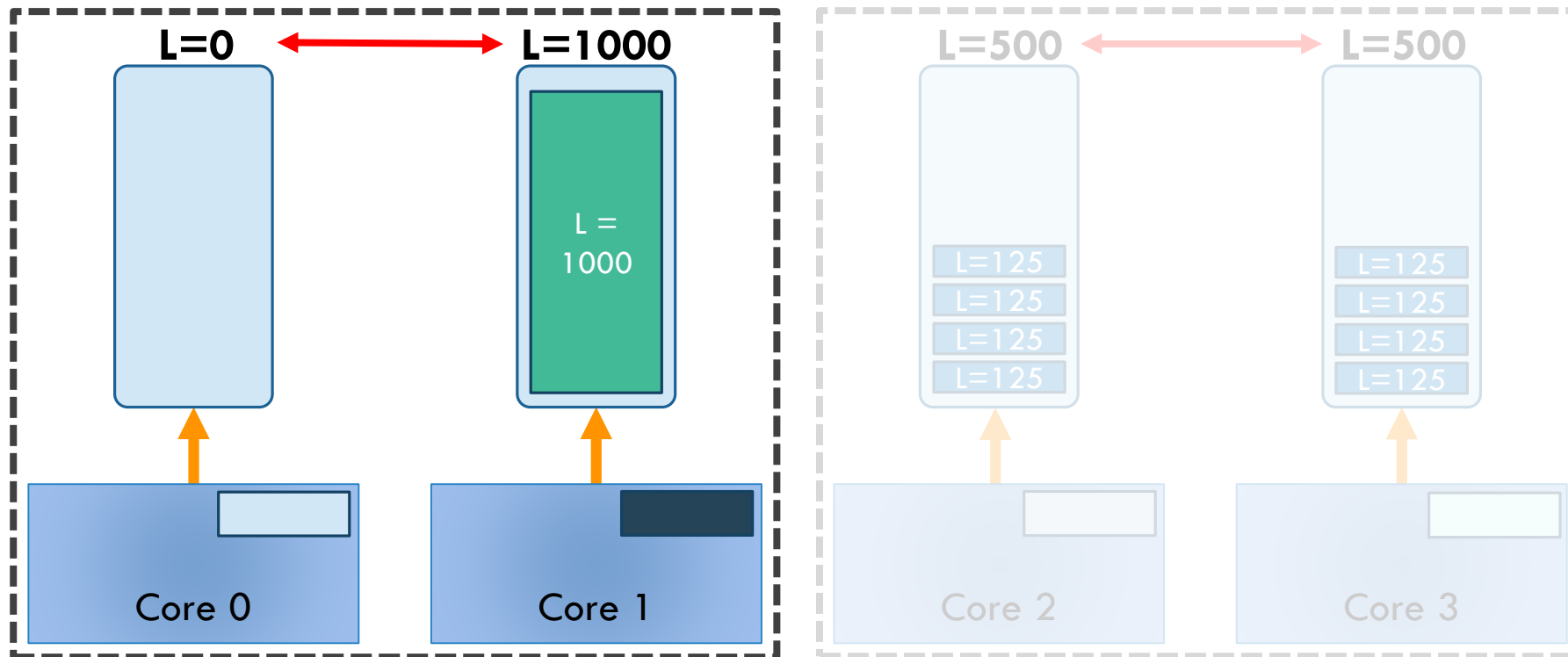
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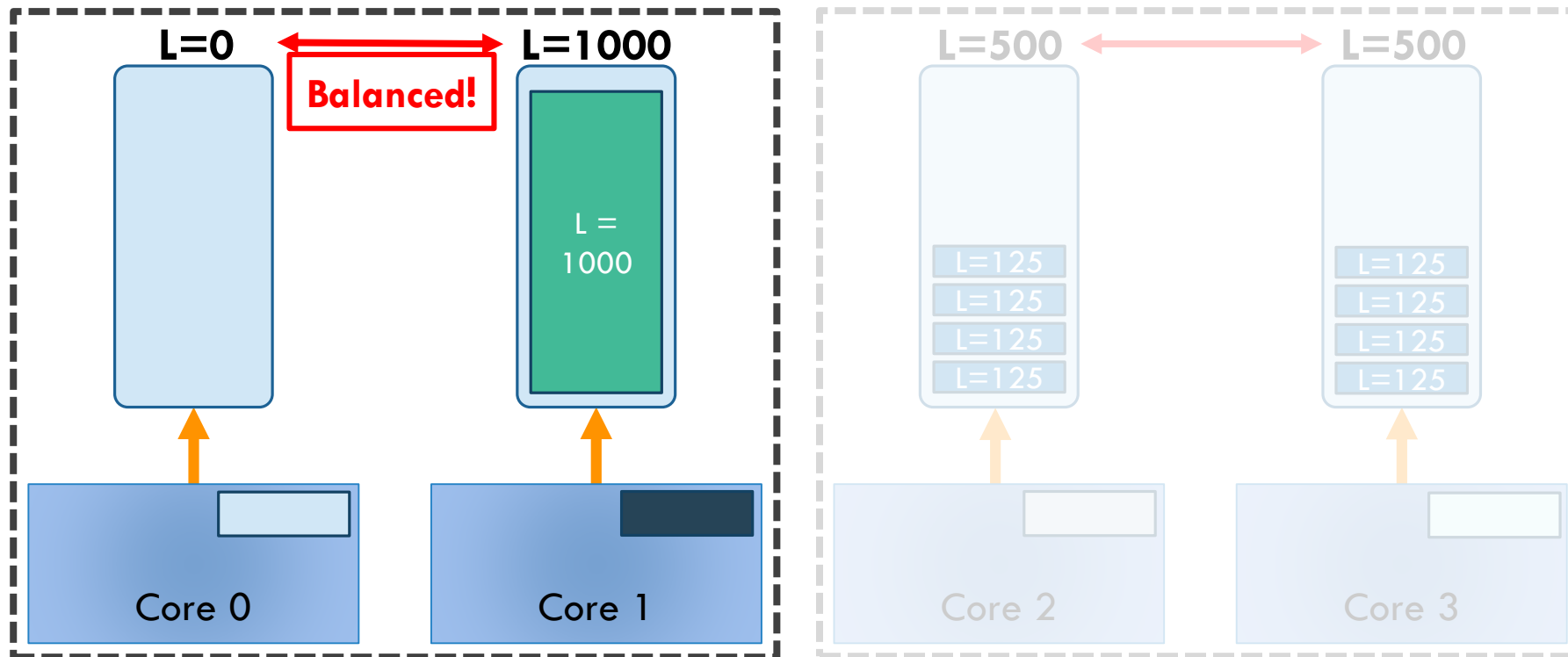
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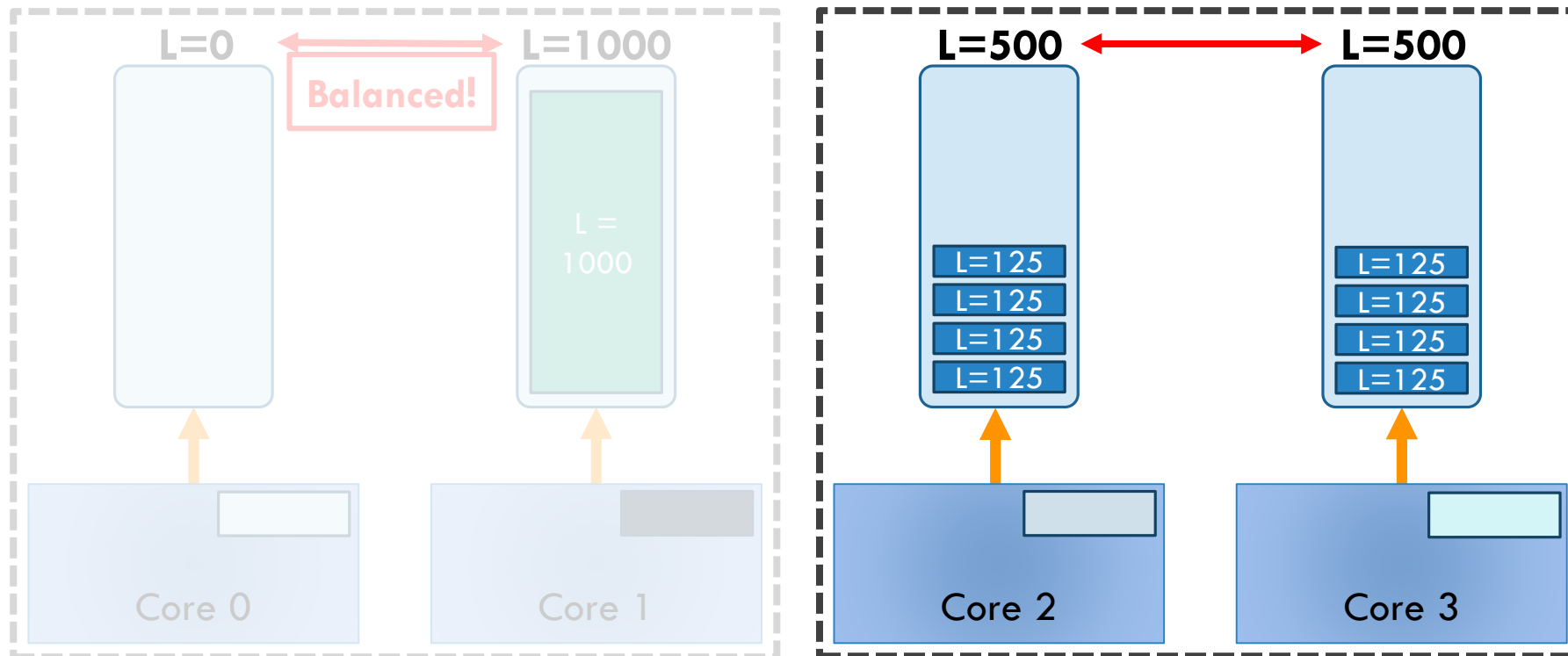
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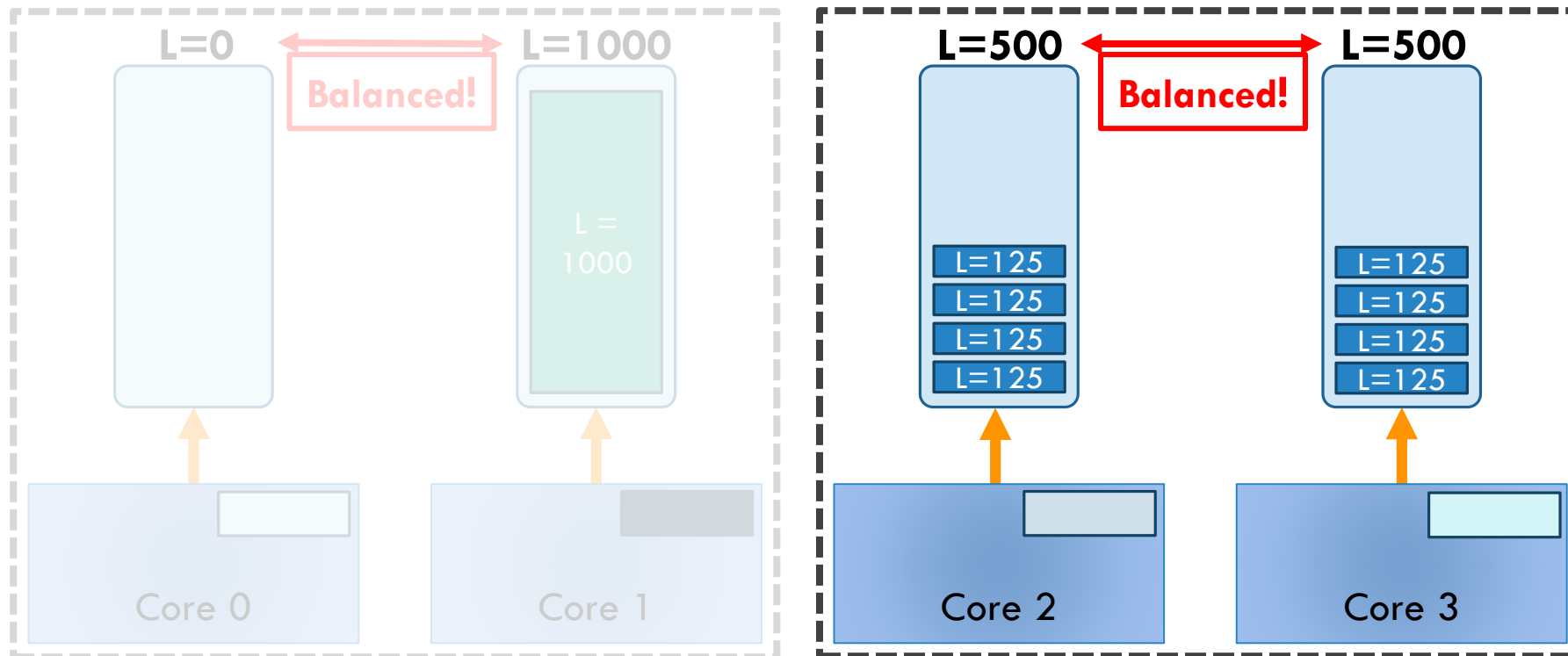
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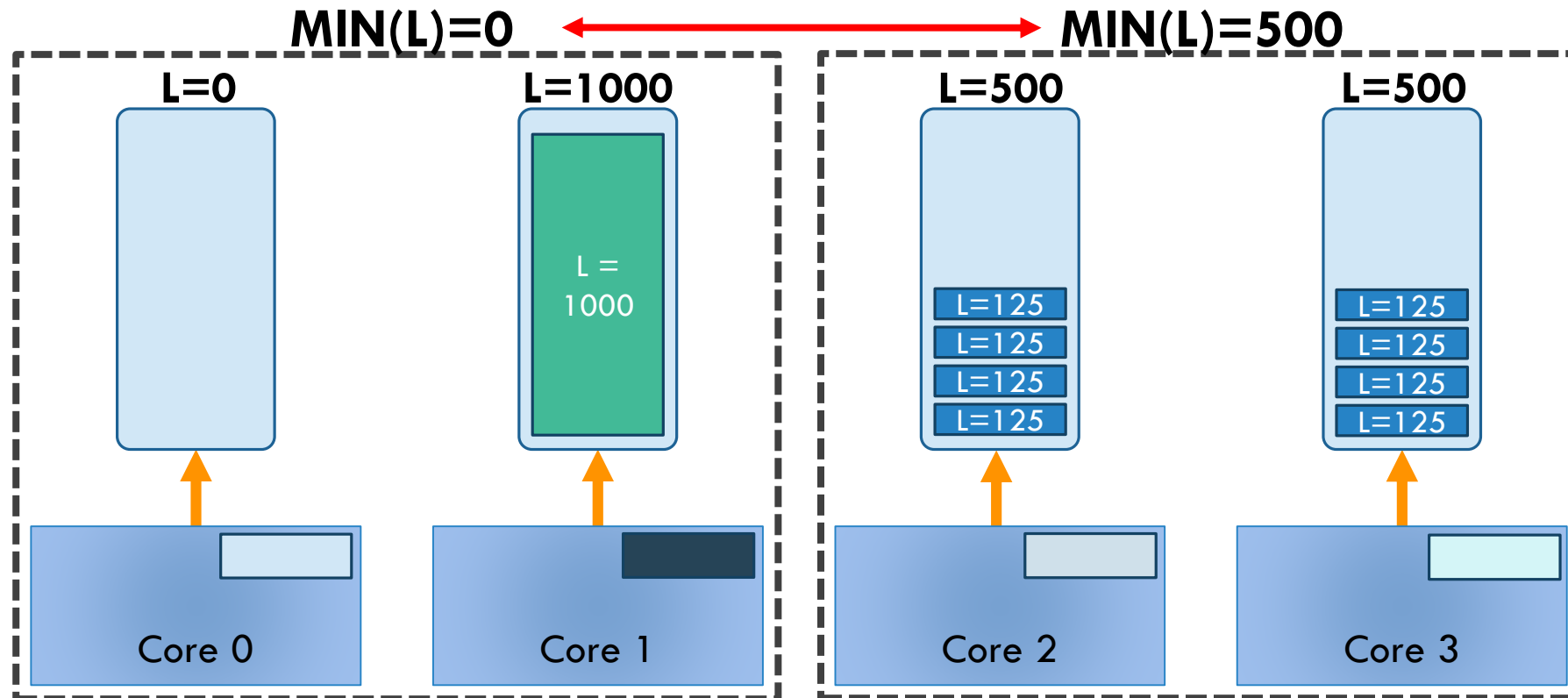
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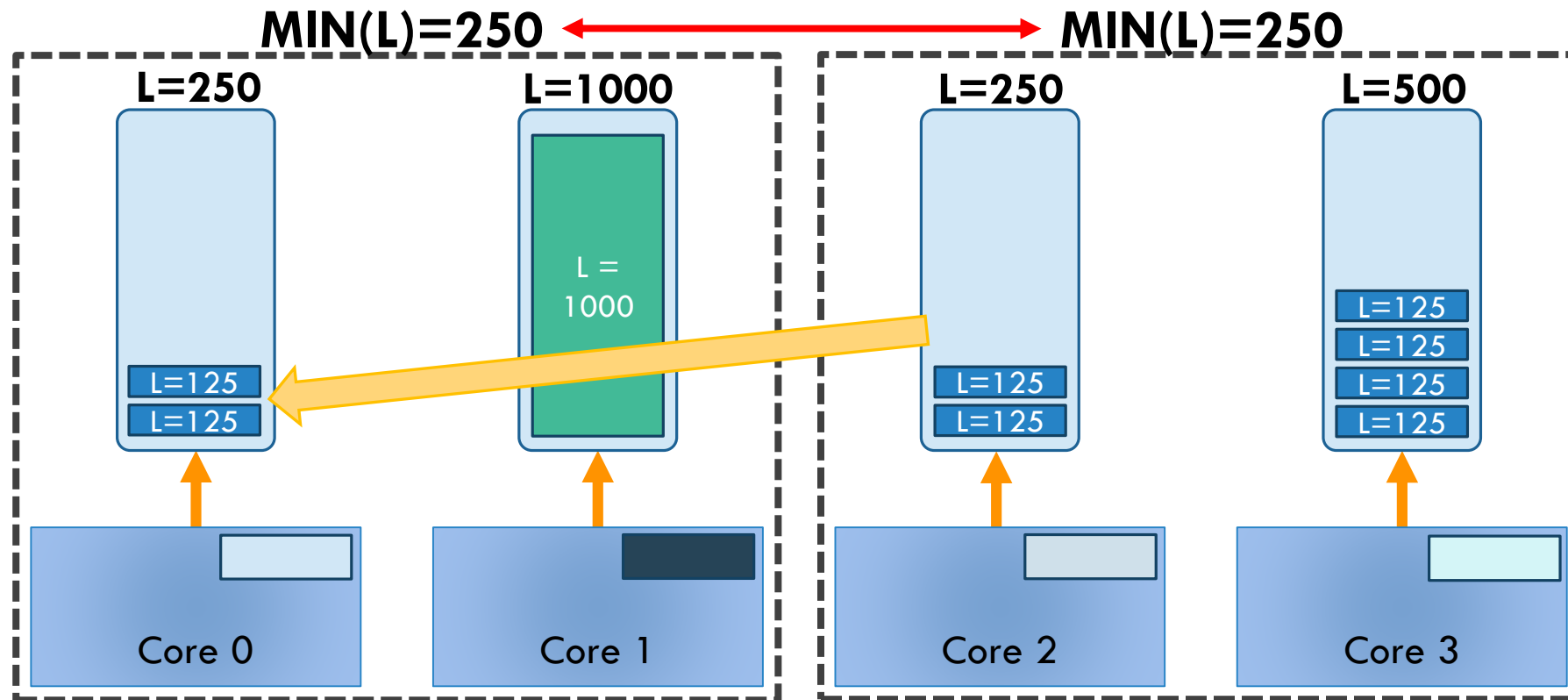
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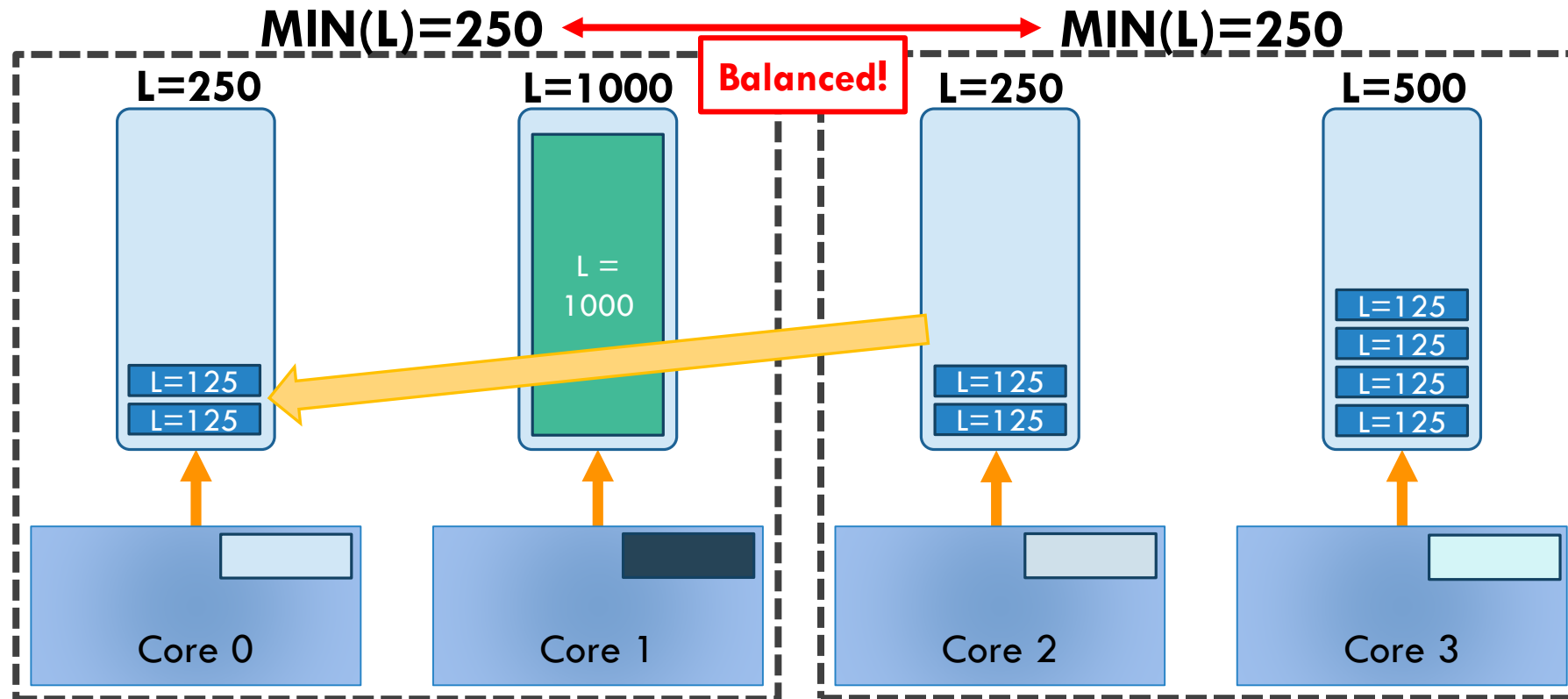
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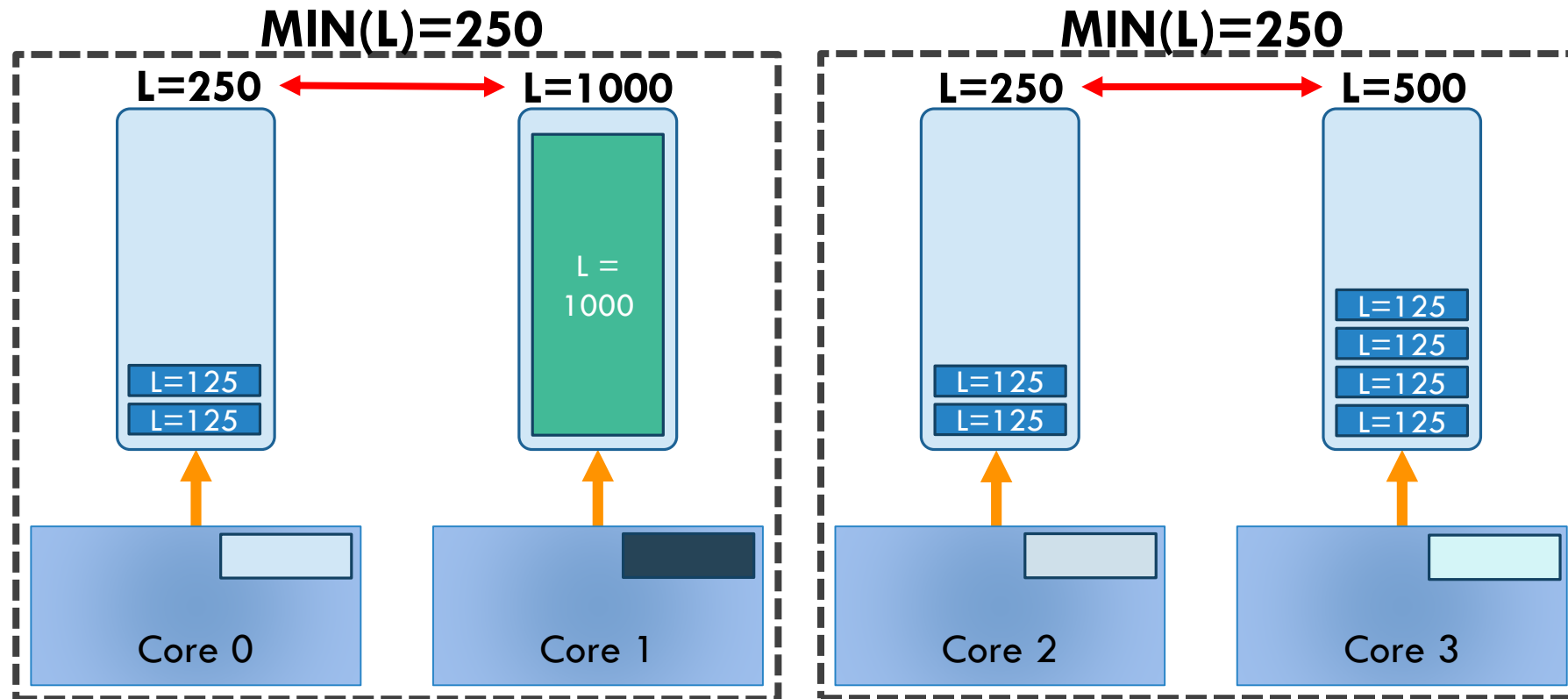
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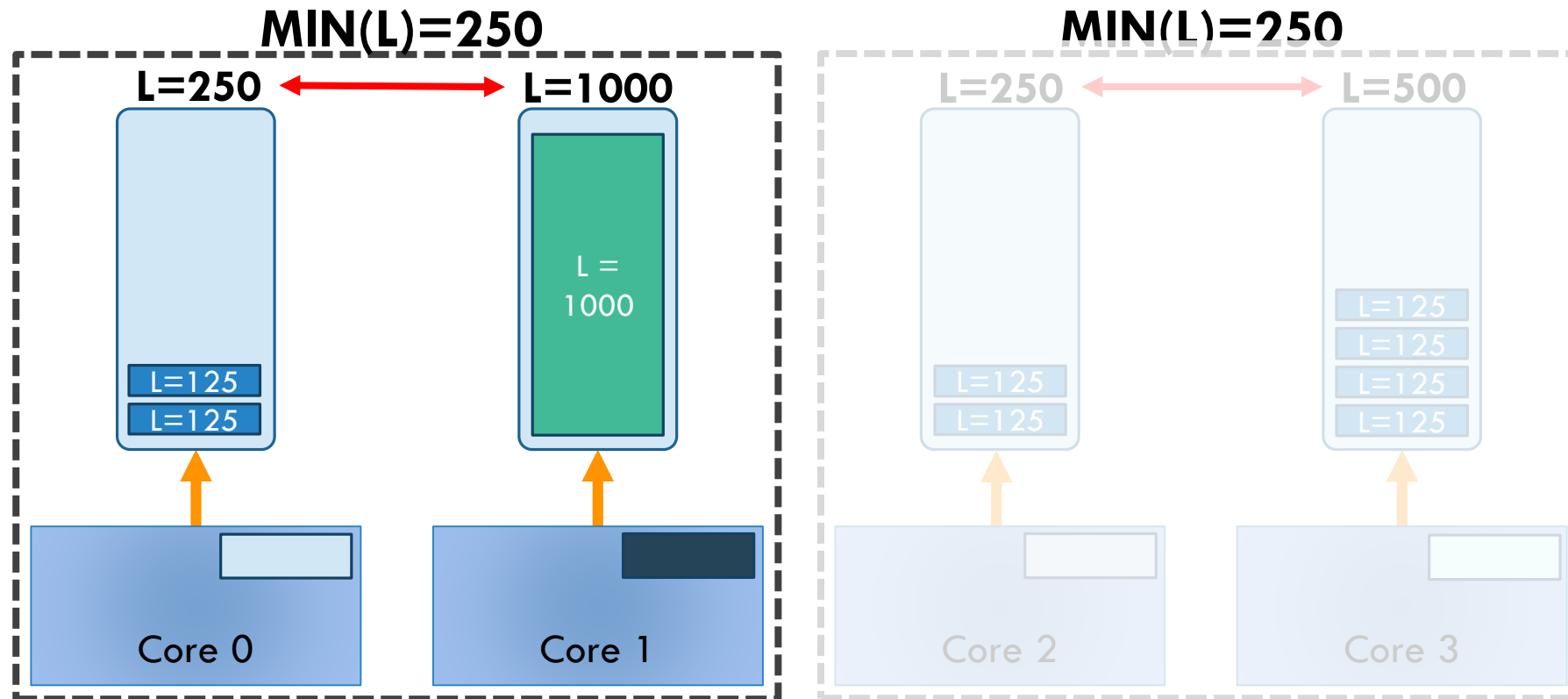
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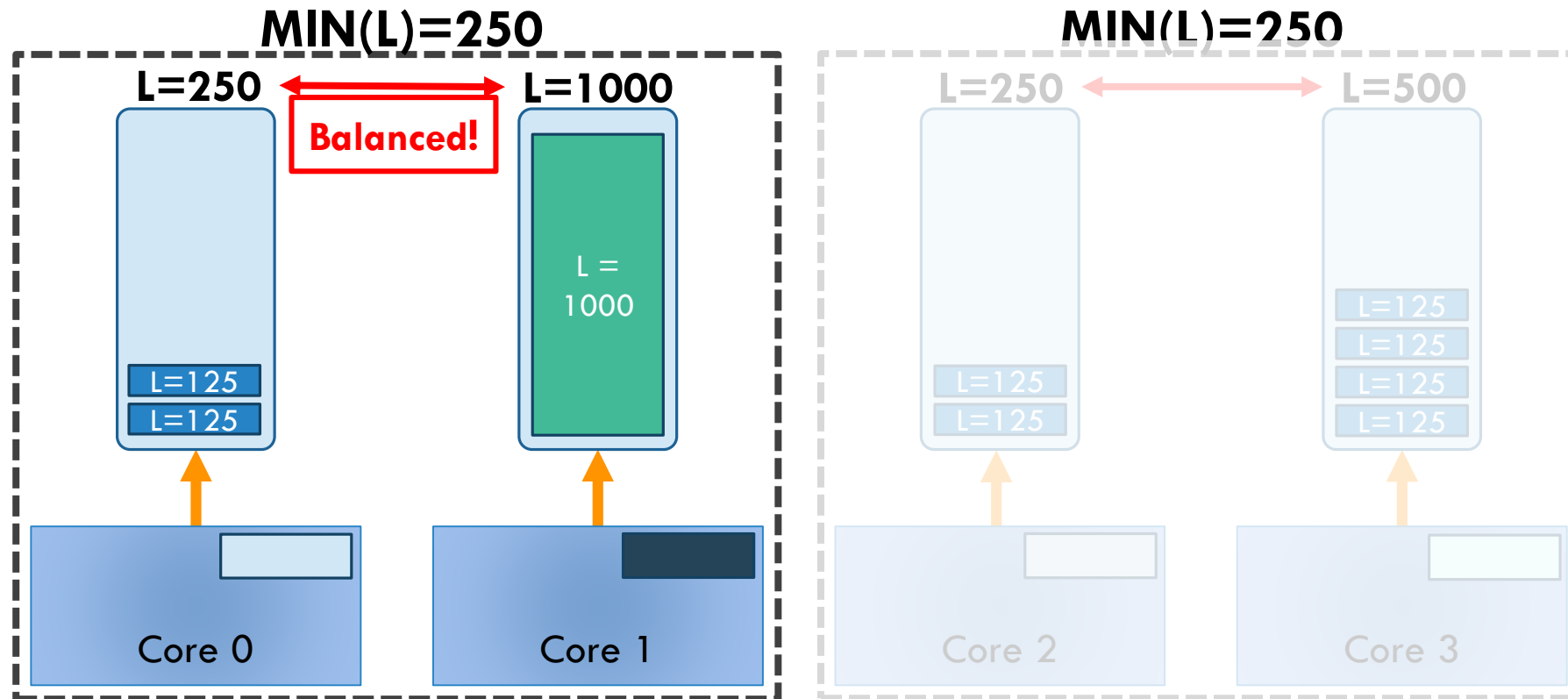
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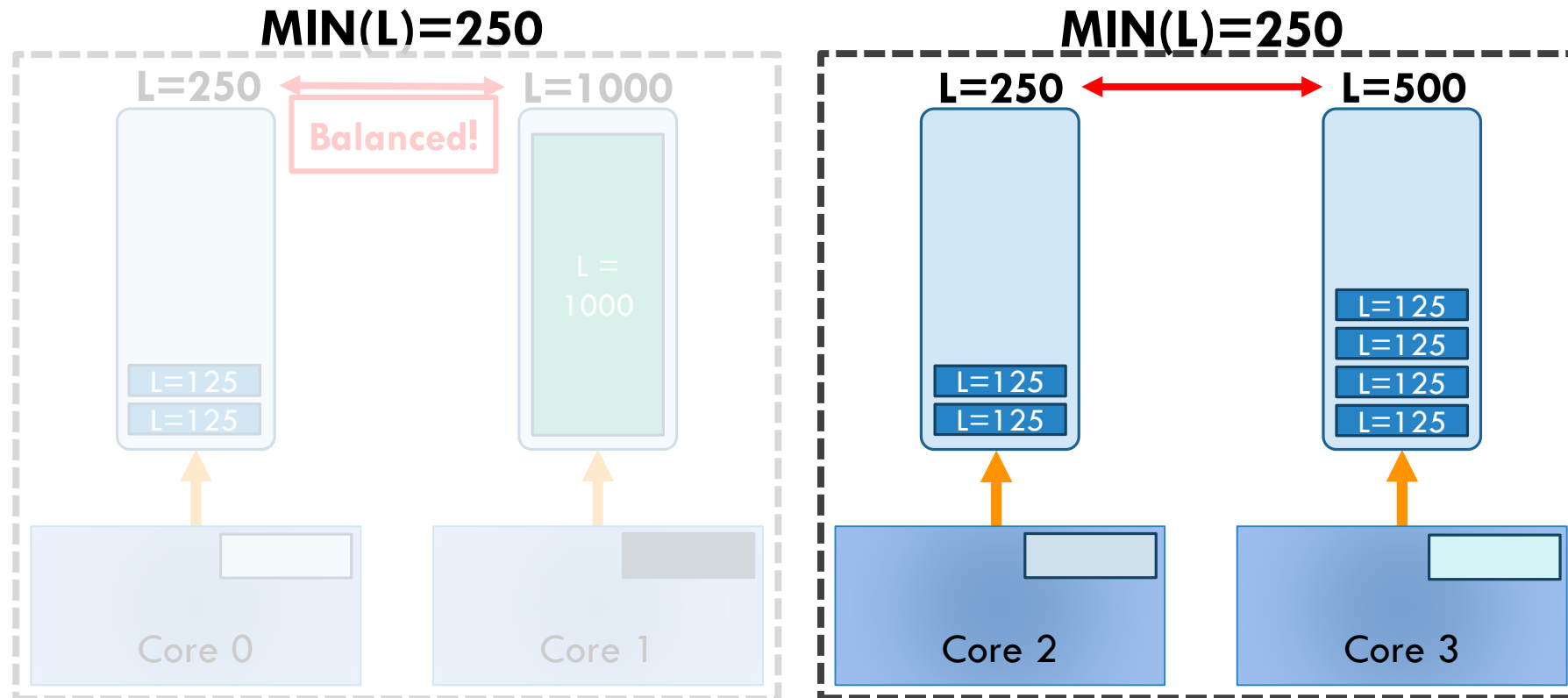
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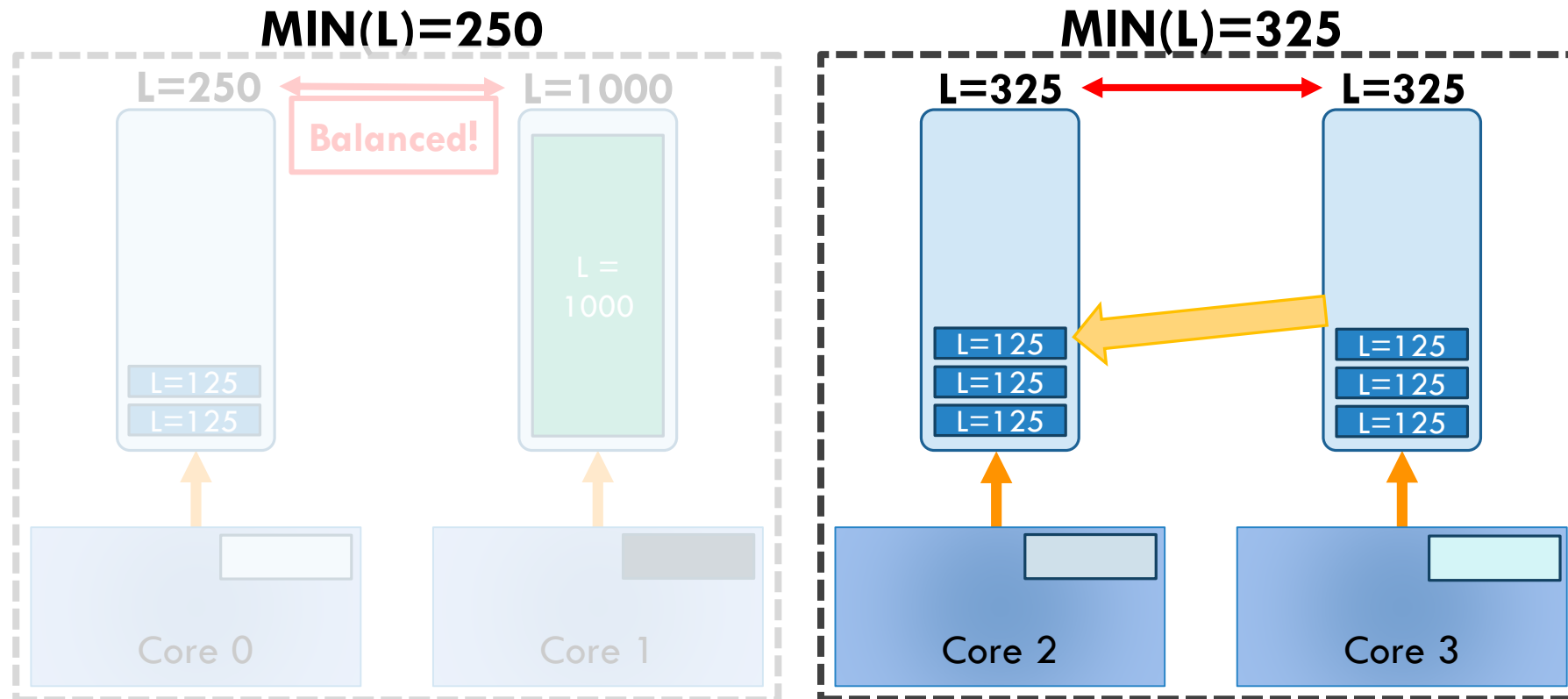
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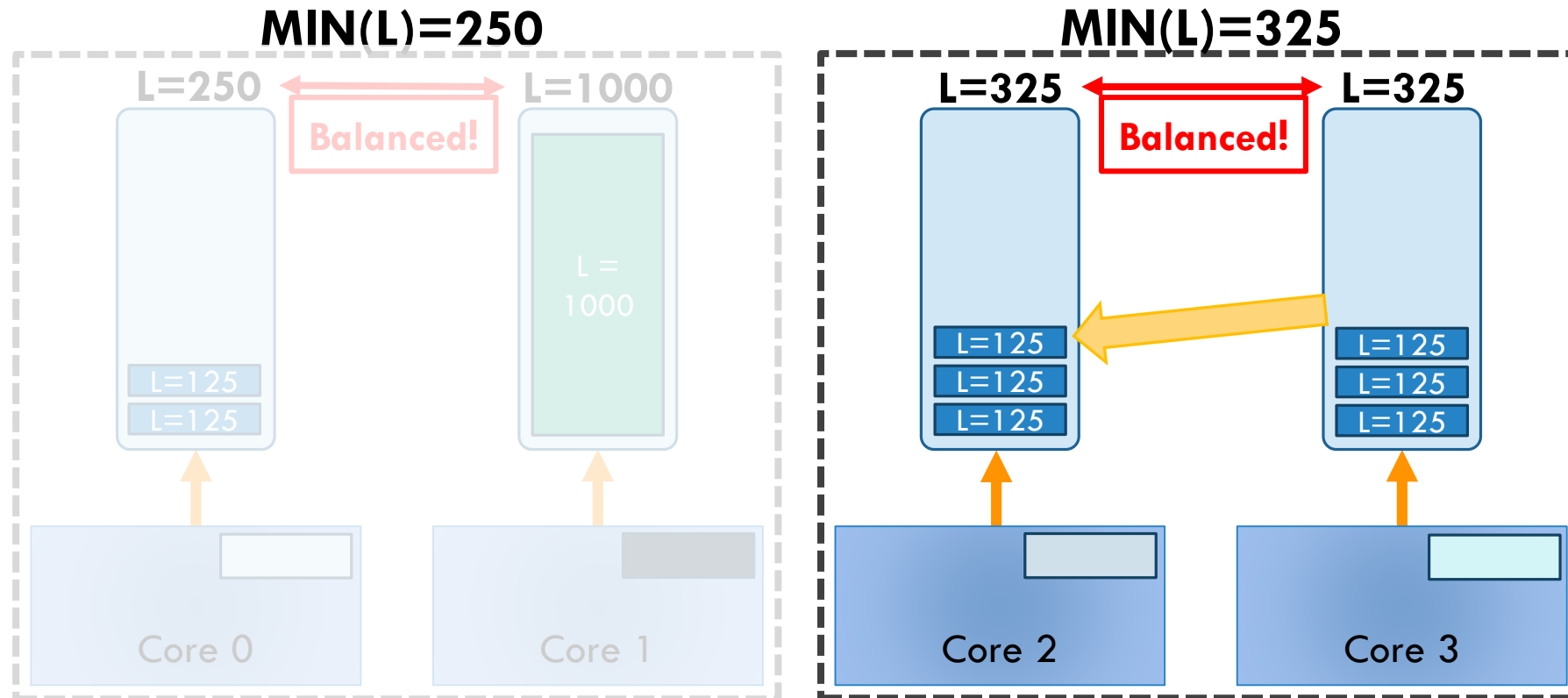
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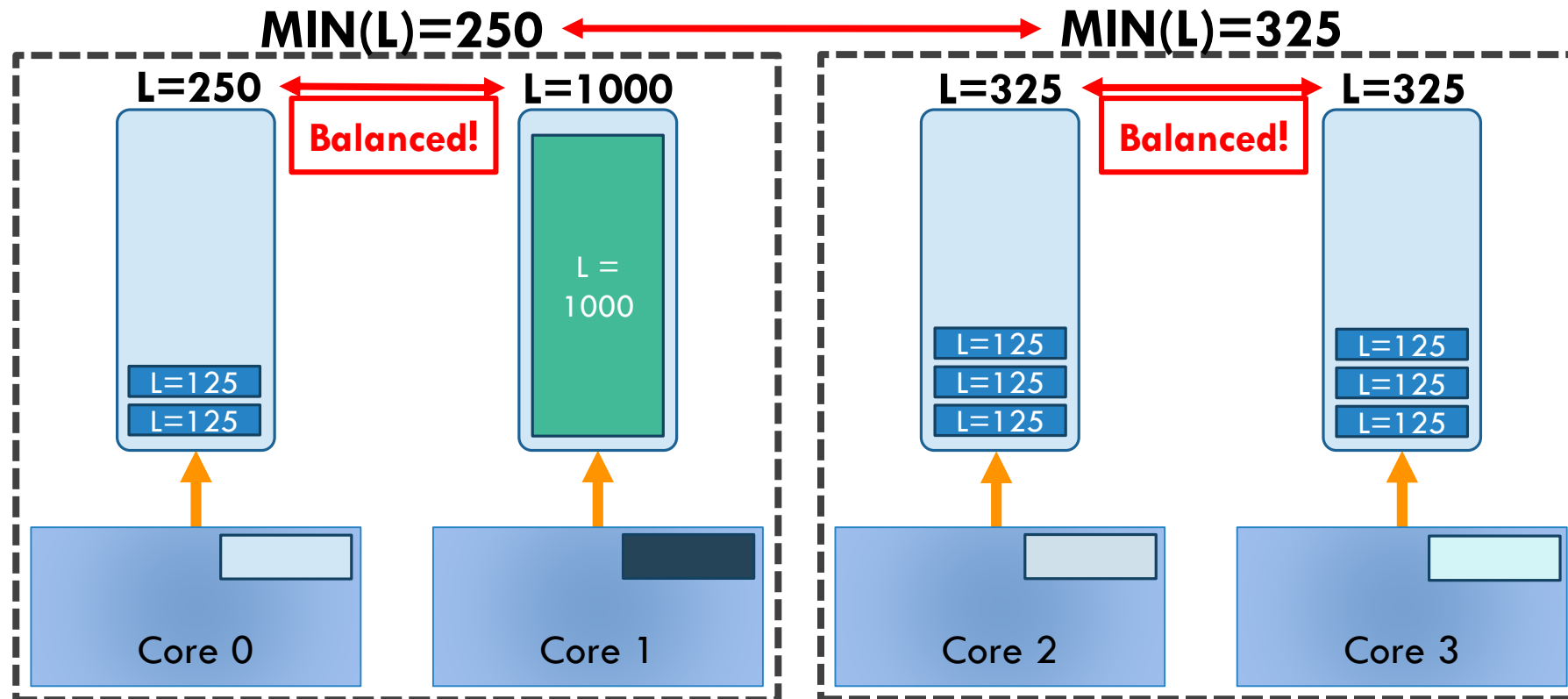
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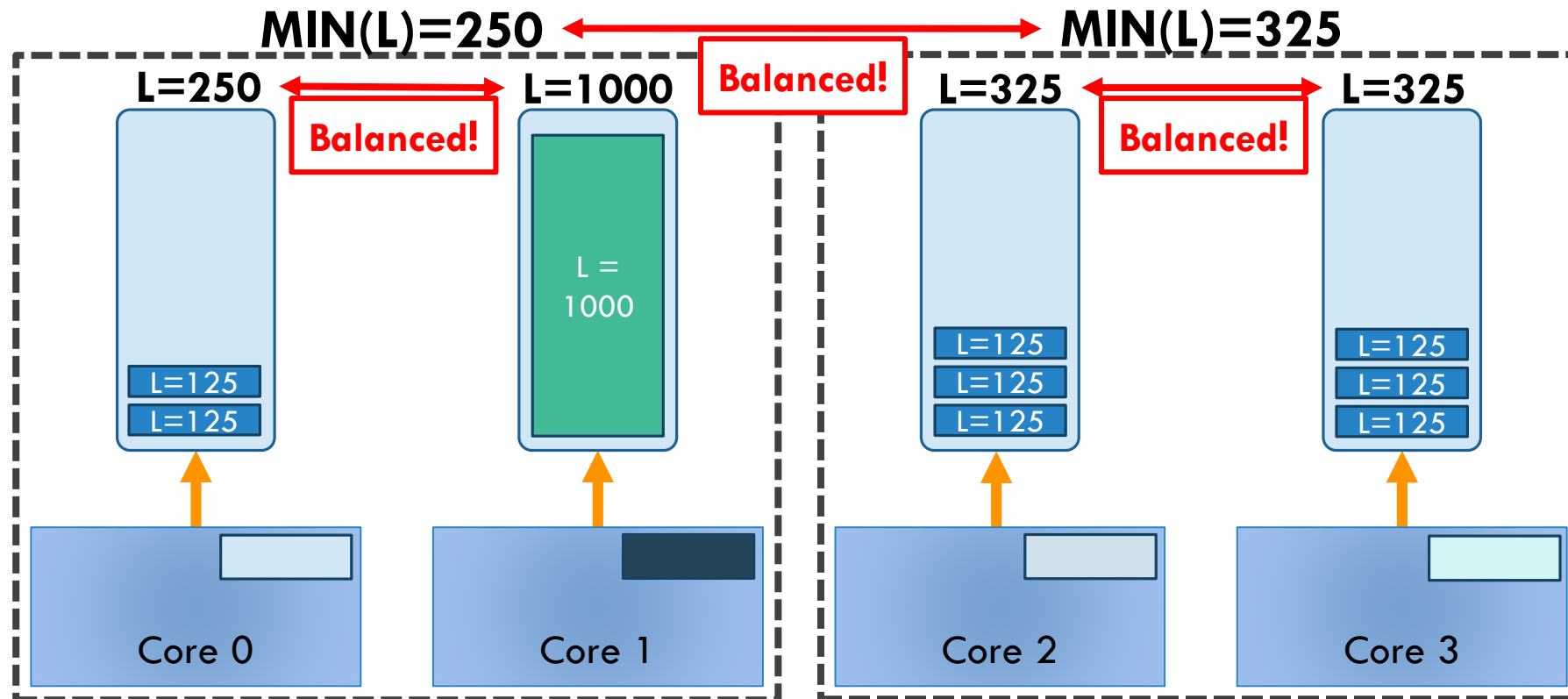
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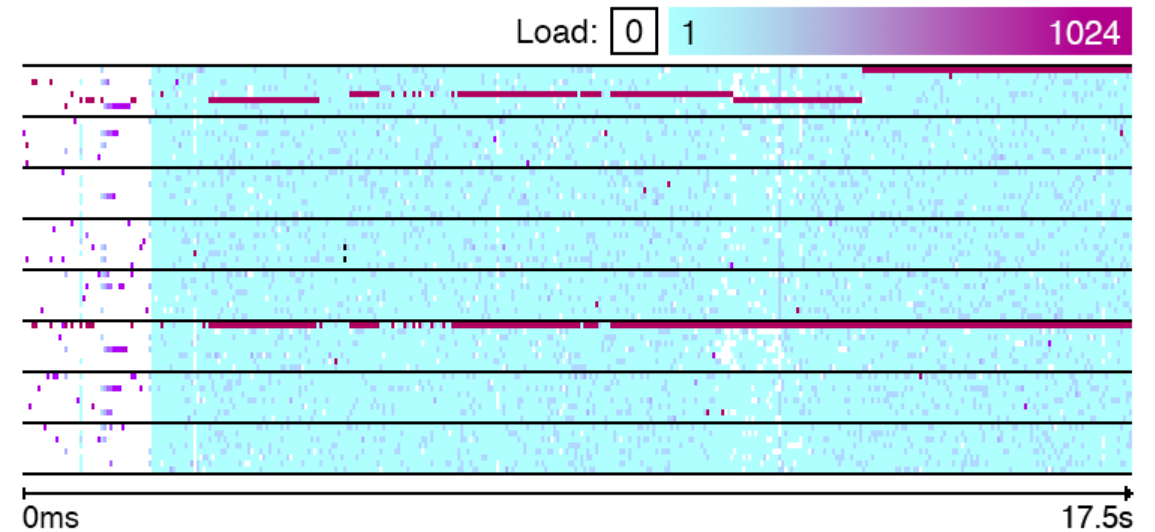
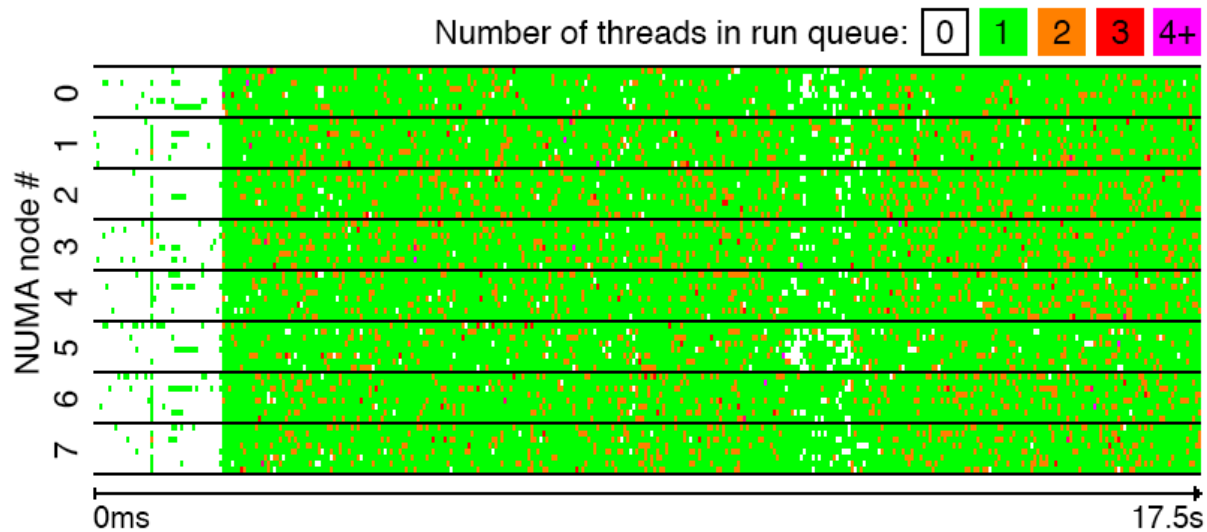
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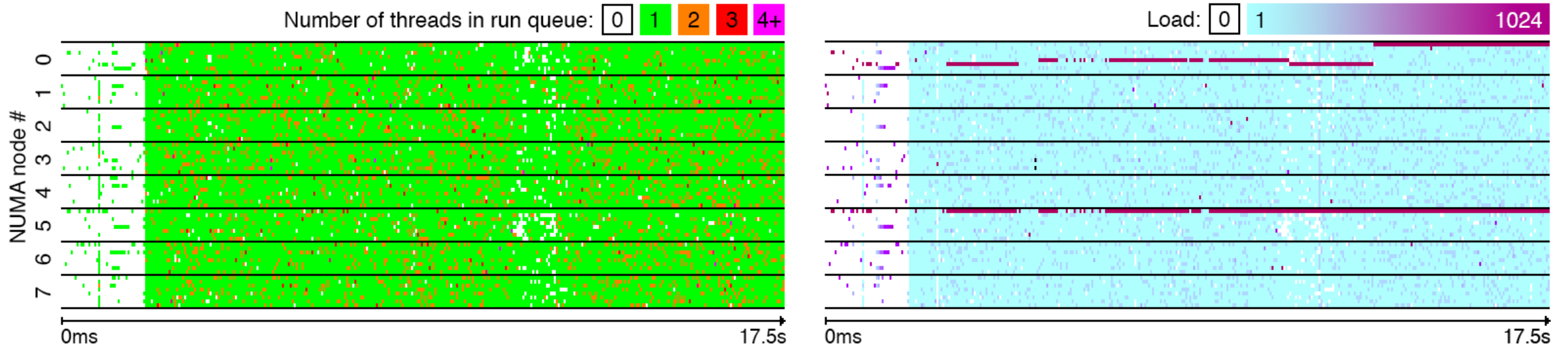
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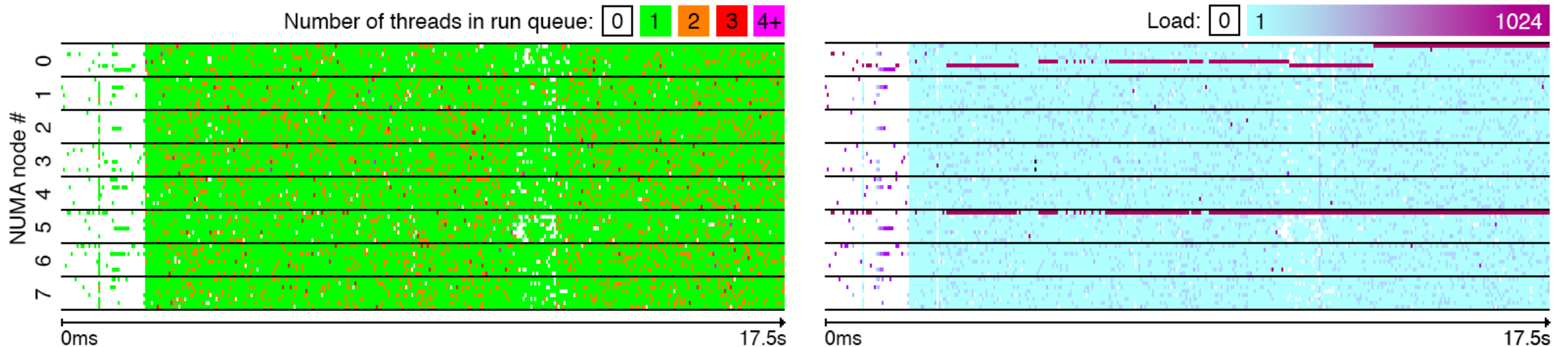
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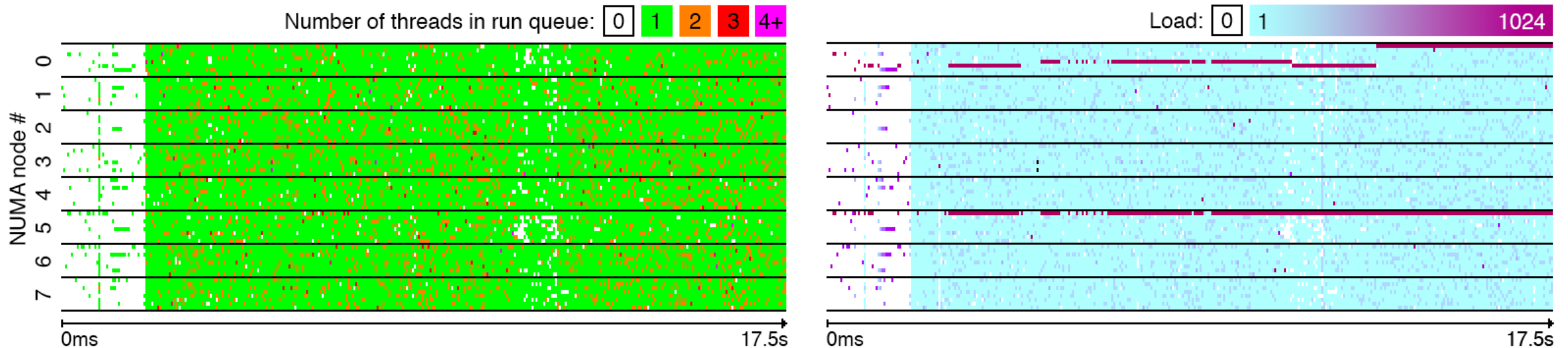
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  - May cause lots of unnecessary rebalancing. Revamping load calculations needed?

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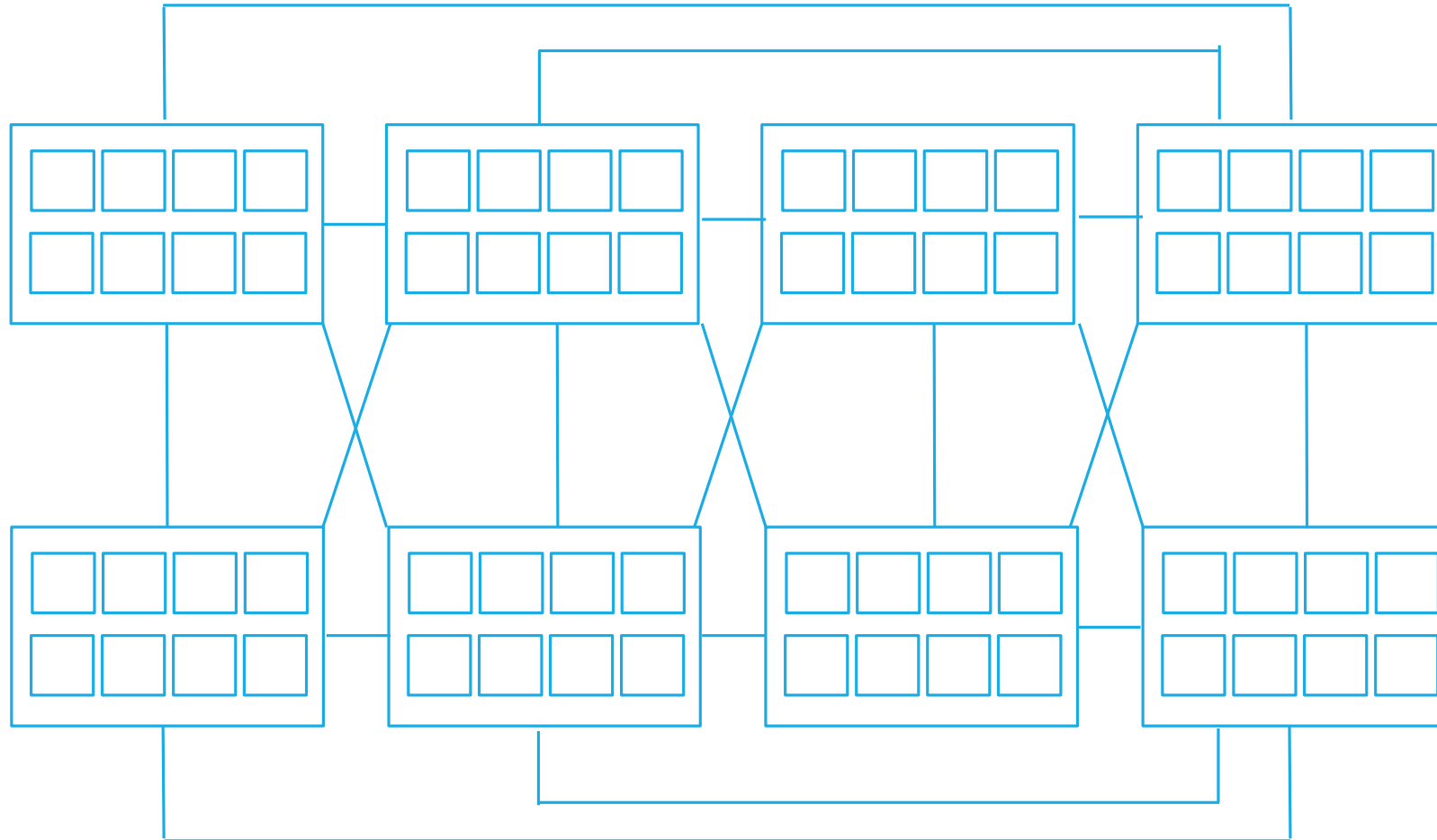
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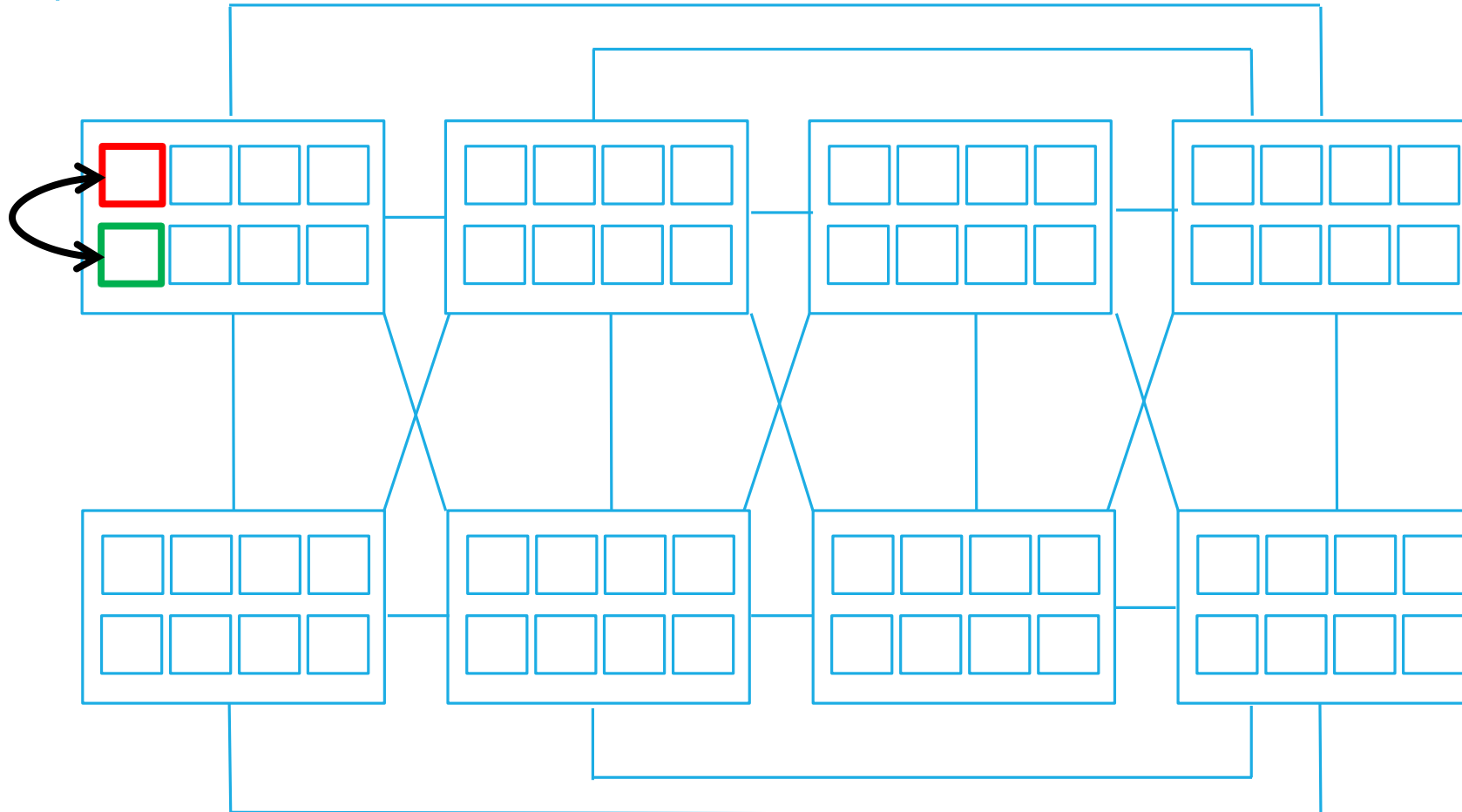
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  - At level 4, the **whole machine** (s.d.) contains **group of directly connected CPUs** (s.g.)

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



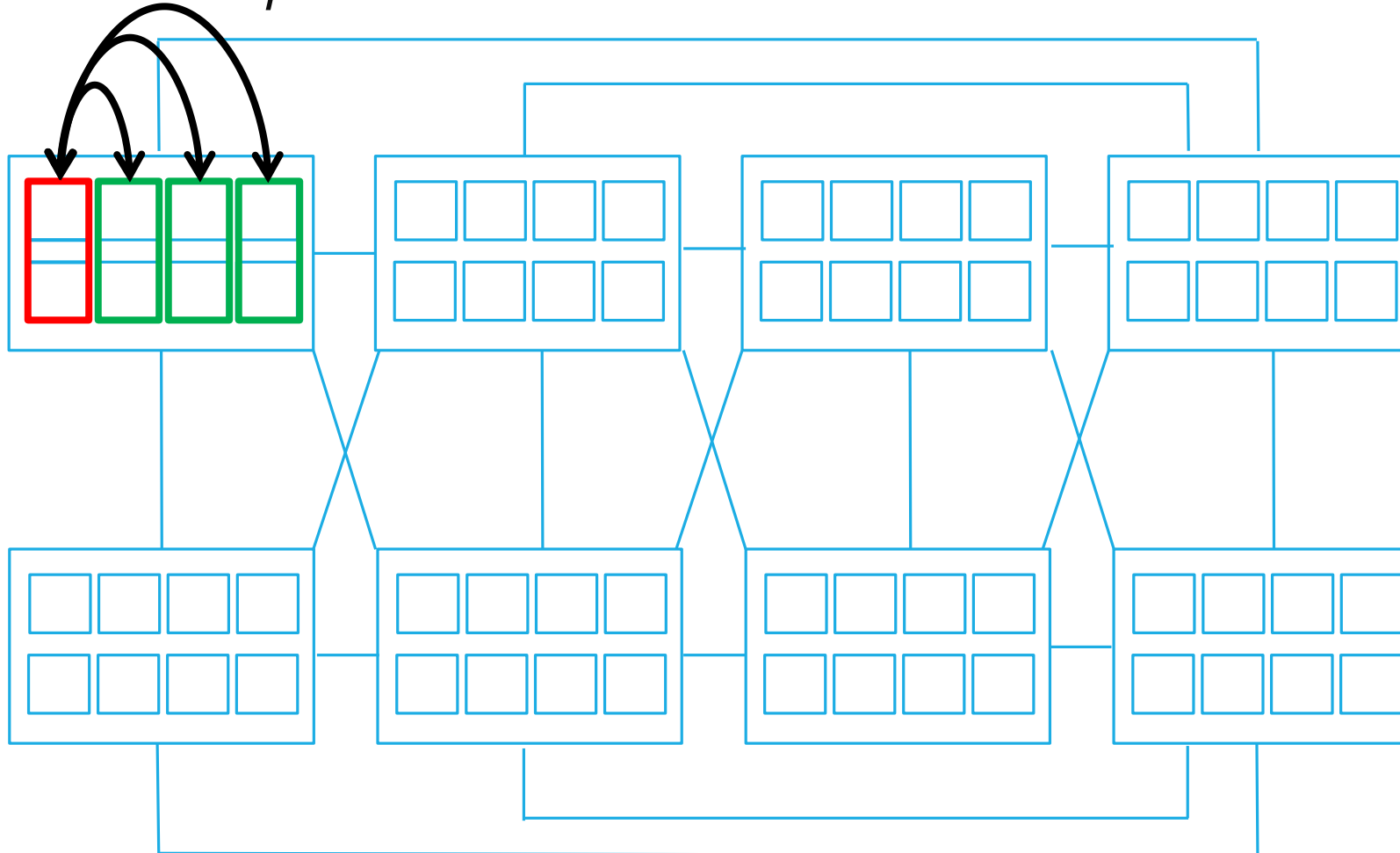
**Bulldozer 64-core:**  
Eight CPUs, with  
8 cores each,  
**non-complete**  
**interconnect graph!**

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

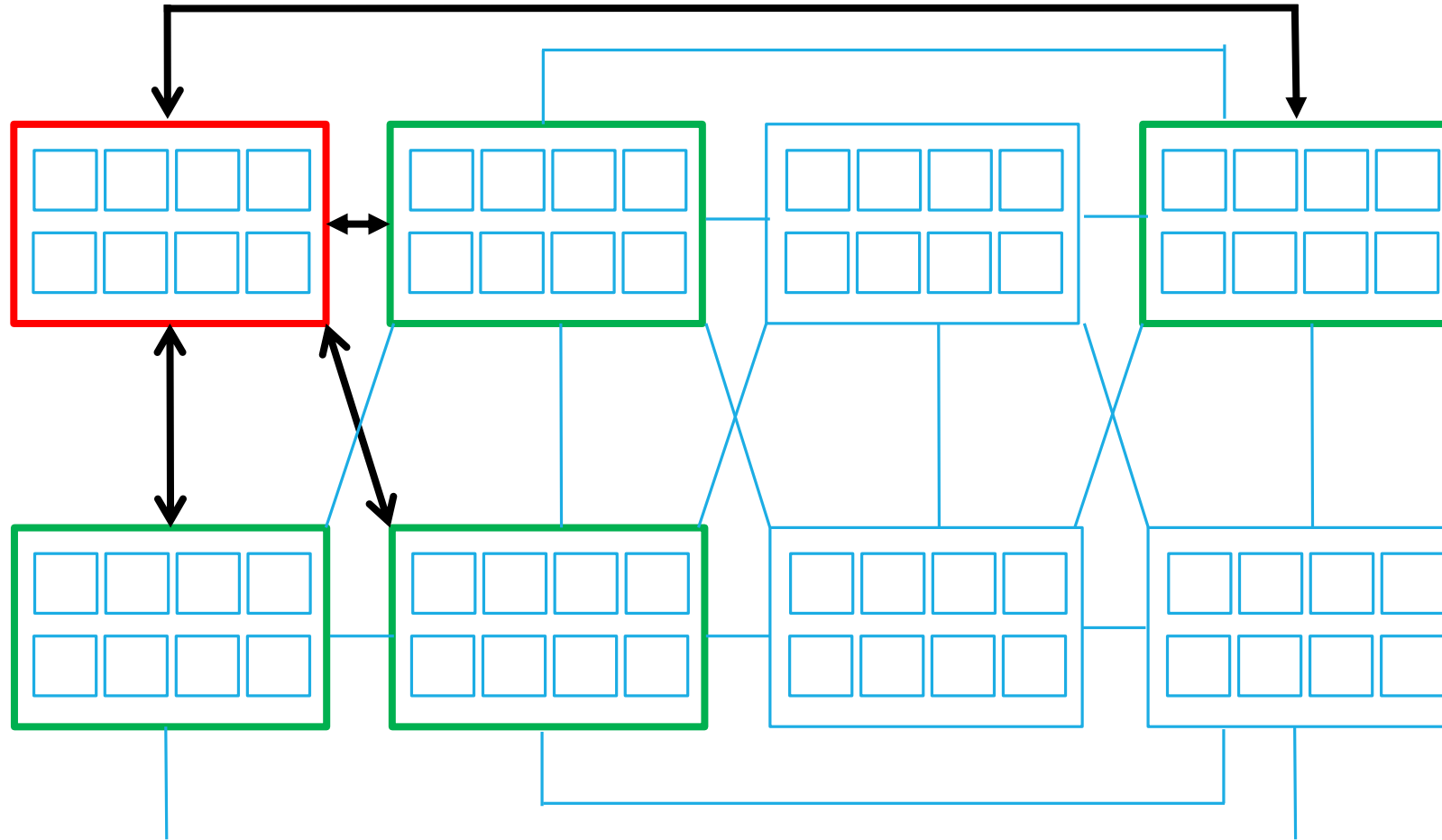
# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

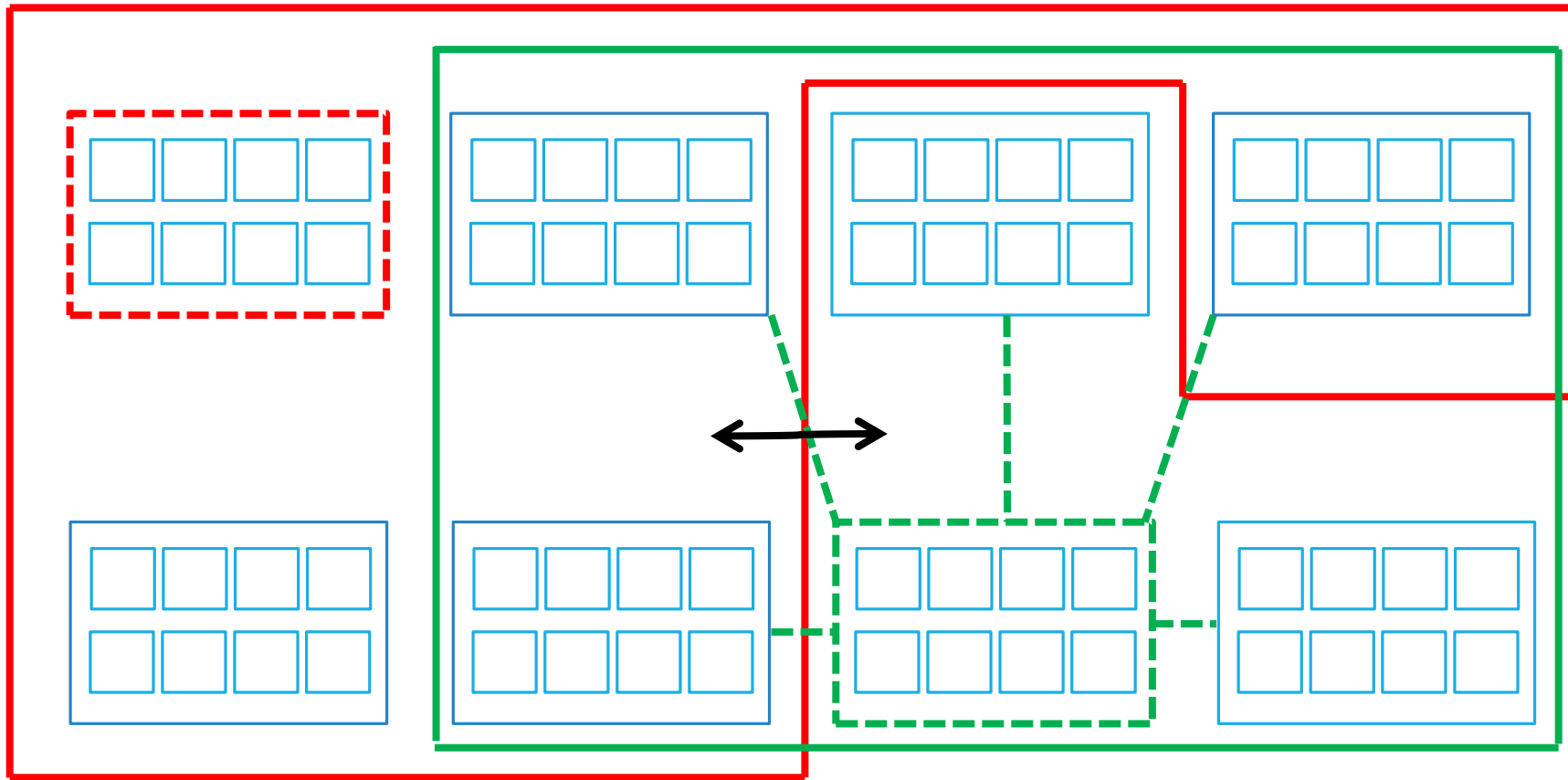


# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



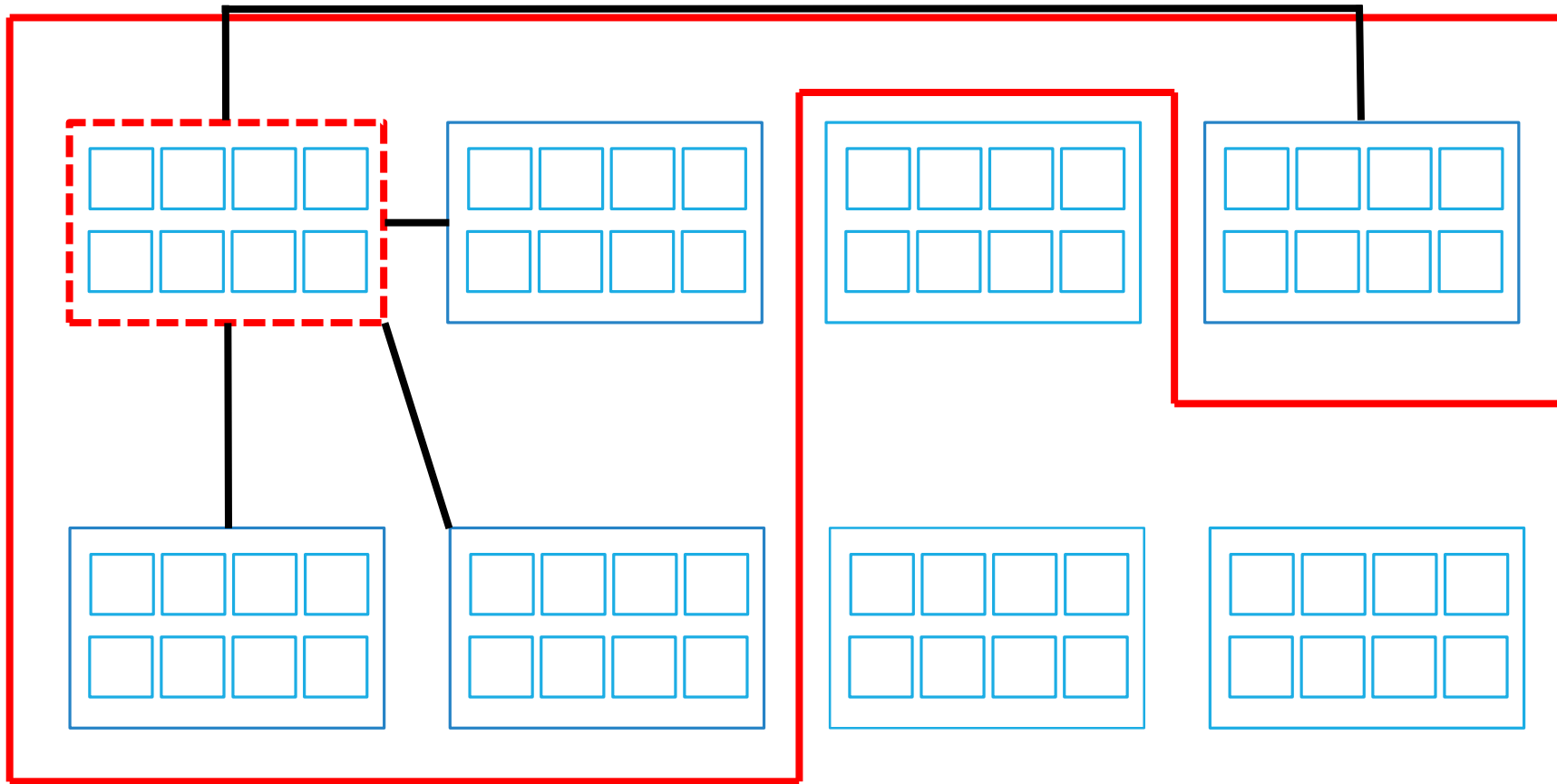
At the 3<sup>rd</sup> level,  
the **first CPU**  
balances load  
with **directly**  
**connected CPUS**

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

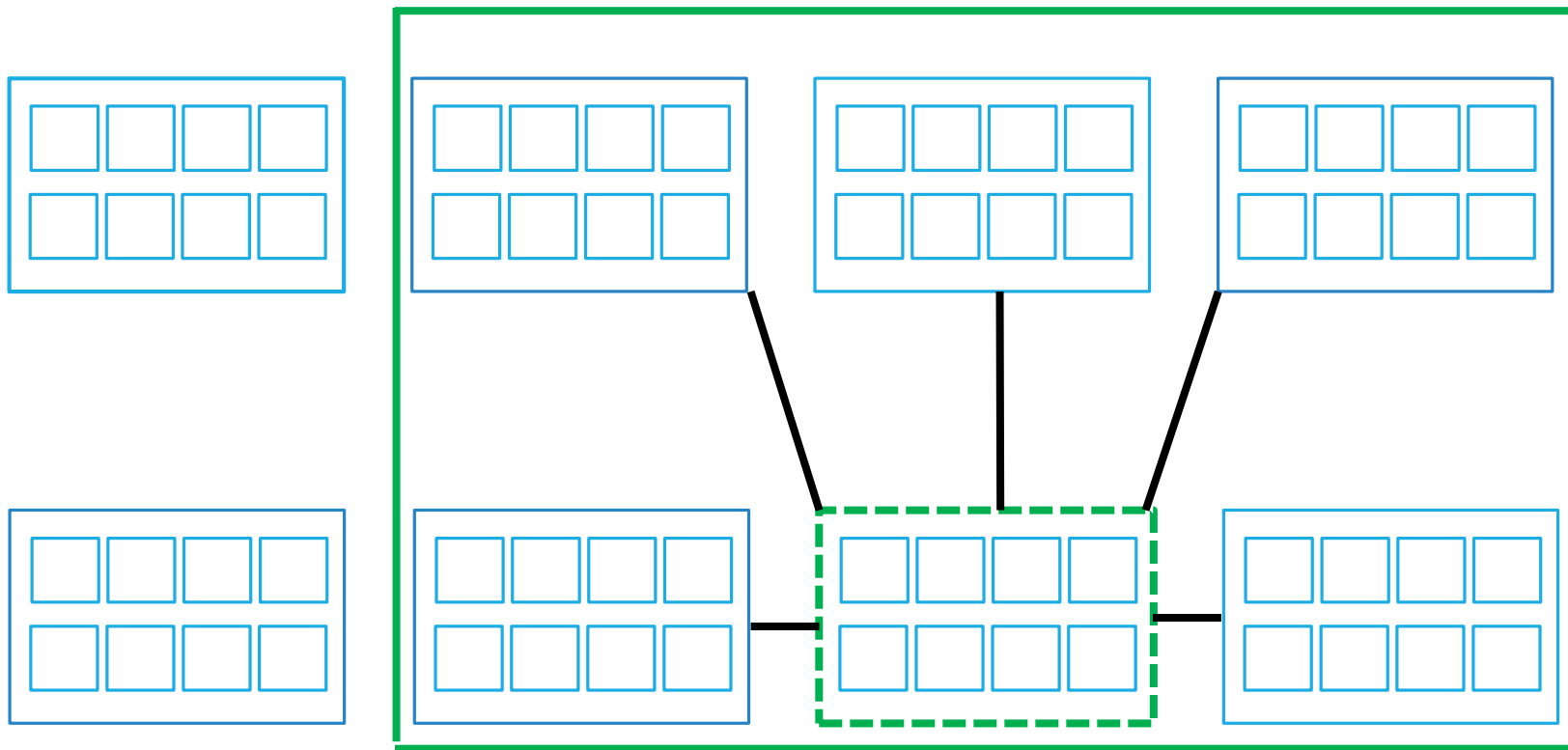
# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



**Groups of CPUs  
built by:**

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

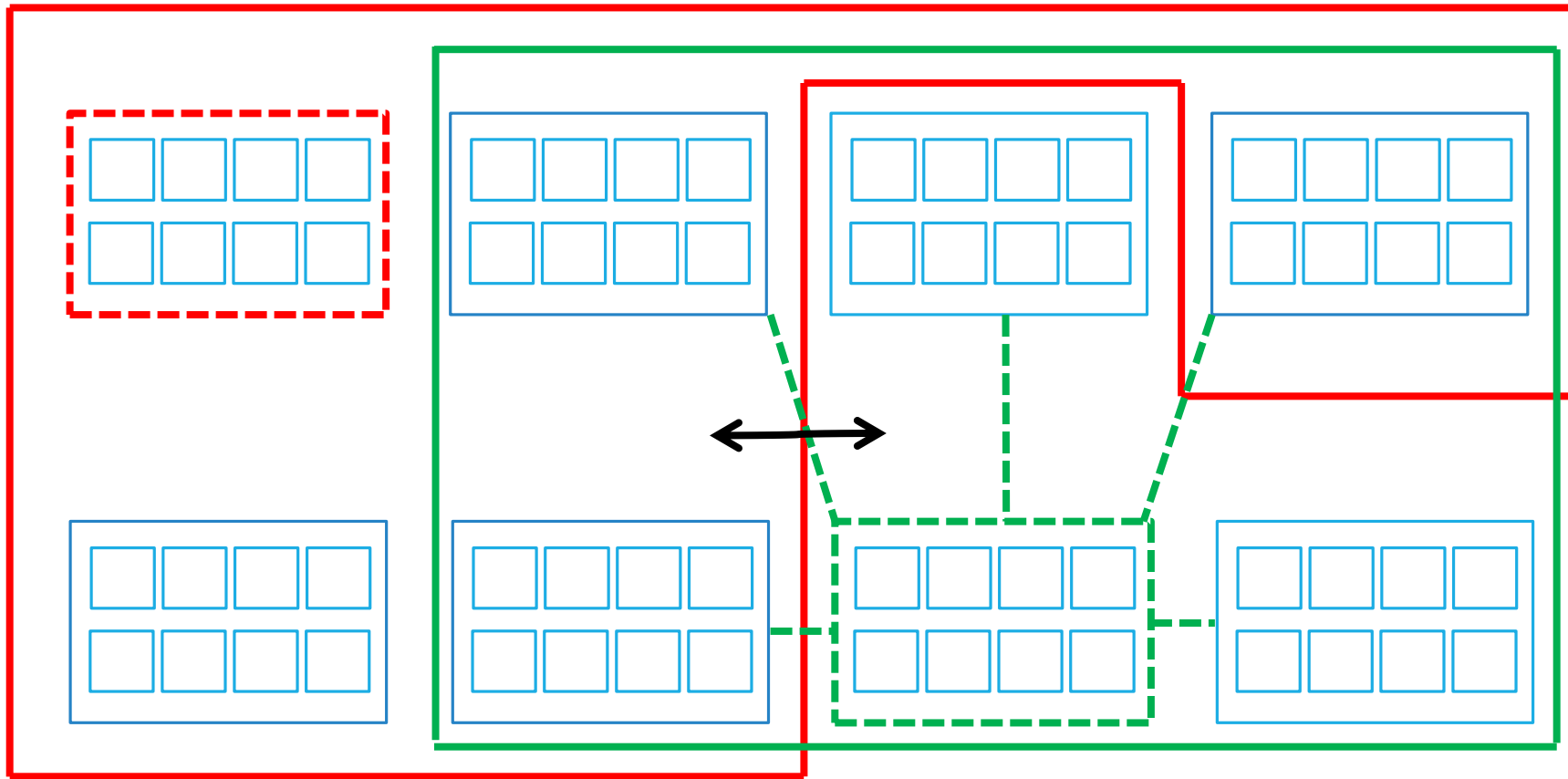
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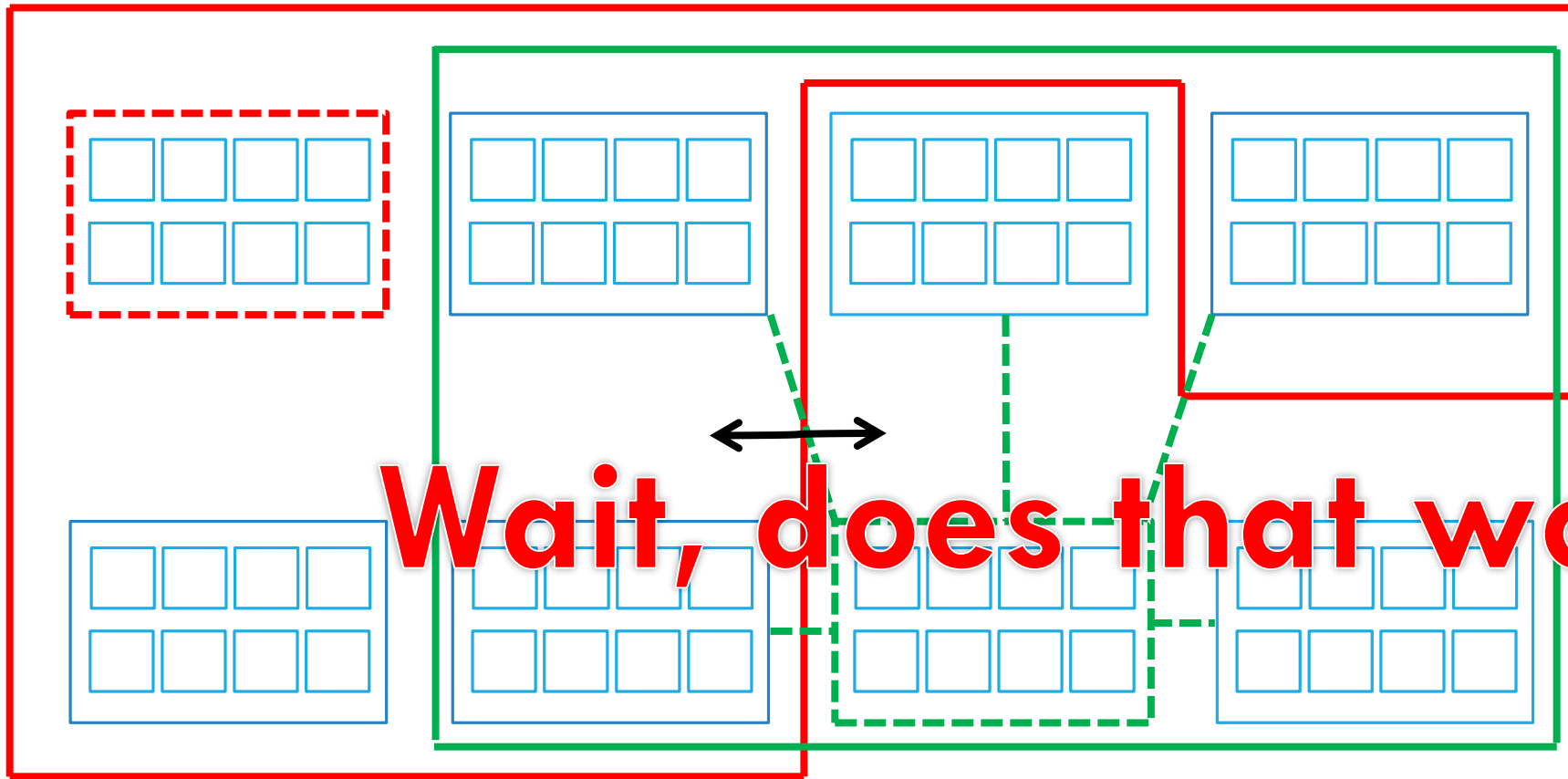
**(2) picking first  
CPU not in a  
group and  
looking for all  
directly  
connected CPUs**

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

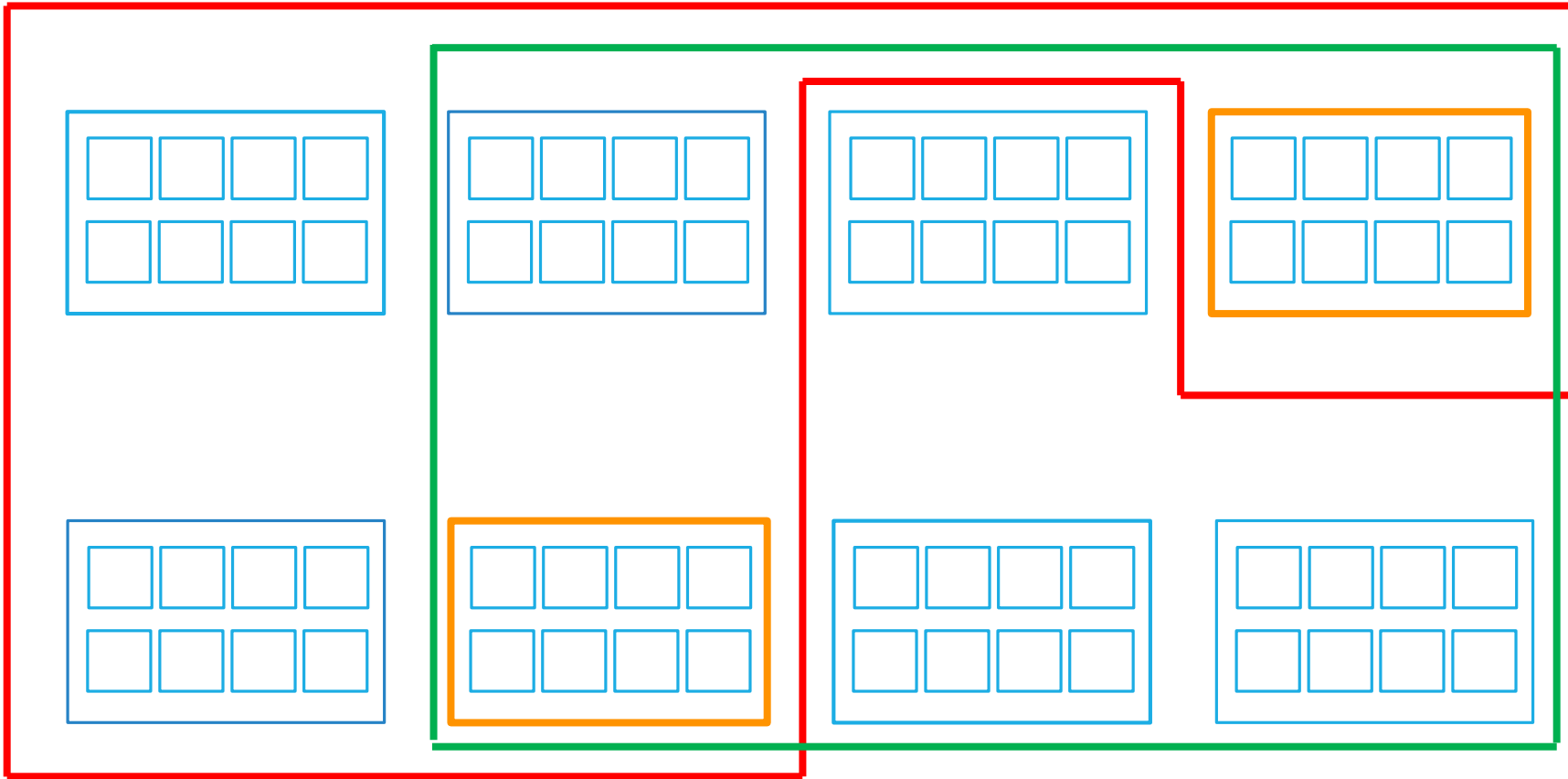
## BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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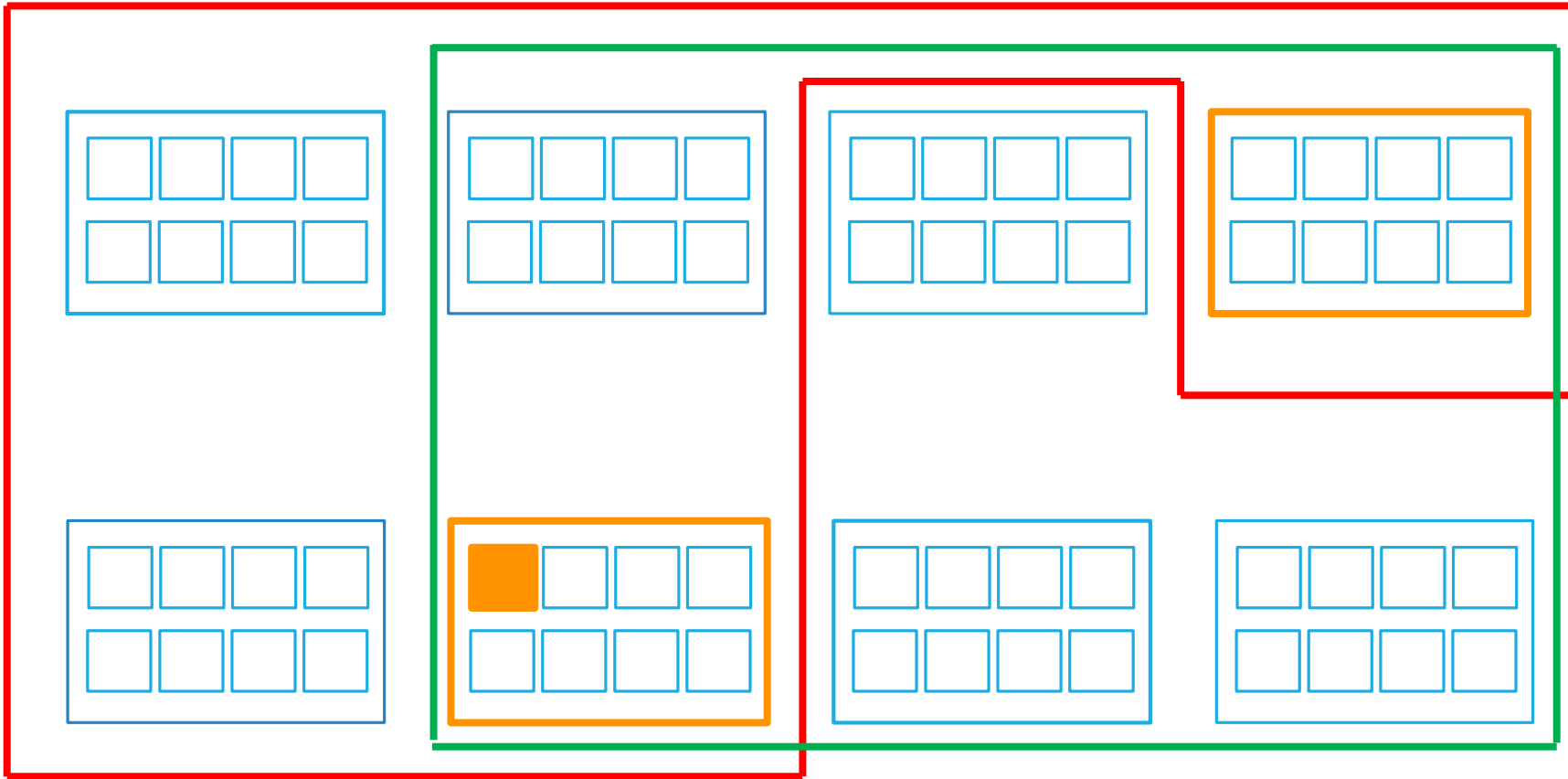
**Wait, does that work?**

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

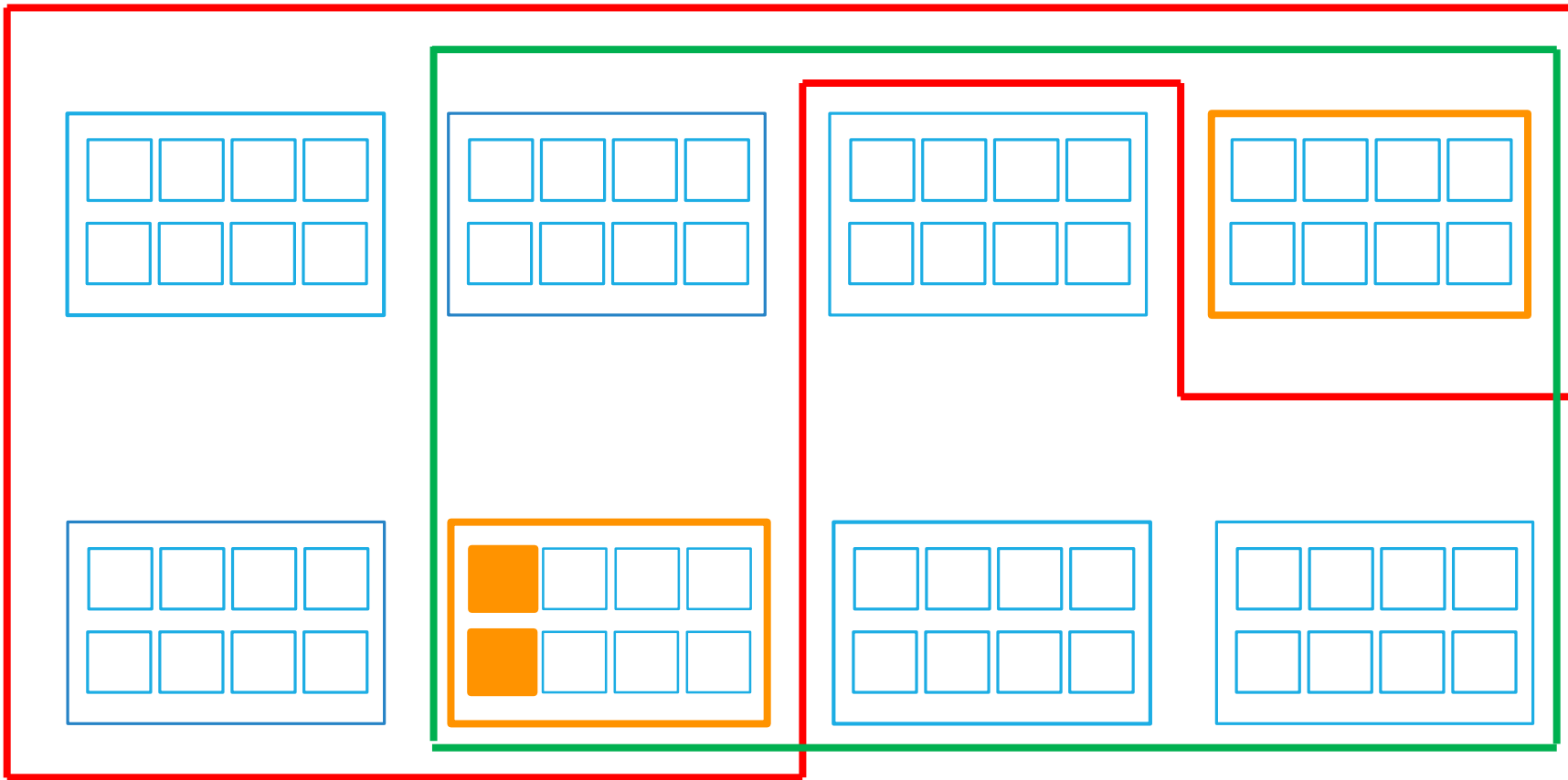
# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



And threads  
are created  
**on this core**

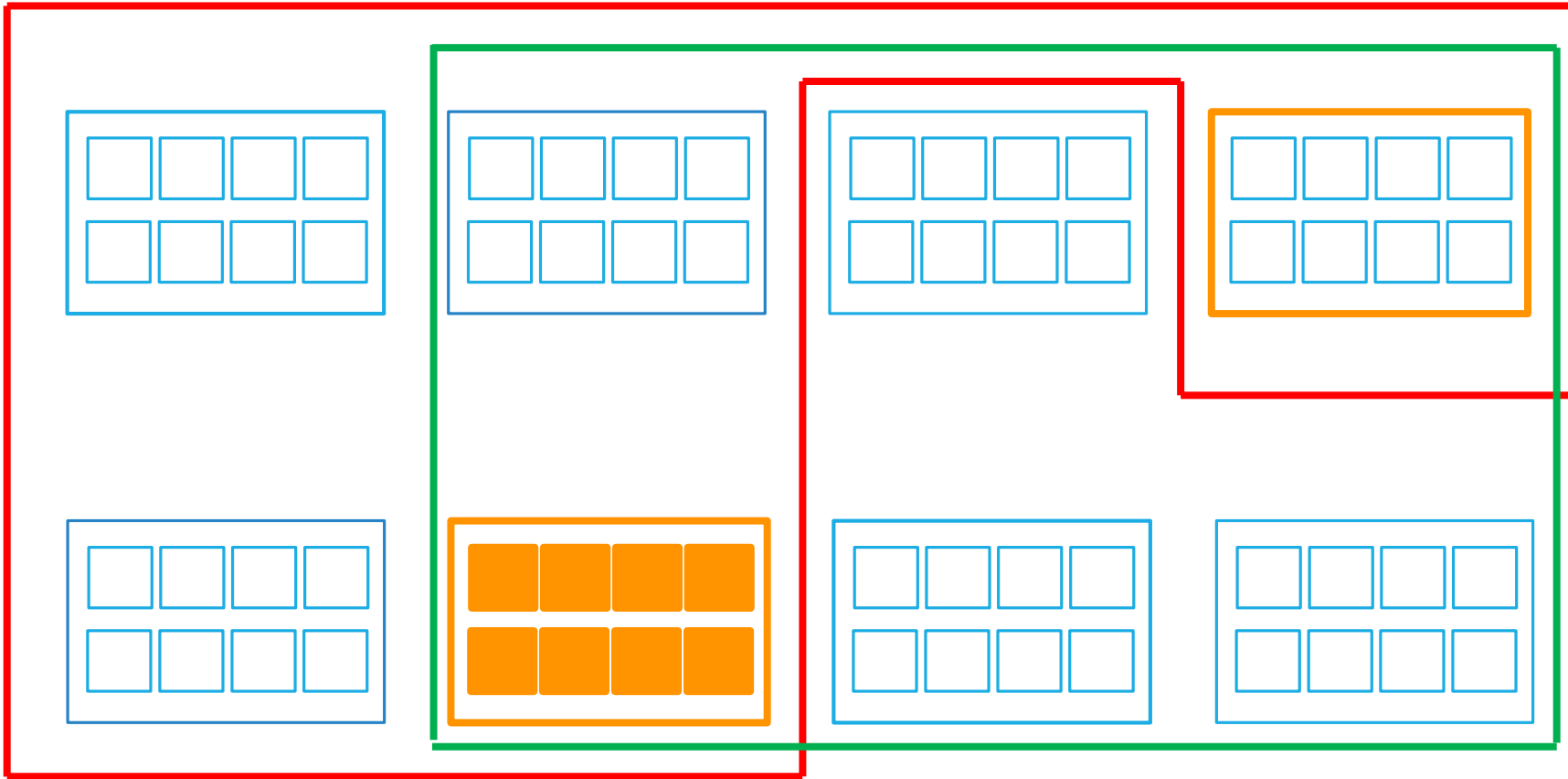


# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



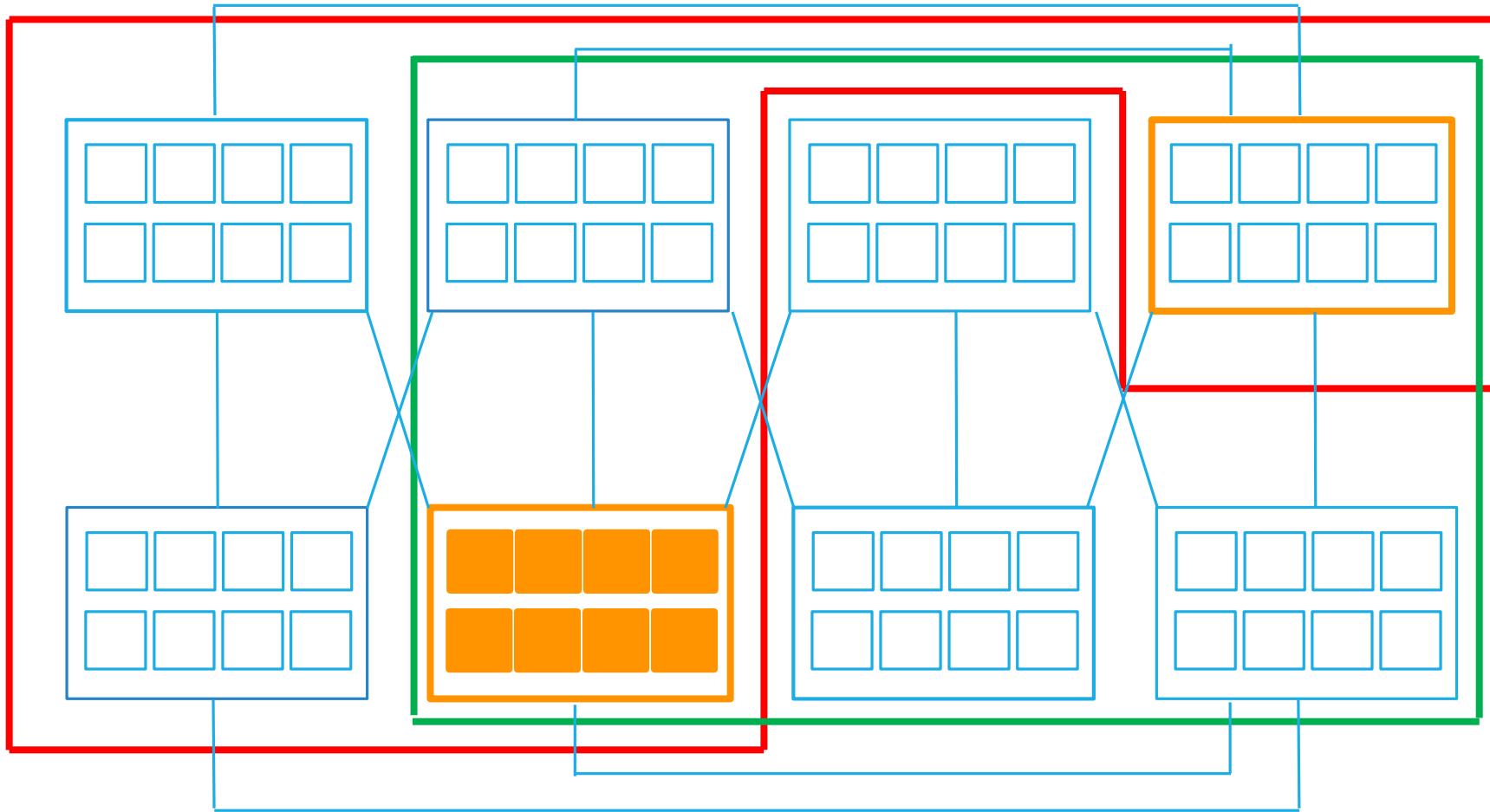
Load gets  
correctly balanced  
**on the pair of  
cores**

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



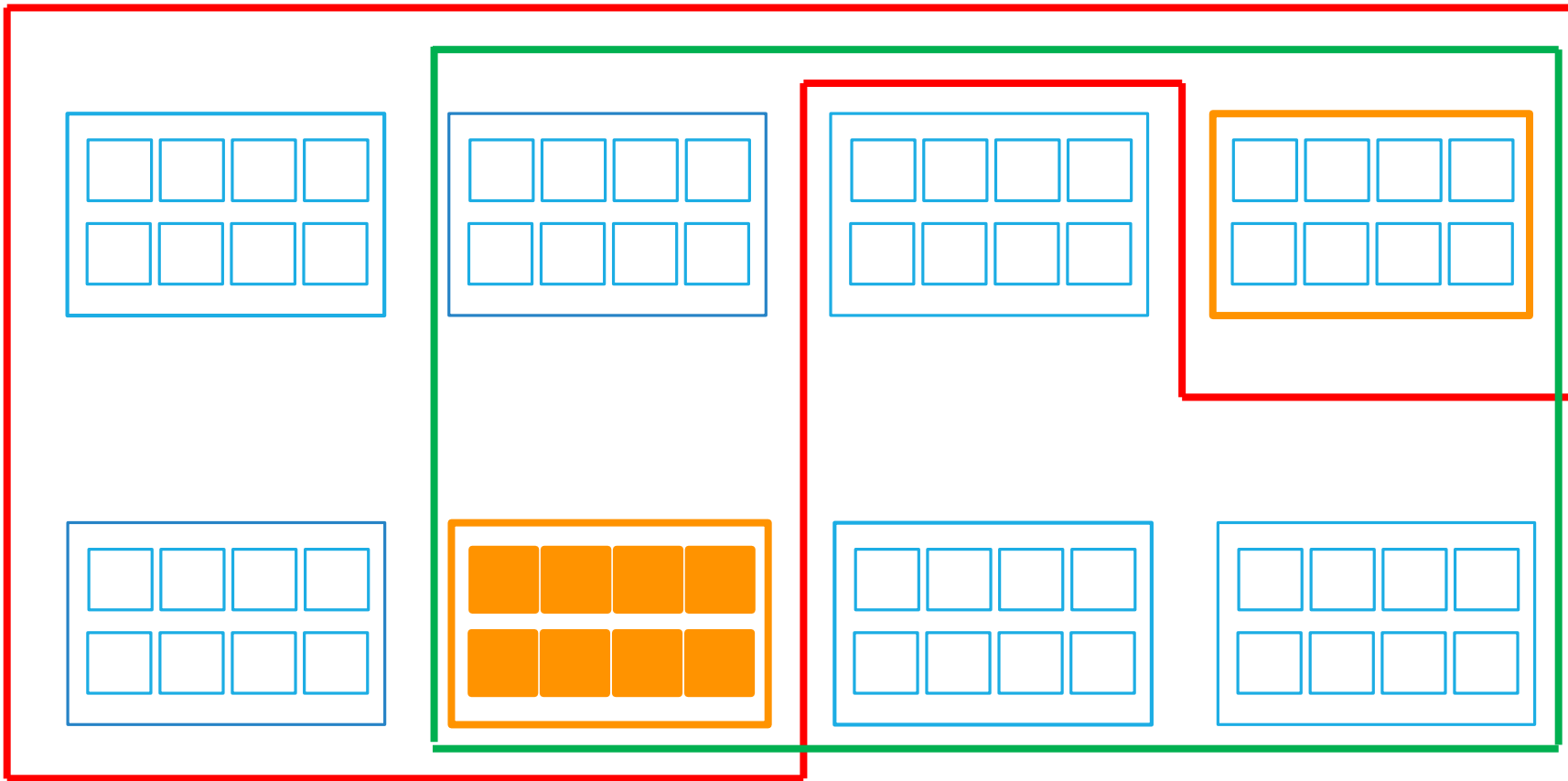
Load gets  
correctly balanced  
**on the CPU**  
(8 threads)

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



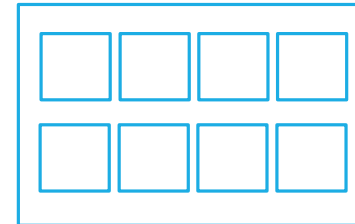
No stealing  
at level 3,  
because nodes  
not directly  
connected (1 hop  
apart)

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



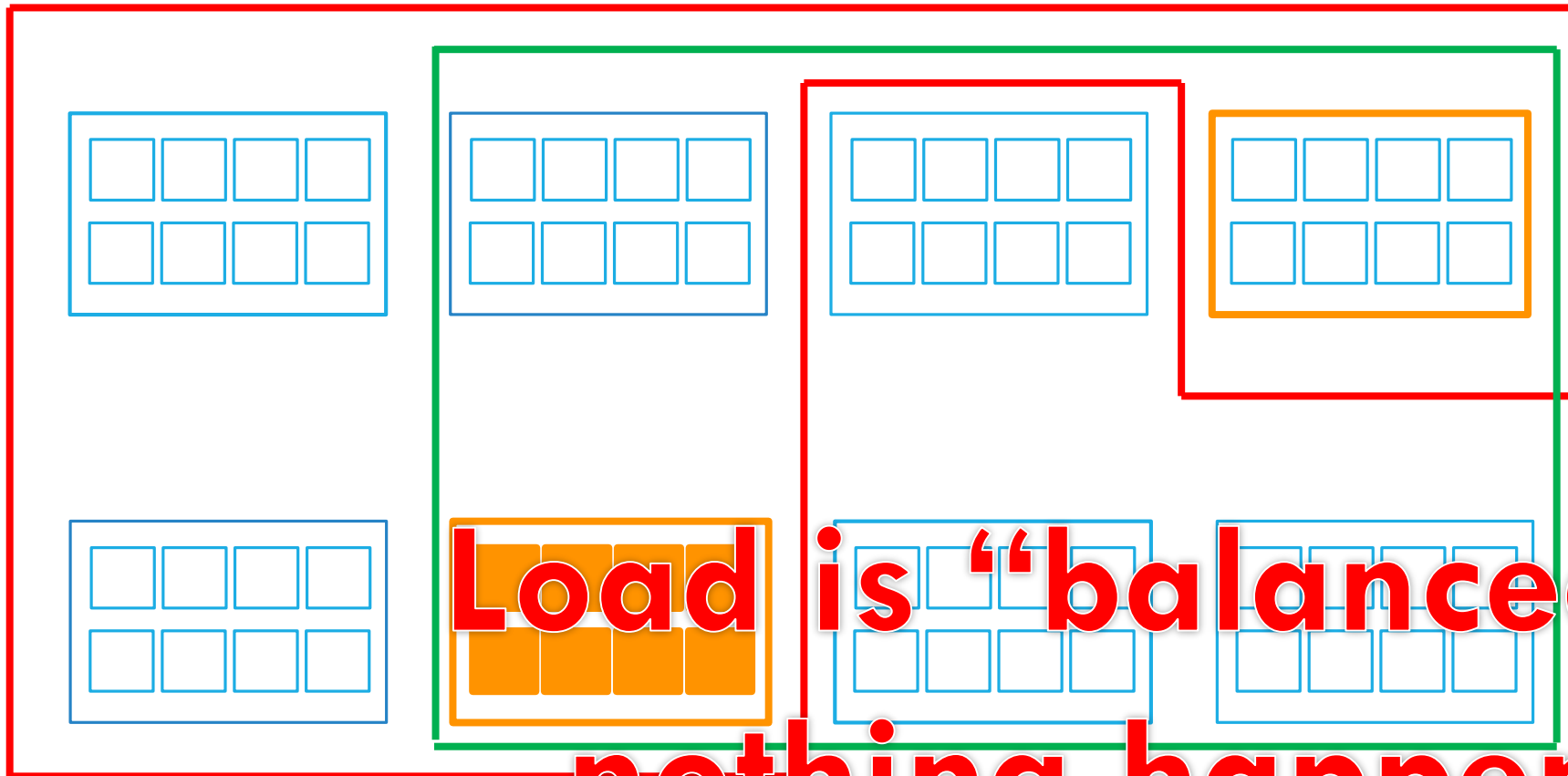
At level 4,  
stealing between  
the **red** and **green**  
groups...

**Overloaded node  
in both groups!**



```
load(red) =  
16 * load(thread)
```

# BUG 2/4: SCHEDULING GROUP CONSTRUCTION

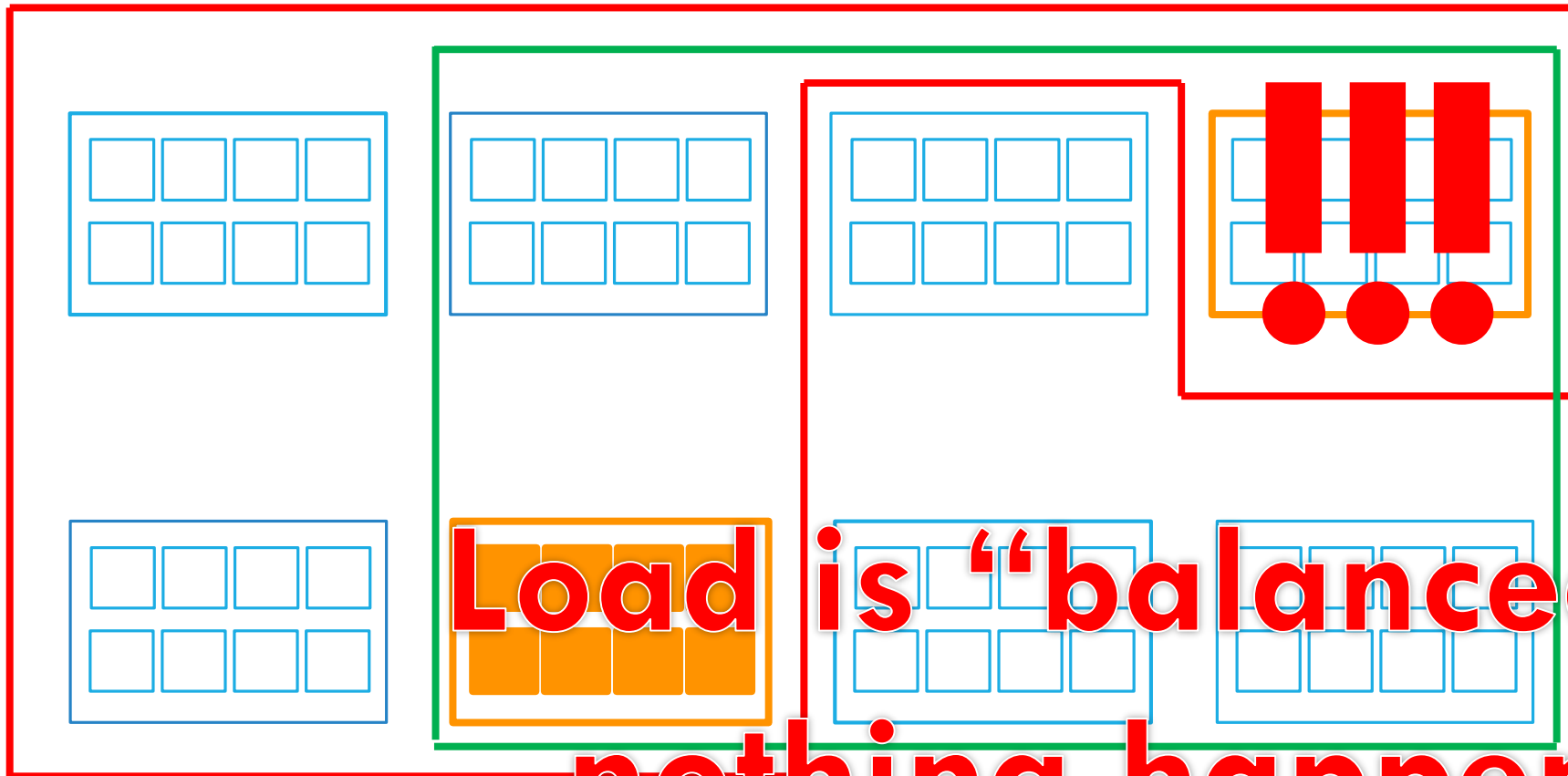


**load(red) =  
16 \* load(thread)**

**load(green) =  
16 \* load(thread)**

**Load is "balanced"!**  
**nothing happens**

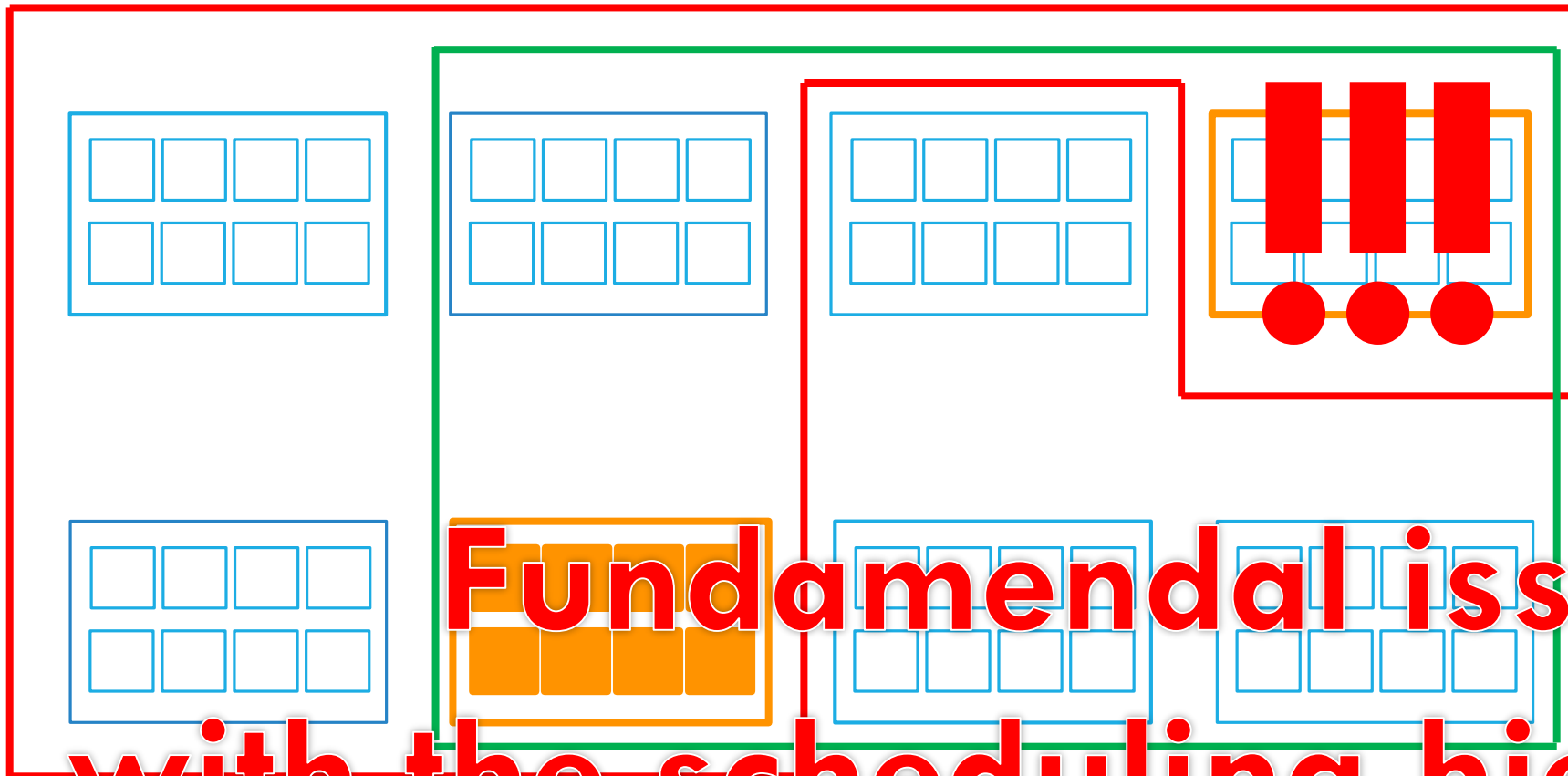
# BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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$$\text{load}(\text{green}) = 16 * \text{load}(\text{thread})$$

**Fundamental issue**  
**with the scheduling hierarchy !**



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- **Fix: build the domains by creating one “directly connected” group for every CPU**
  - Instead of the first CPU and the first one not “covered” by a group

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  - Instead of the first CPU and the first one not “covered” by a group
- Performance improvement of NAS applications on two nodes :

Application	With bug	After fix	Improvement
BT	99	56	1.75x
CG	42	15	2.73x
EP	73	36	2x
LU	1040	38	27x

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  - Instead of the first CPU and the first one not “covered” by a group
- Performance improvement of NAS applications on two nodes :

Application	With bug	After fix	Improvement
BT	99	56	1.75x
CG	42	15	2.73x
EP	73	36	2x
LU	1040	38	27x

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

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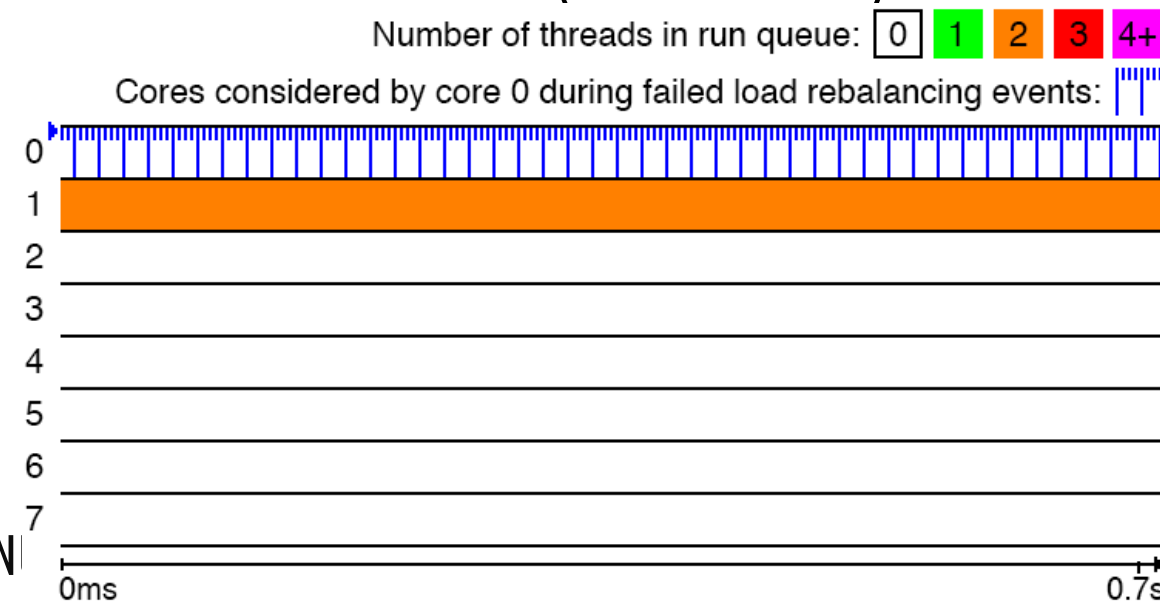


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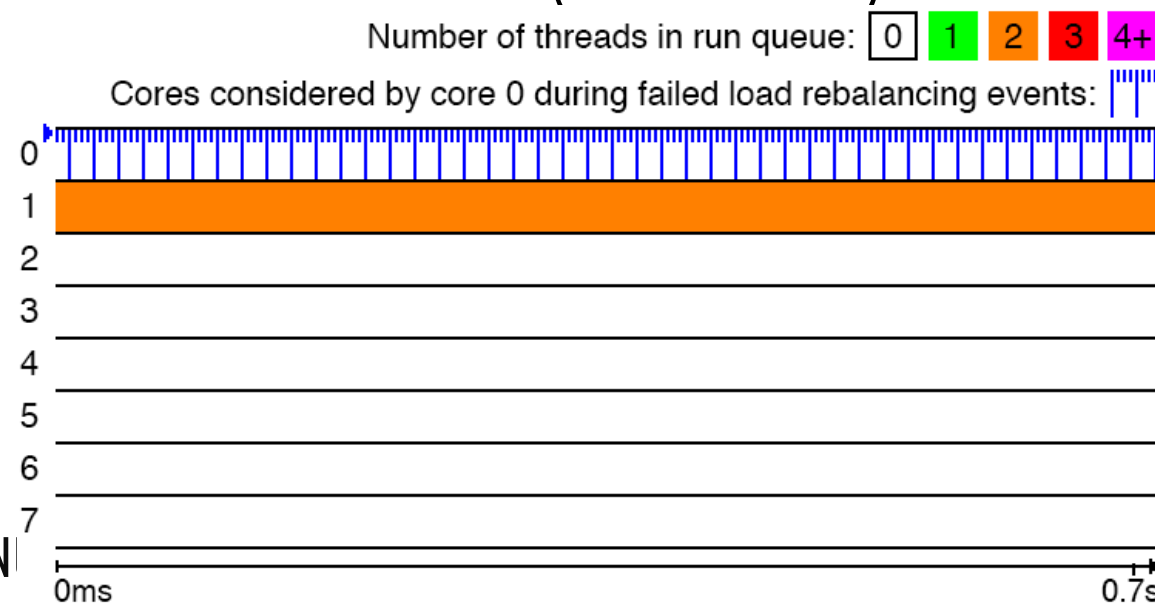
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Application	With bug	After fix	Improvement
BT	122	23	5.2x
CG	134	5.4	25x
EP	72	18	4x
LU	2196	16	137x



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## Wait, does that work?



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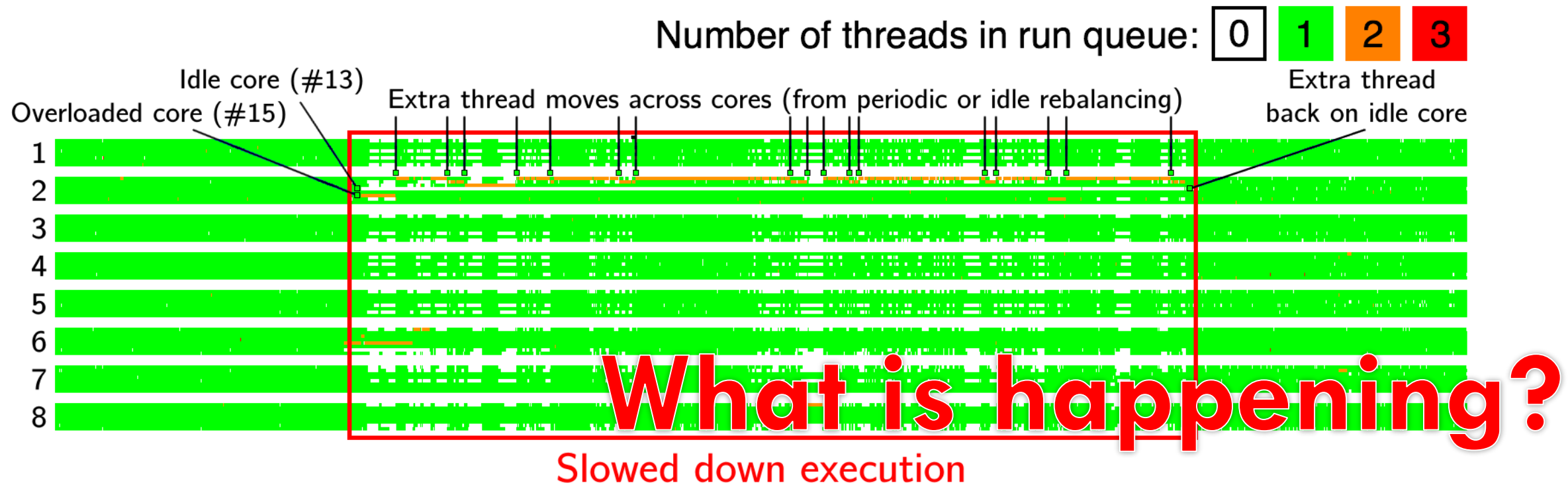
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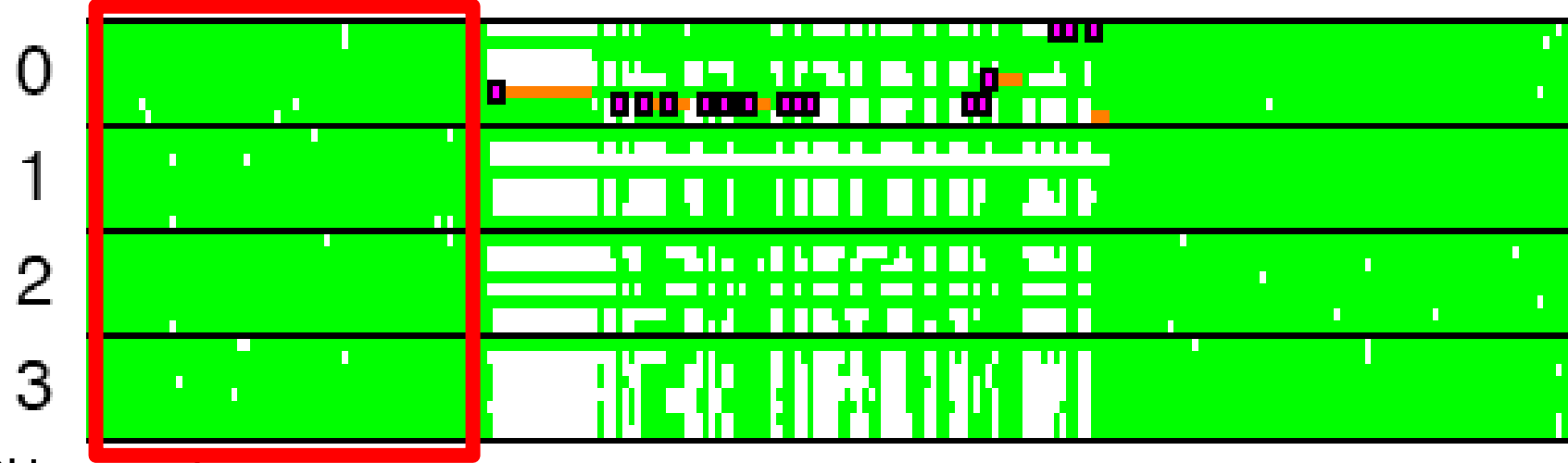


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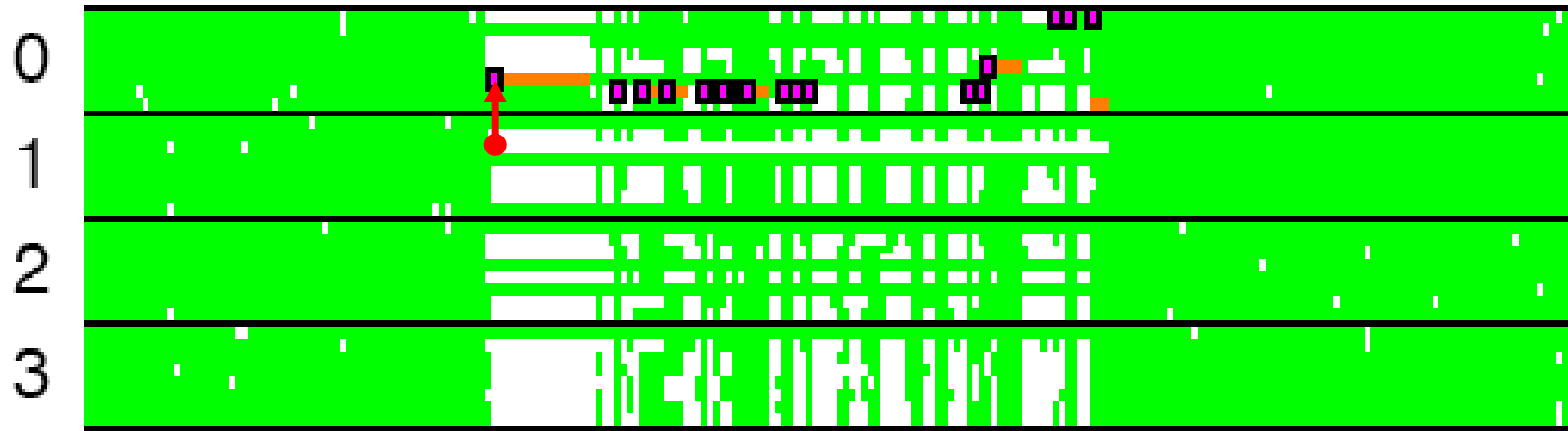


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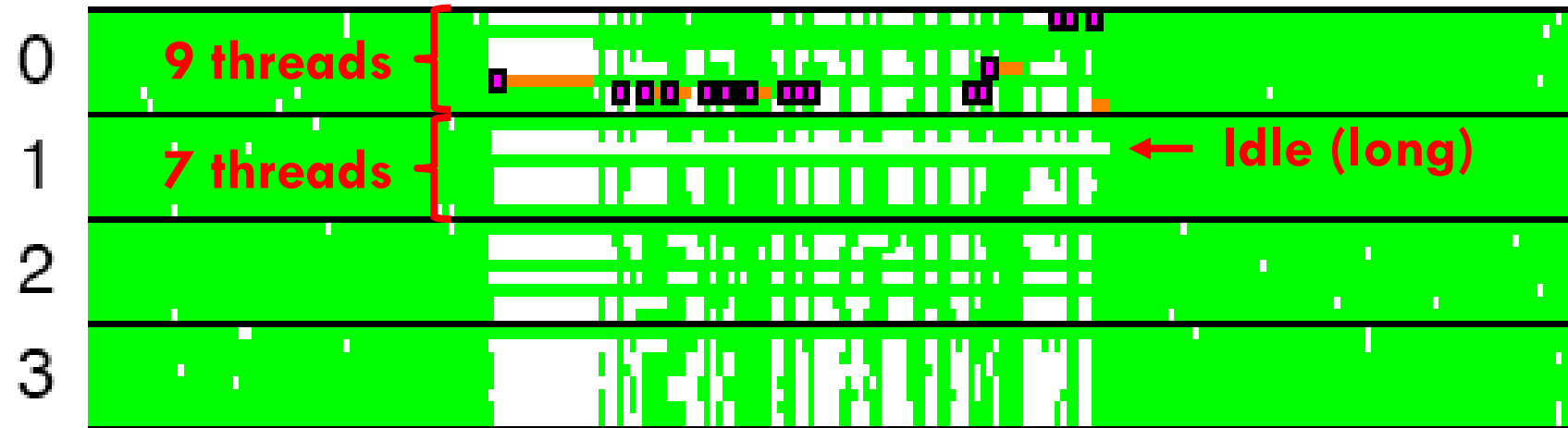
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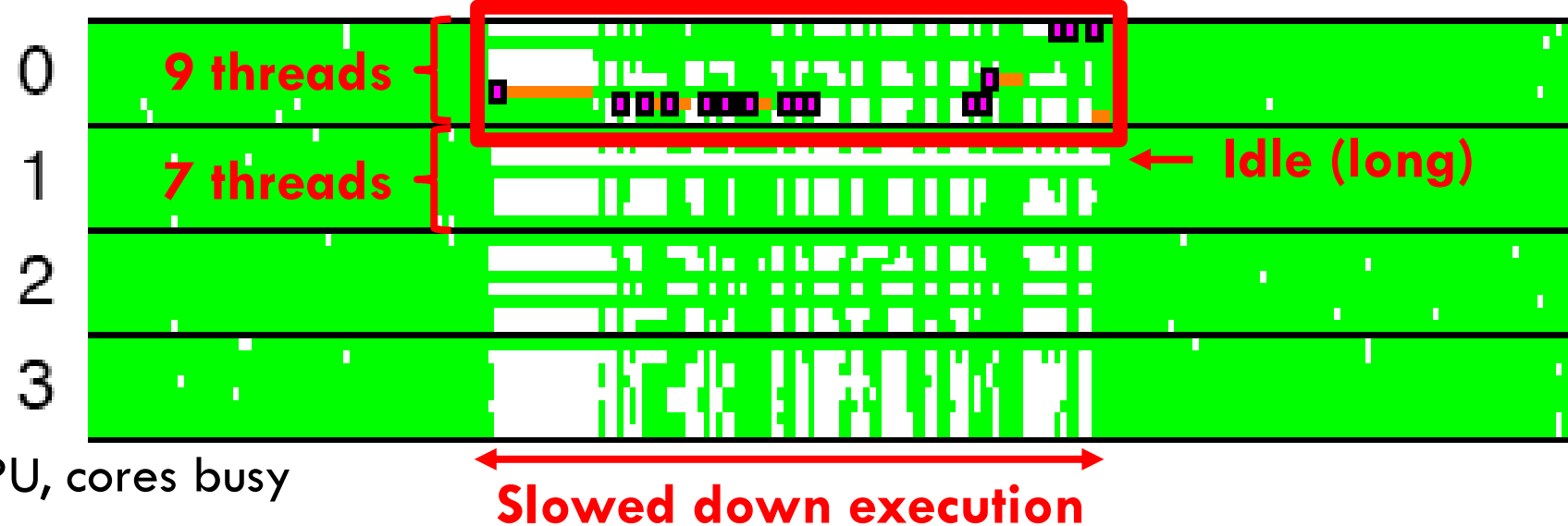
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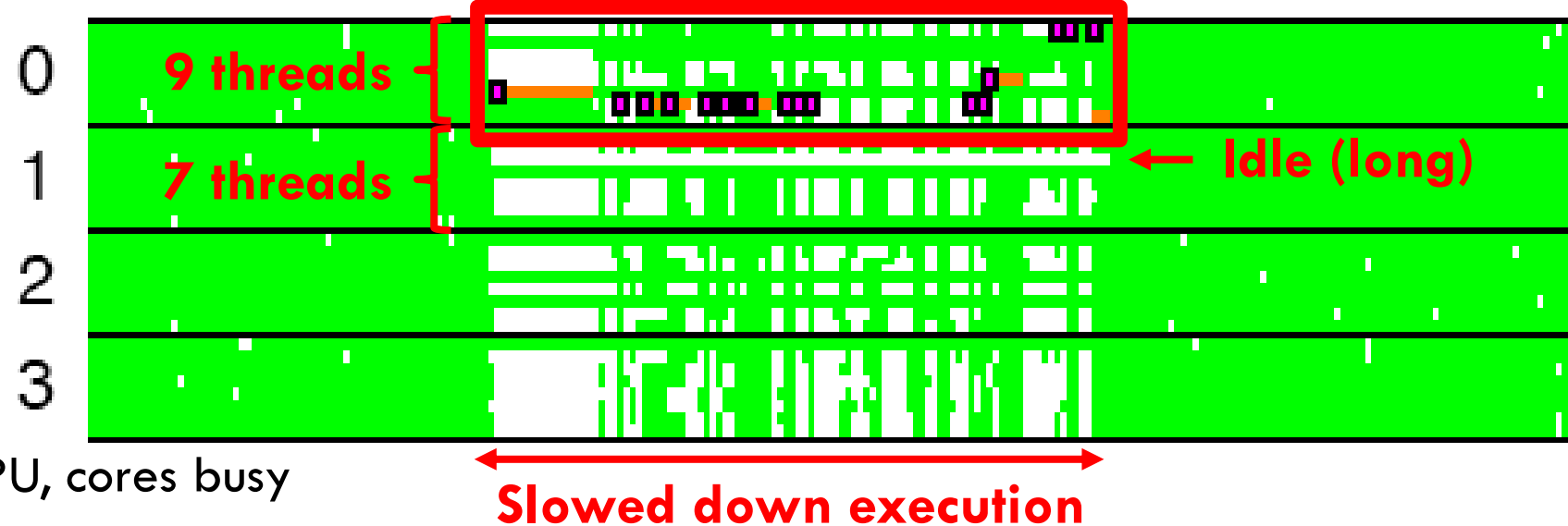
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Bug fixes	TPC-H request #18	Full TPC-H benchmark
None	55.9s	542.9s
<i>Group Imbalance</i>	48.6s (−13.1%)	513.8s (−5.4%)
<i>Overload-on-Wakeup</i>	43.5s (−22.2%)	471.1s (−13.2%)
Both	43.3s (−22.6%)	465.6s (−14.2%)

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- **Model checking, formal proofs**
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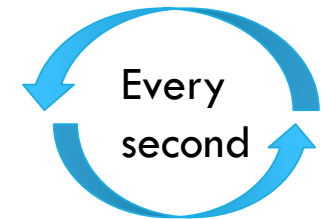
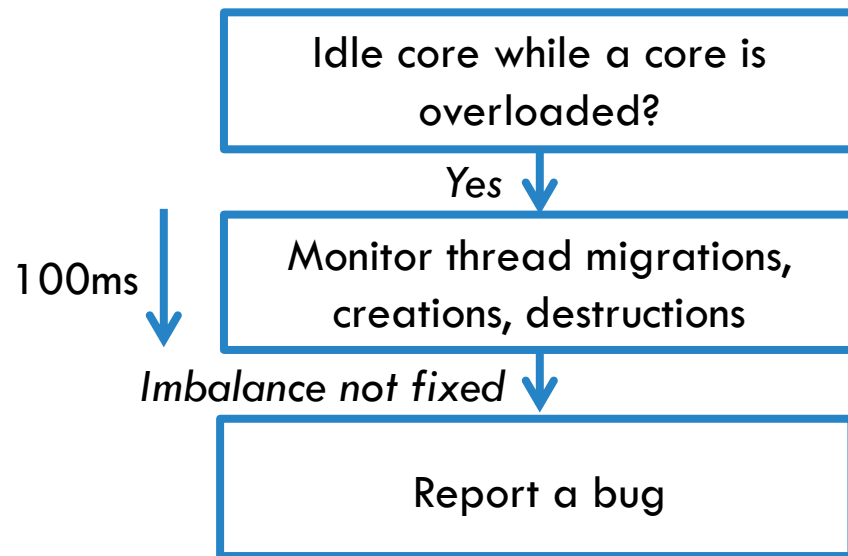
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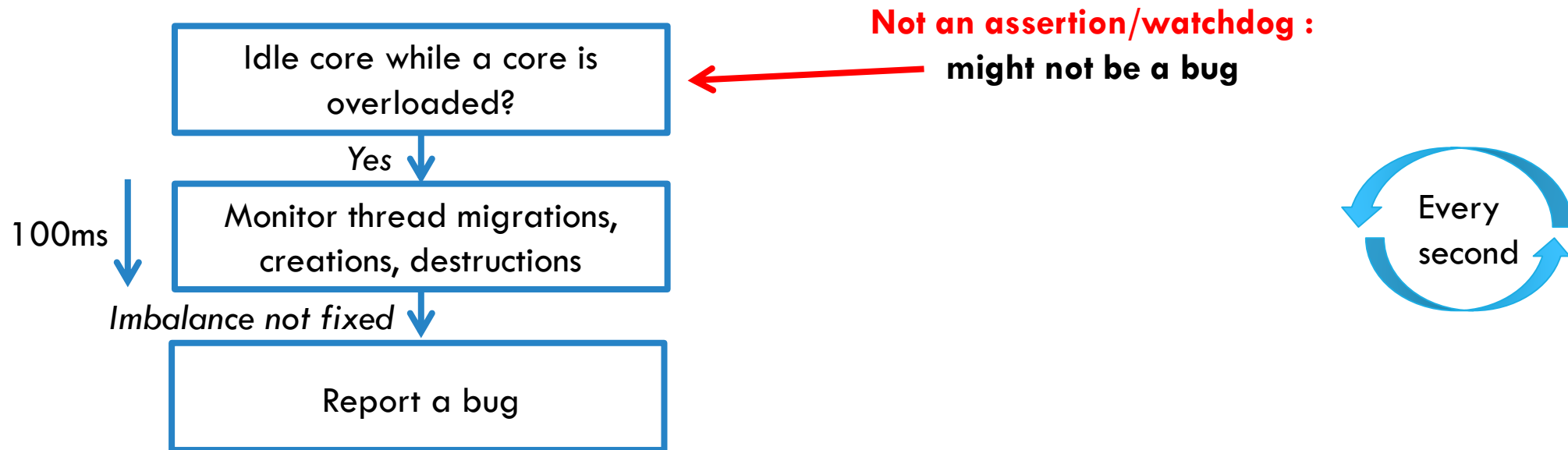
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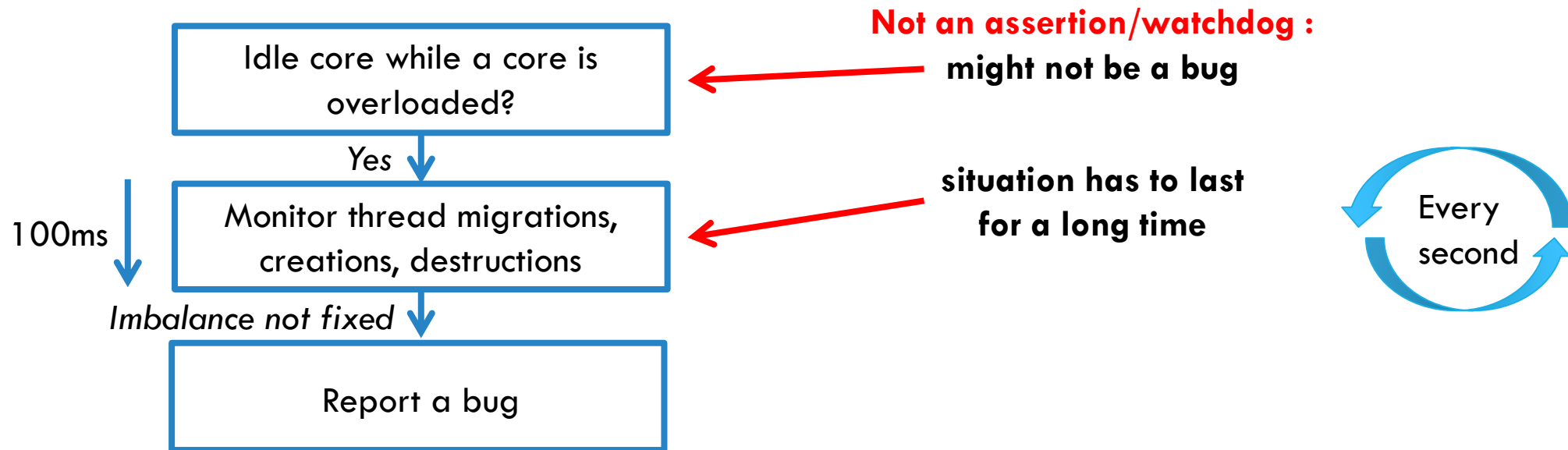
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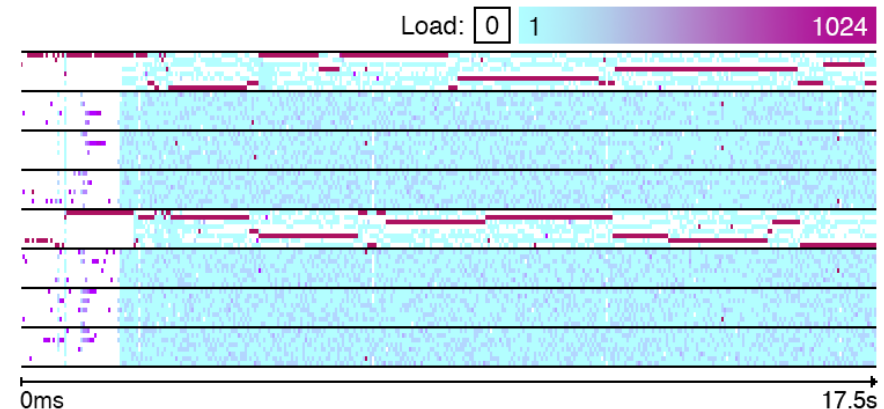
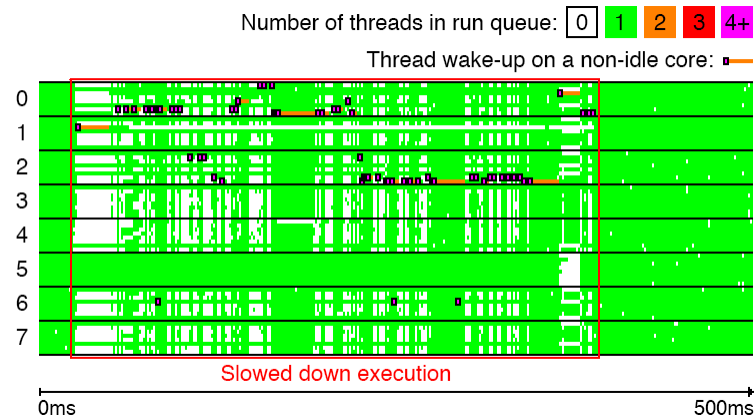
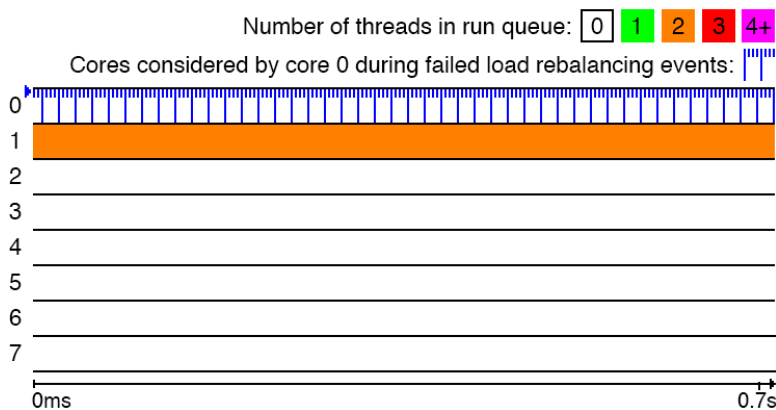
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