THE OS SCHEDULER: A PERFORMANCE-CRITICAL COMPONENT IN LINUX CLUSTER ENVIRONMENTS

KEYNOTE FOR BPOE-9 *@ASPLOS2018*

THE NINTH WORKSHOP ON BIG DATA BENCHMARKS, PERFORMANCE, OPTIMIZATION AND EMERGING HARDWARE

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Oracle Labs

CLUSTER COMPUTING

- **Multicore servers with dozens of cores**
  - Common for e.g., a hadoop cluster, a distributed graph analytics engine, multiple apps…
  - High cost of infrastructure, high energy consumption

- **Linux-based software stack**
  - Low (license) cost, yet high reliability

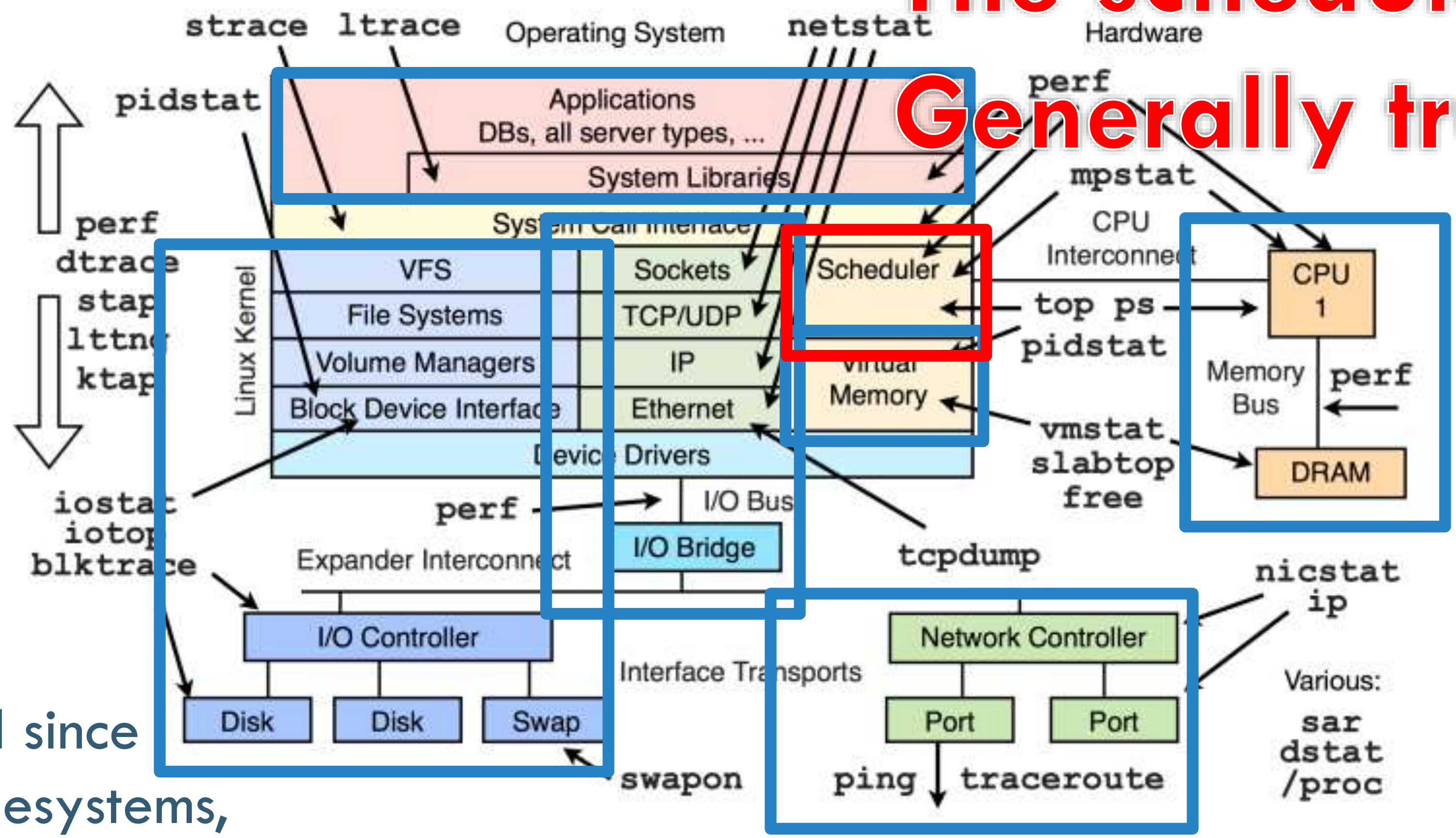
- **Challenge: don't waste cycles!**
  - Reduces infrastructure and energy costs
  - Improves bandwidth and latency

WHERE TO HUNT FOR CYCLES?

The scheduler???

Generally trusted!

Applications, libraries: often main focus



NUMA, bus usage: Placement, replication, interleaving, many recent papers

Storage: optimized since decades! E.g., many filesystems, RDBMSes bypassing the OS

Network stack, NICs, reducing network usage (e.g. HDFS): common optimizations

IS THE SCHEDULER WORKING IN YOUR CLUSTER?

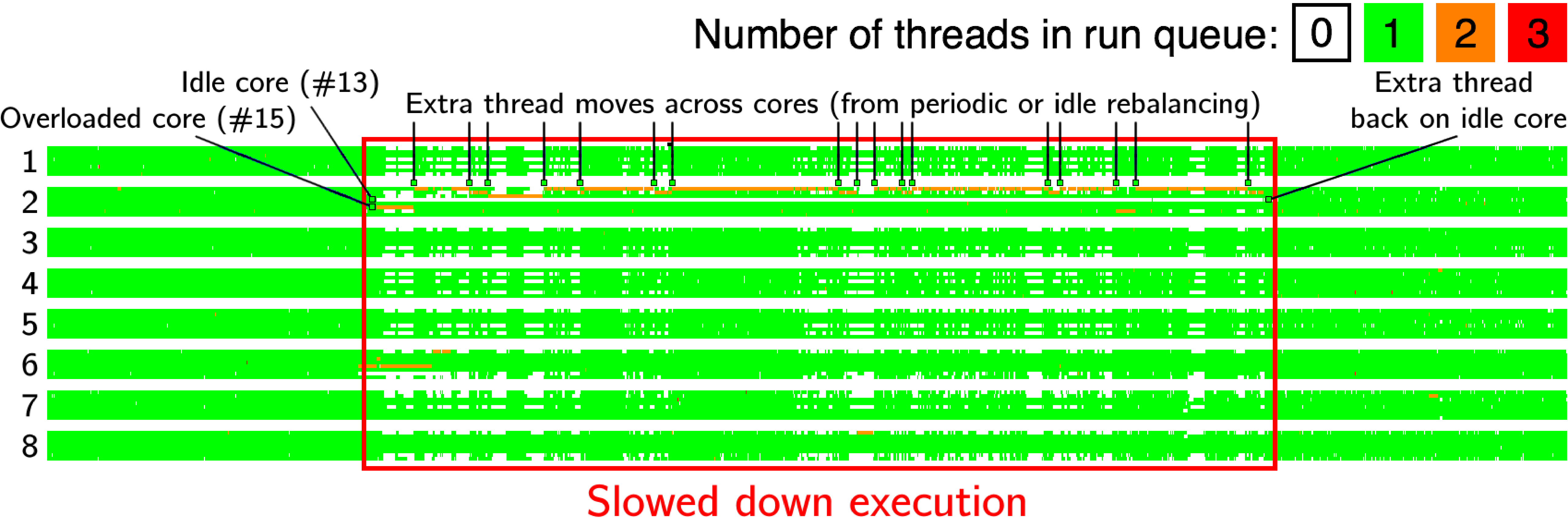
- It must be! 15 years ago, Linus Torvalds was already saying:

"And you have to realize that there are not very many things that have aged as well as the scheduler. ***Which is just another proof that scheduling is easy."***

- Since then, people have been running applications on their multicore machines all the time, and they run, CPU usage is high, everything seems fine.
- But would you notice if some cores remained idle intermittently, when they shouldn't?
  - **Do you keep monitoring tools (`htop`) running all the time?**
  - **Even if you do, would you be able to identify faulty behavior from normal noise?**
  - **Would you ever suspect the scheduler?**

THIS TALK

- Over the past few years of working on various projects, we sometimes saw strange, hard to explain performance results.



THIS TALK

- **This is how we found our first performance bug.** Which made us investigate more…
- **In the end: four Linux scheduler performance bugs that we found and analyzed**
- **Always the same symptom: idle cores while others are overloaded**
  - The bug-hunting was tough, and led us to develop our own tools
- **Performance overhead of 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?

THIS TALK

The Linux Scheduler: a Decade of Wasted Cores

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Main takeaway of our analysis: ***more research must be directed towards implementing an efficient scheduler for multicore architectures, because contrary to what a lot of us think, this is *not* a solved problem!***

Need convincing? Let's go through it together...

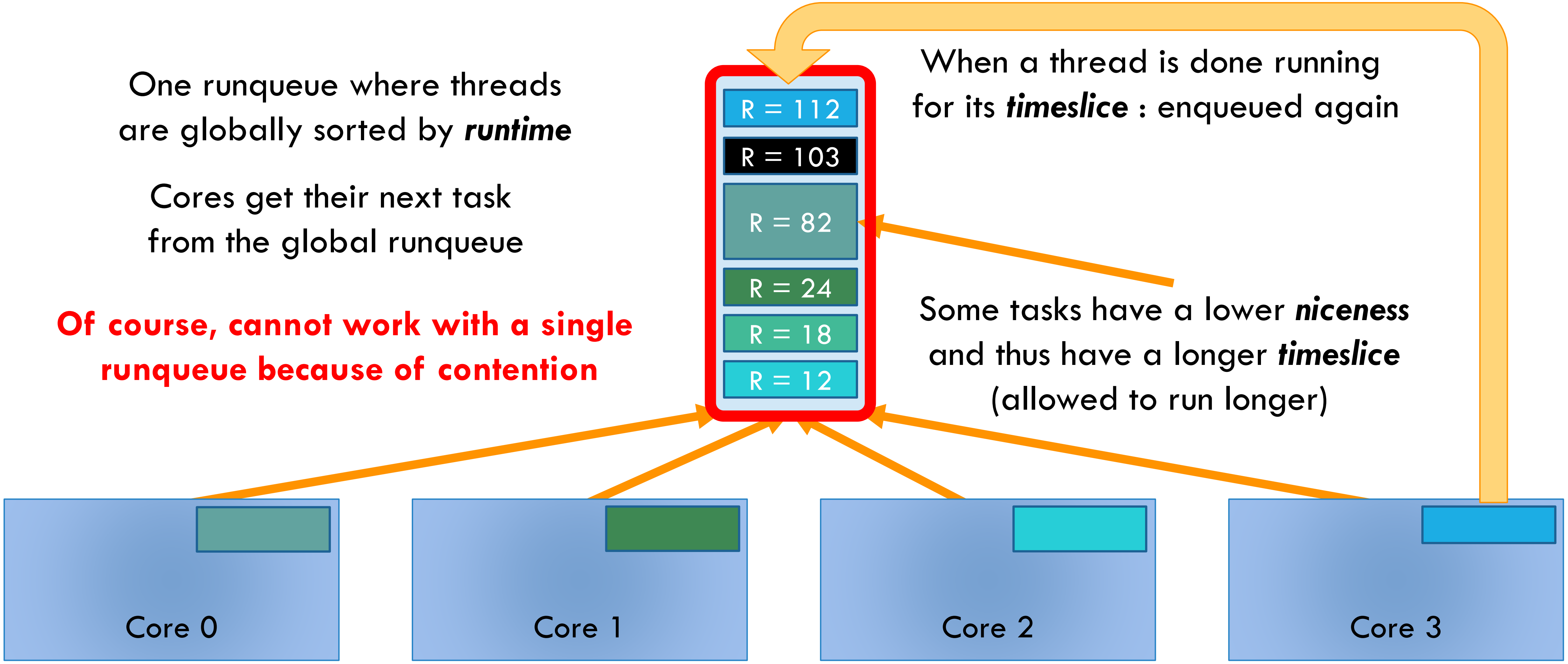
...starting with a bit of background...

THE COMPLETELY FAIR SCHEDULER (CFS): CONCEPT

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

Cores get their next task from the global runqueue

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



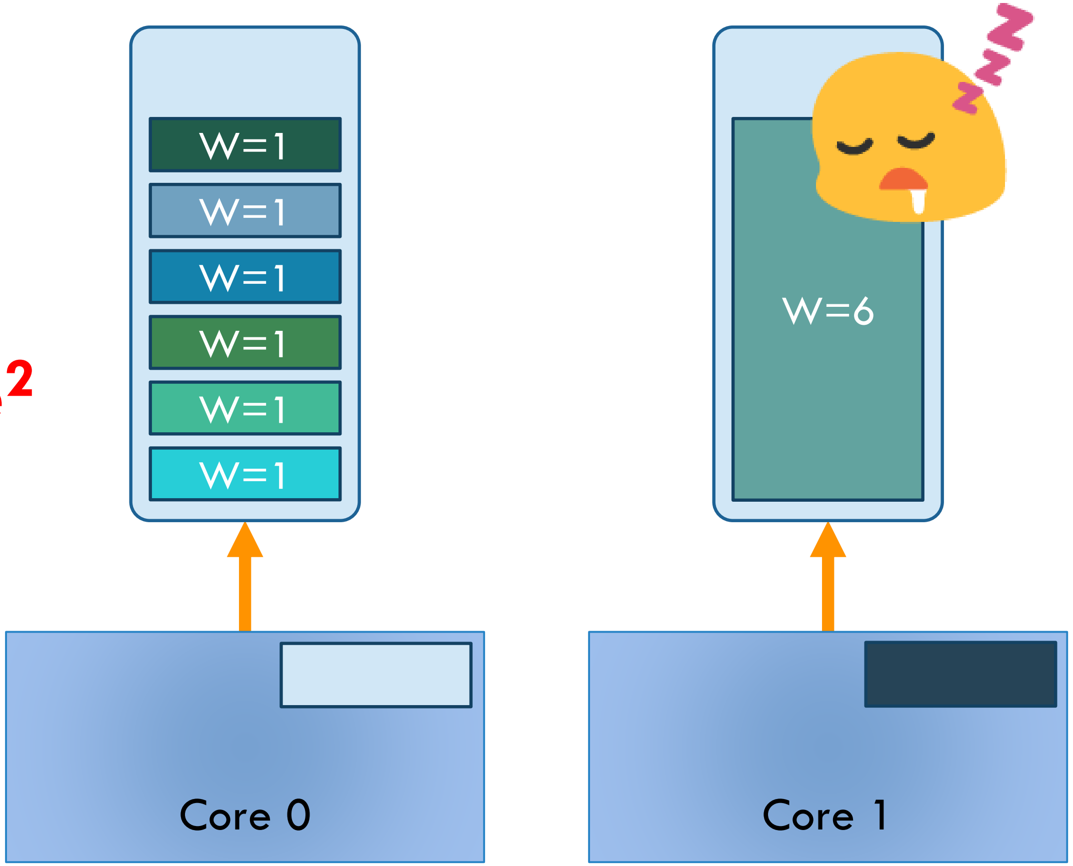
CFS: IN PRACTICE

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

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

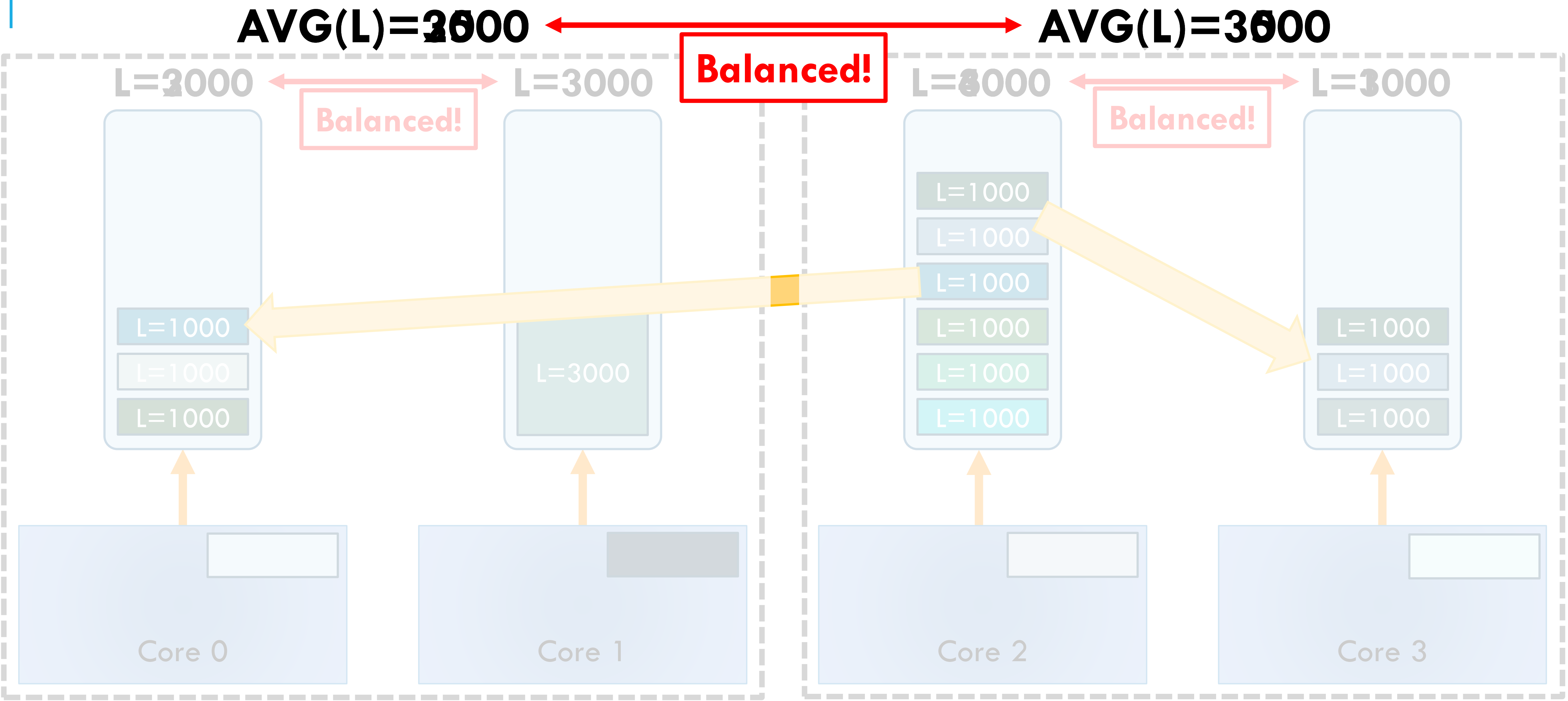
[1]The lower the niceness, the higher the weight

[2]We don't want a high-priority thread that sleeps a lot to take a whole CPU for itself and then mostly sleep!



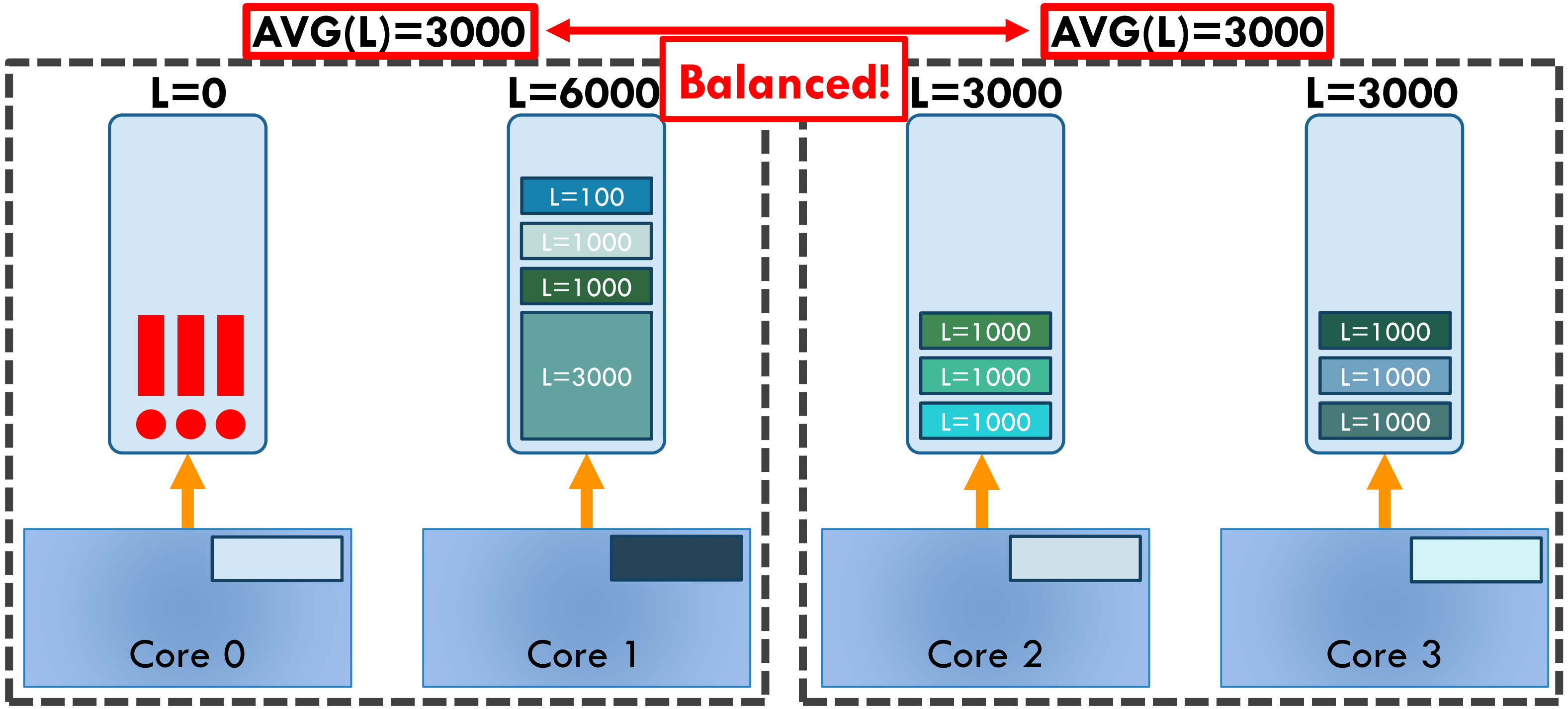
- **Since there can be many cores: hierarchical approach!**

CFS IN PRACTICE : HIERARCHICAL LOAD BALANCING



CFS IN PRACTICE : HIERARCHICAL LOAD BALANCING

- **Note that only the *average* load of groups is considered**
- If for some reason the lower-level load-balancing fails, nothing happens at a higher level:



CFS IN PRACTICE: MORE HEURISTICS

- **Load calculations are actually more complicated, use more heuristics.**
- **One of them aims to increase fairness between "sessions".**
- **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...

CFS IN PRACTICE: MORE HEURISTICS

- **Load calculations are actually more complicated, use more heuristics.**
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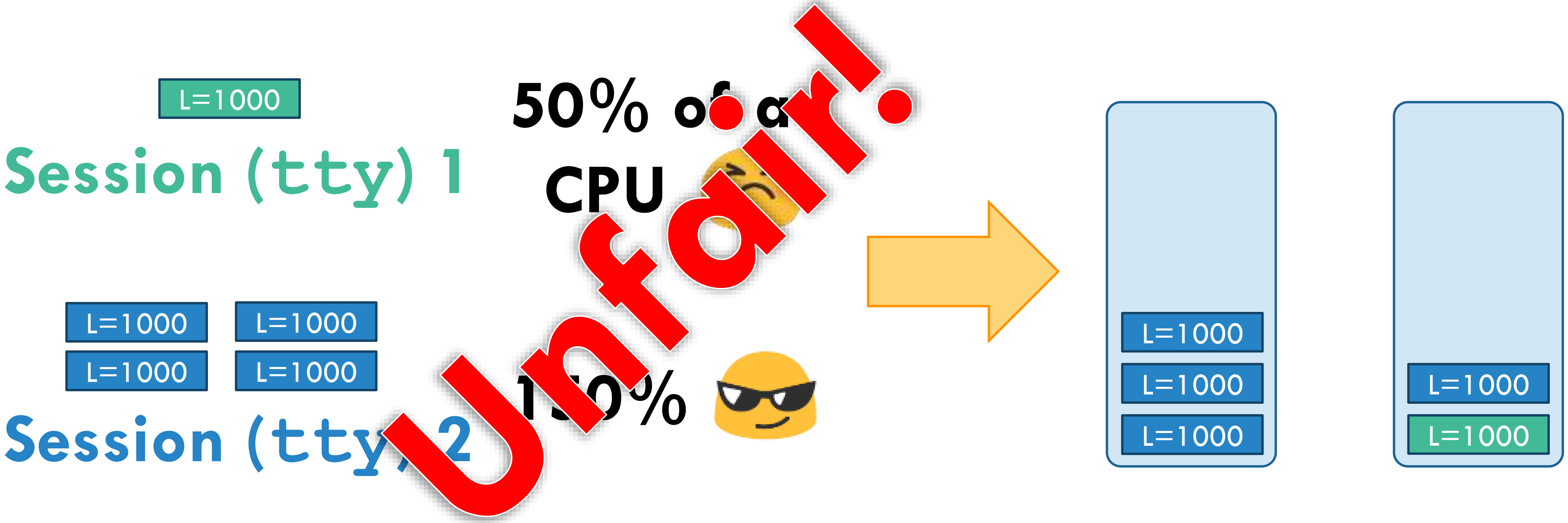
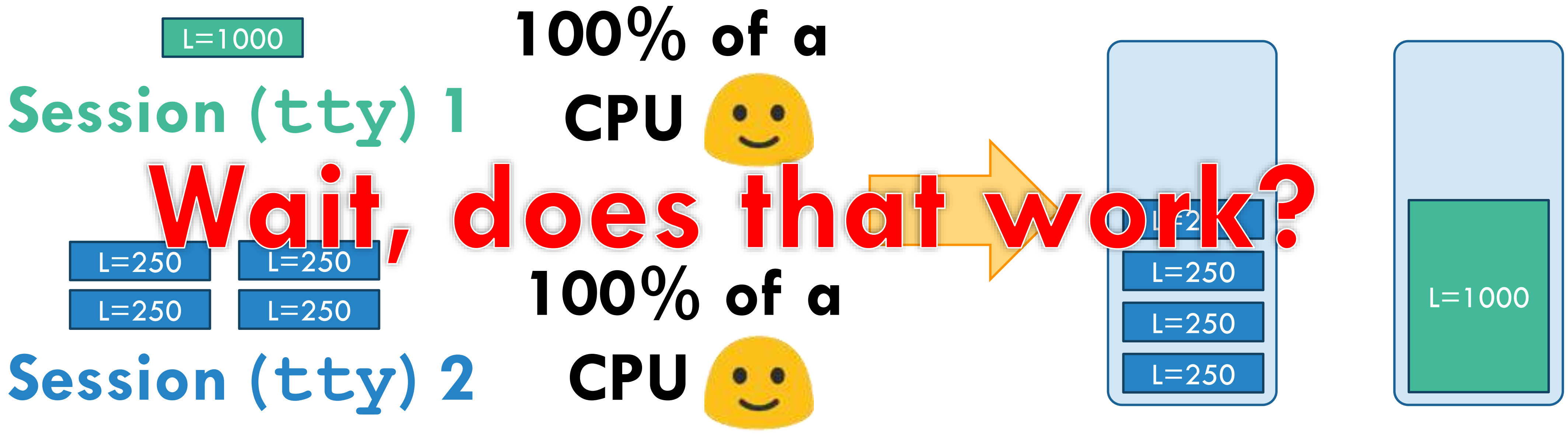
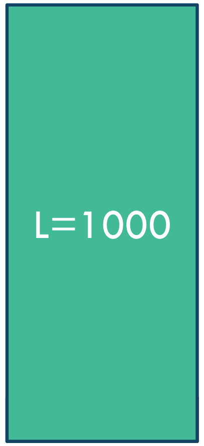


CFS IN PRACTICE: MORE HEURISTICS

- **Load calculations are actually more complicated, use more heuristics.**
- **Solution:** divide the load of a task by the number of threads in its `tty`…

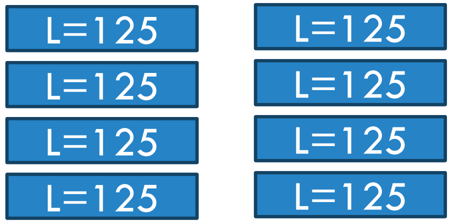


BUG 1/4: GROUP IMBALANCE



Session (tty) 1

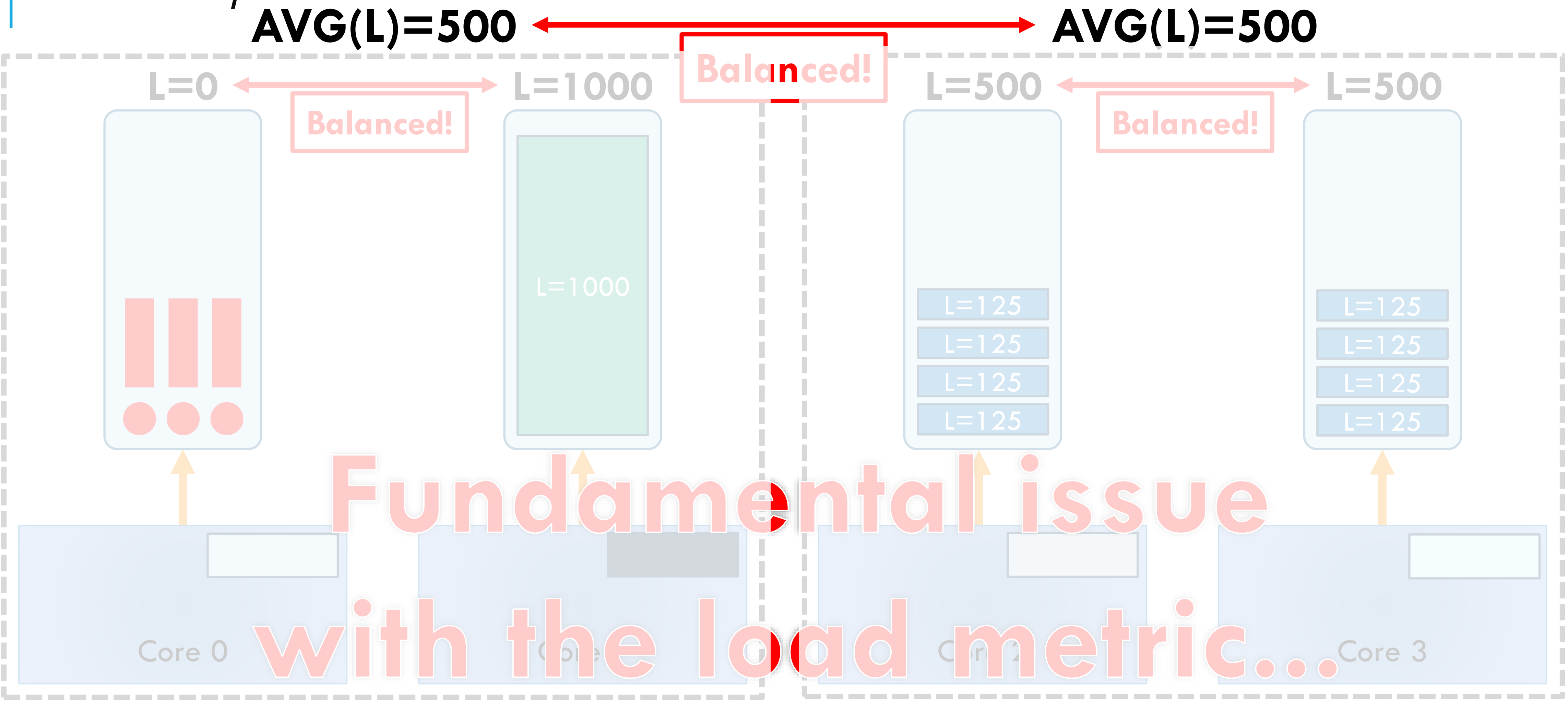
Load(thread) = %cpu × weight / #threads
= 100 × 10 / 1
= 1000

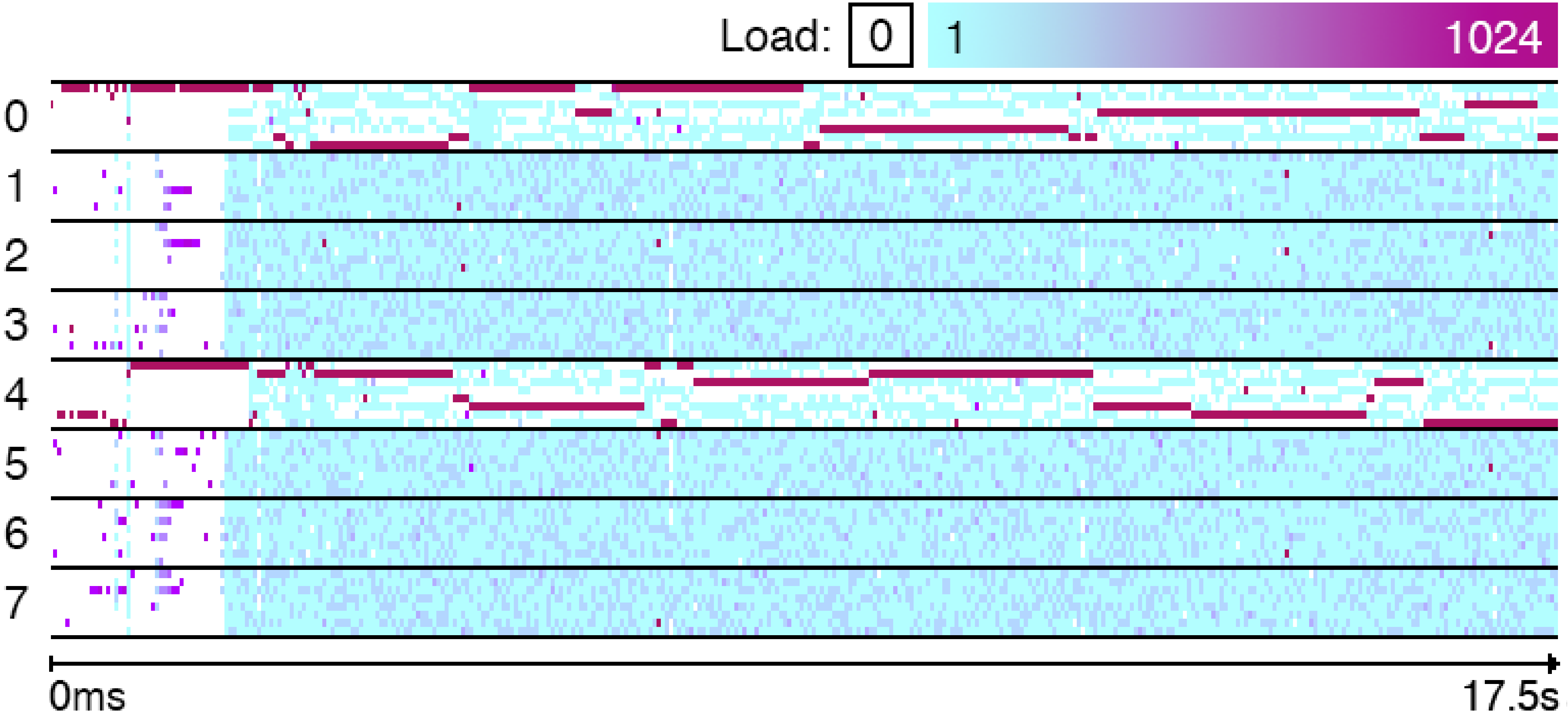


Session (tty) 2

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

BUG 1/4: GROUP IMBALANCE

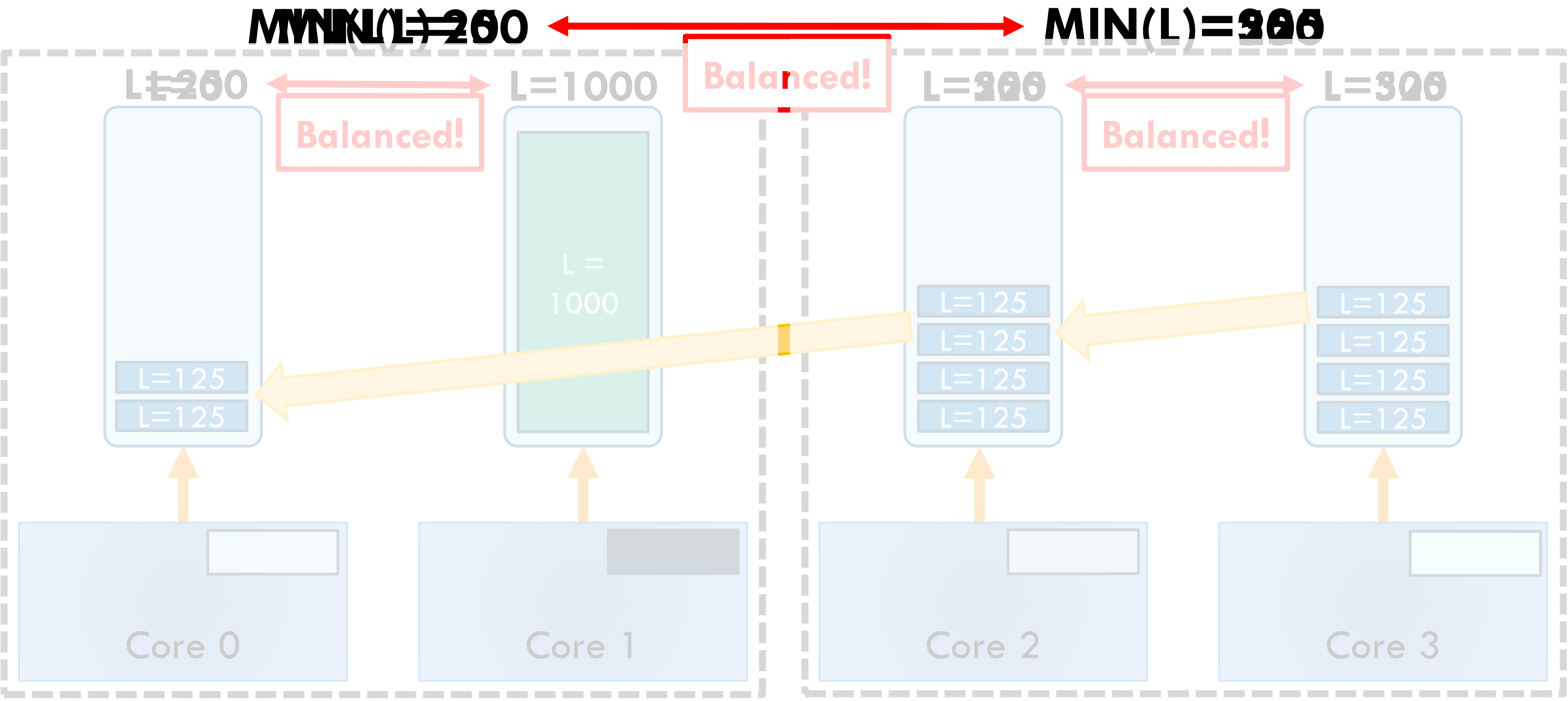




- **The bug happens at two levels :**
  - Other core on pair of core idle
  - Other cores on NUMA node less busy…

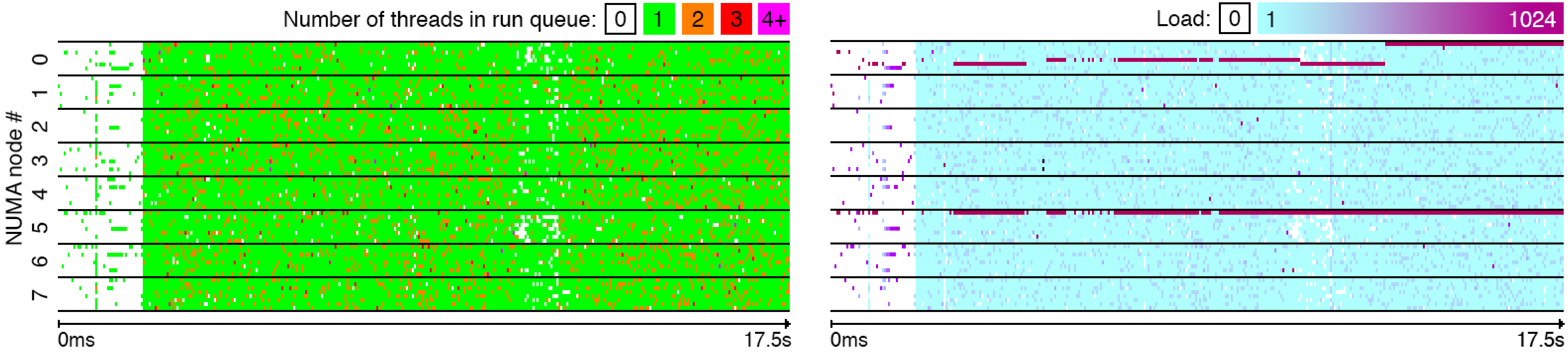
BUG 1/4: GROUP IMBALANCE

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



BUG 1/4: GROUP IMBALANCE

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



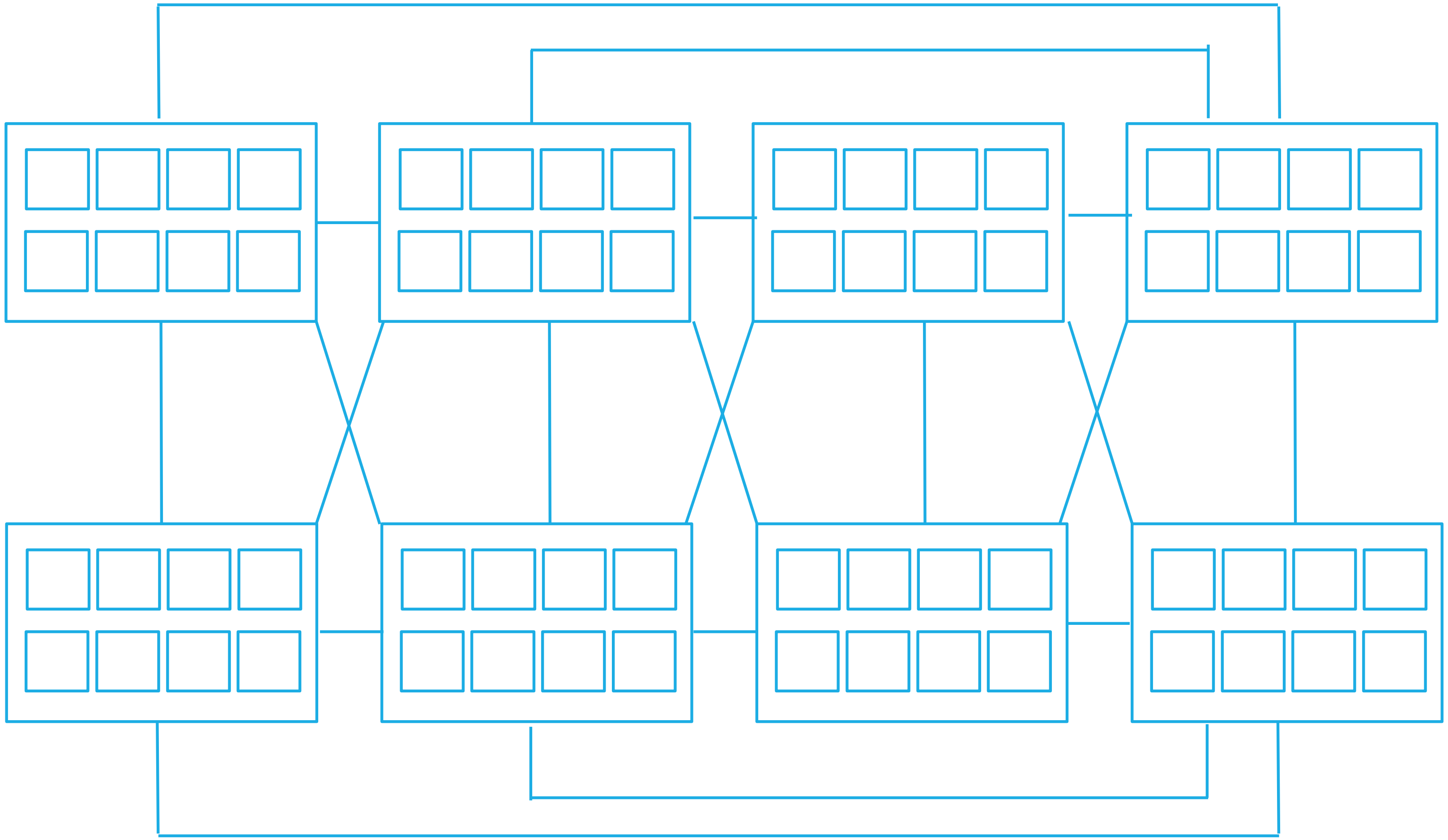
- **After the fix, make runs 13% faster, and R is not impacted**

- **A simple solution, but is it ideal? Minimum load more volatile than average…**
  - *May cause lots of unnecessary rebalancing. Revamping load calculations needed?*

BUG 2/4: SCHEDULING GROUP CONSTRUCTION

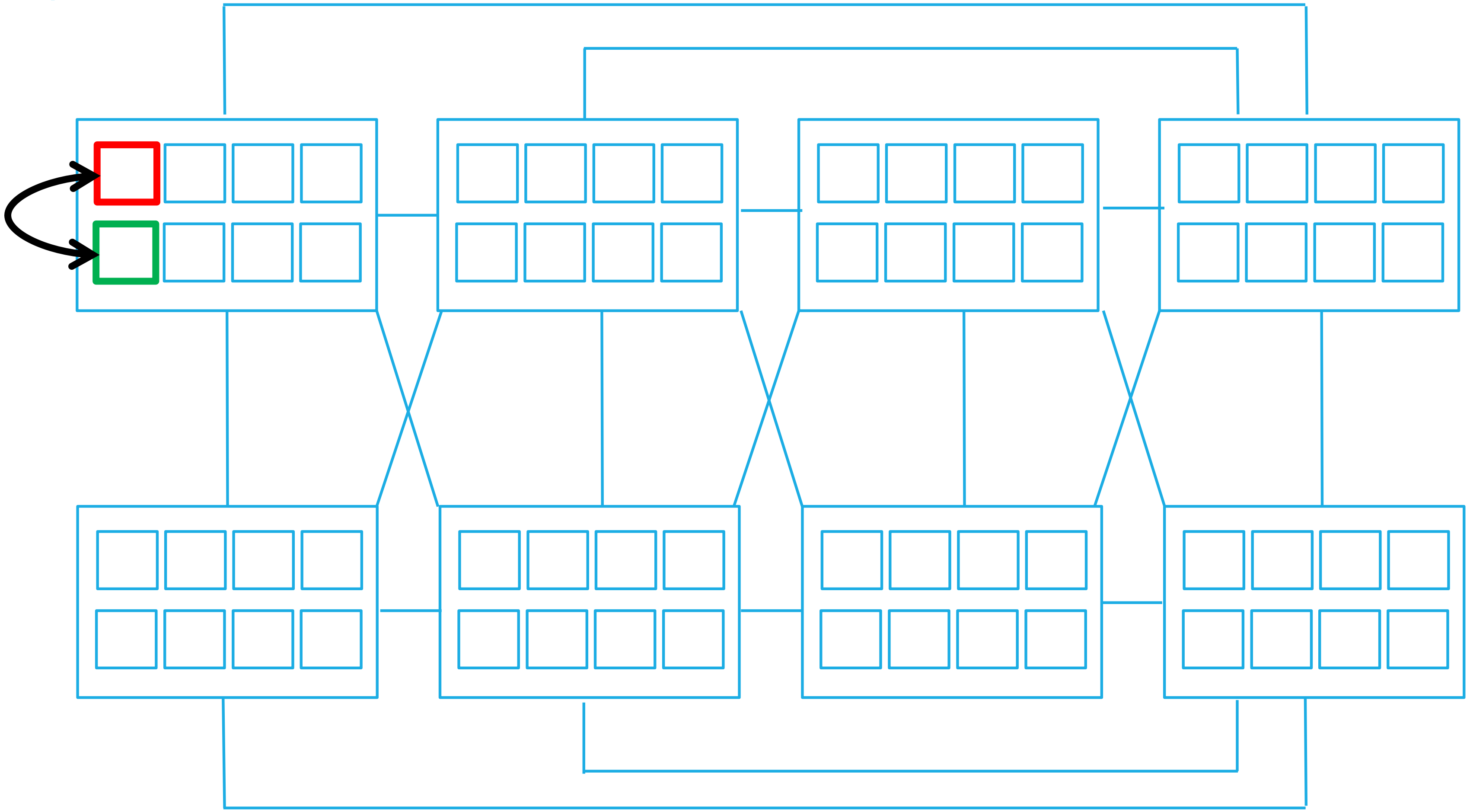
- **Hierarchical load balancing** is based on groups of cores named *scheduling domains*
  - Based on affinity, i.e., pairs of cores, dies, CPUs, NUMA nodes, etc.
- Each scheduling domain contains groups that are the lower-level scheduling domains
- **For instance, on our 64-core AMD Bulldozer machine:**
  - At level 1, each pair of core (scheduling domains) contain cores (scheduling groups)
  - At level 2, each CPU (s.d.) contain pairs of cores (s.g.)
  - At level 3, each group of directly connected CPUs (s.d.) contain CPUs (s.g.)
  - At level 4, the whole machine (s.d.) contains group of directly connected CPUs (s.g.)

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



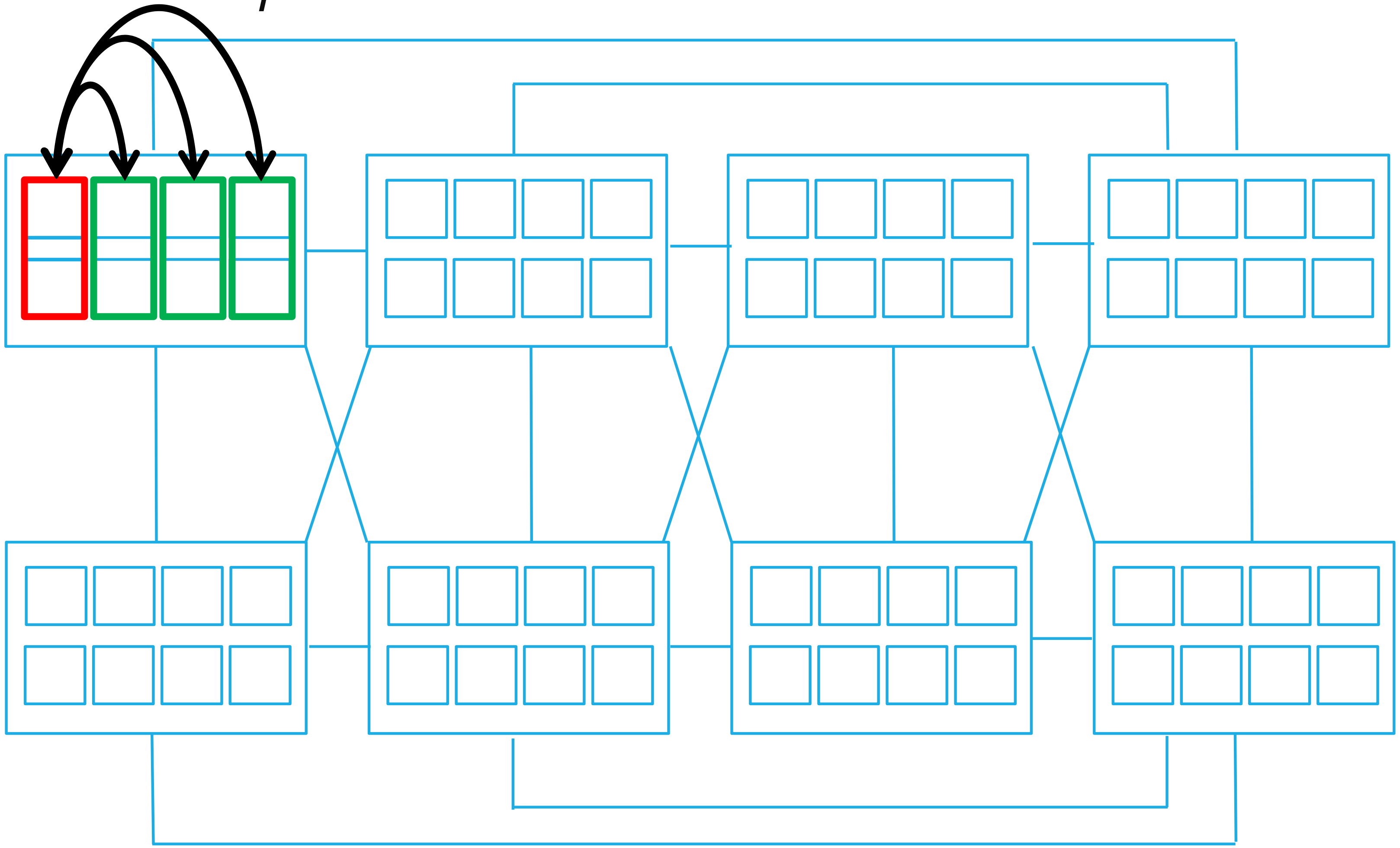
Bulldozer 64-core:
Eight CPUs, with
8 cores each,
non-complete
interconnect graph!

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



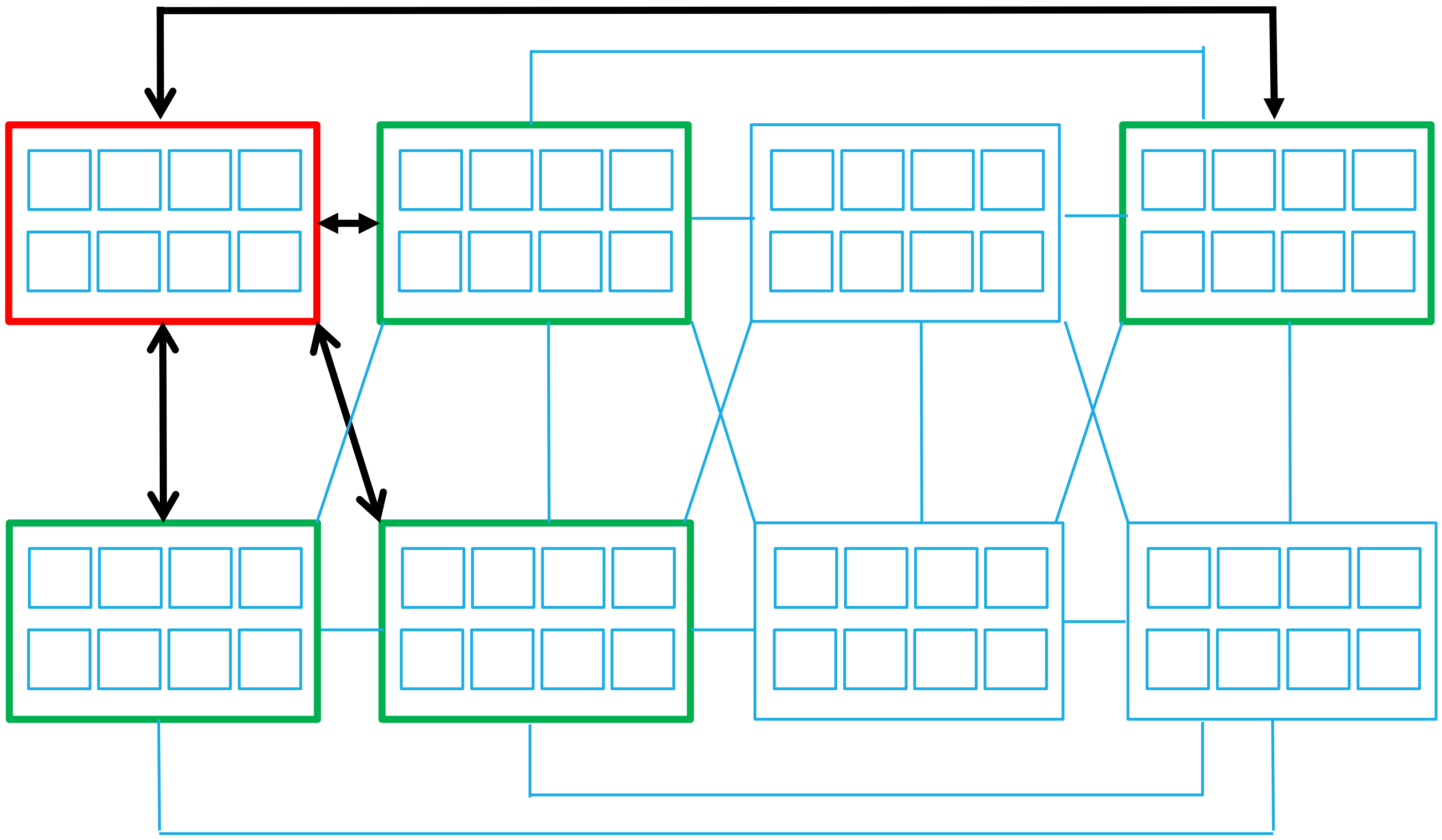
At the **first level**, the **first core** balances load with the other core **on the same pair** (because they share resources, high affinity)

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



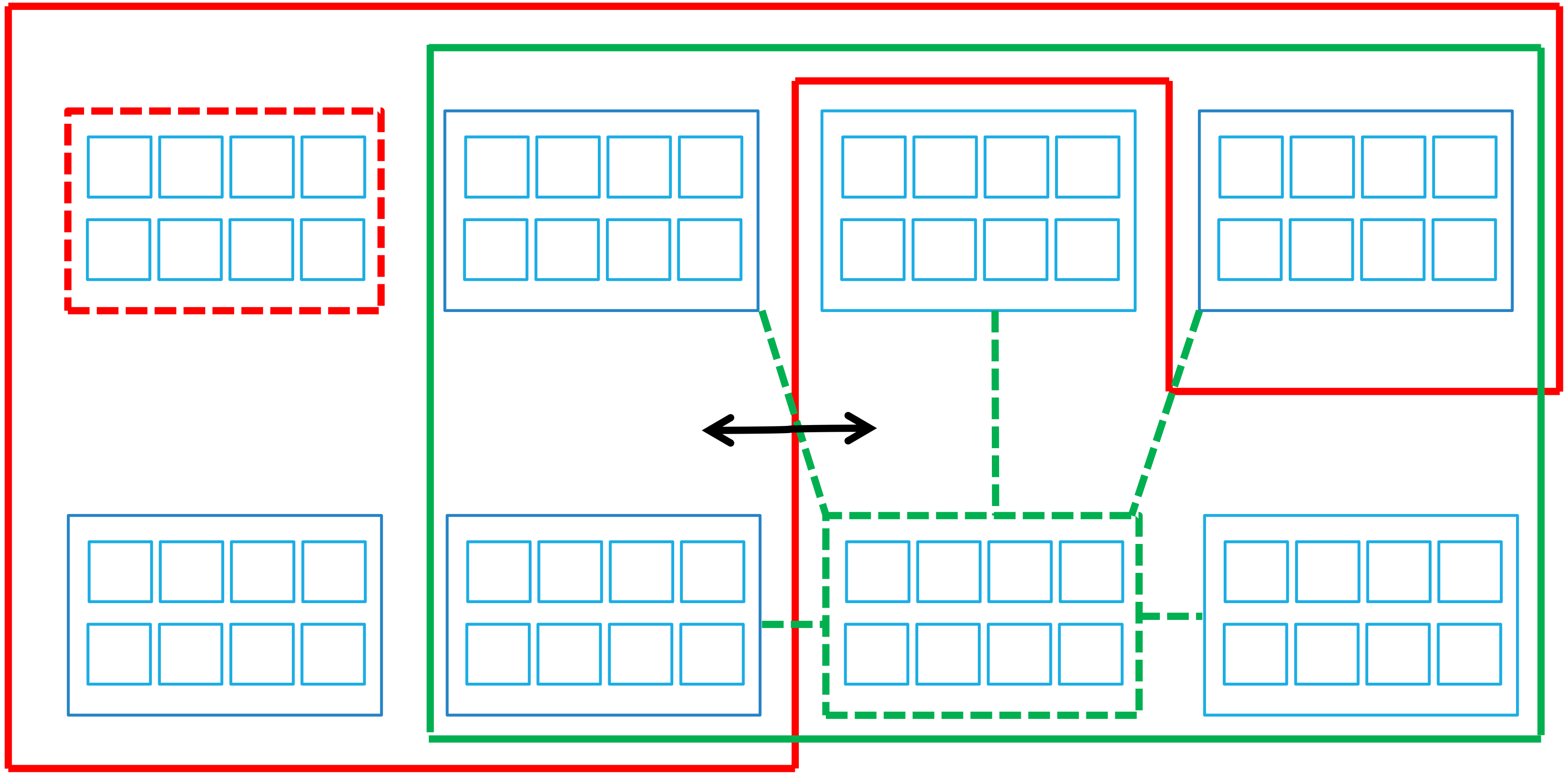
At the 2nd level, the **first pair** balances load with other pairs **on the same CPU**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



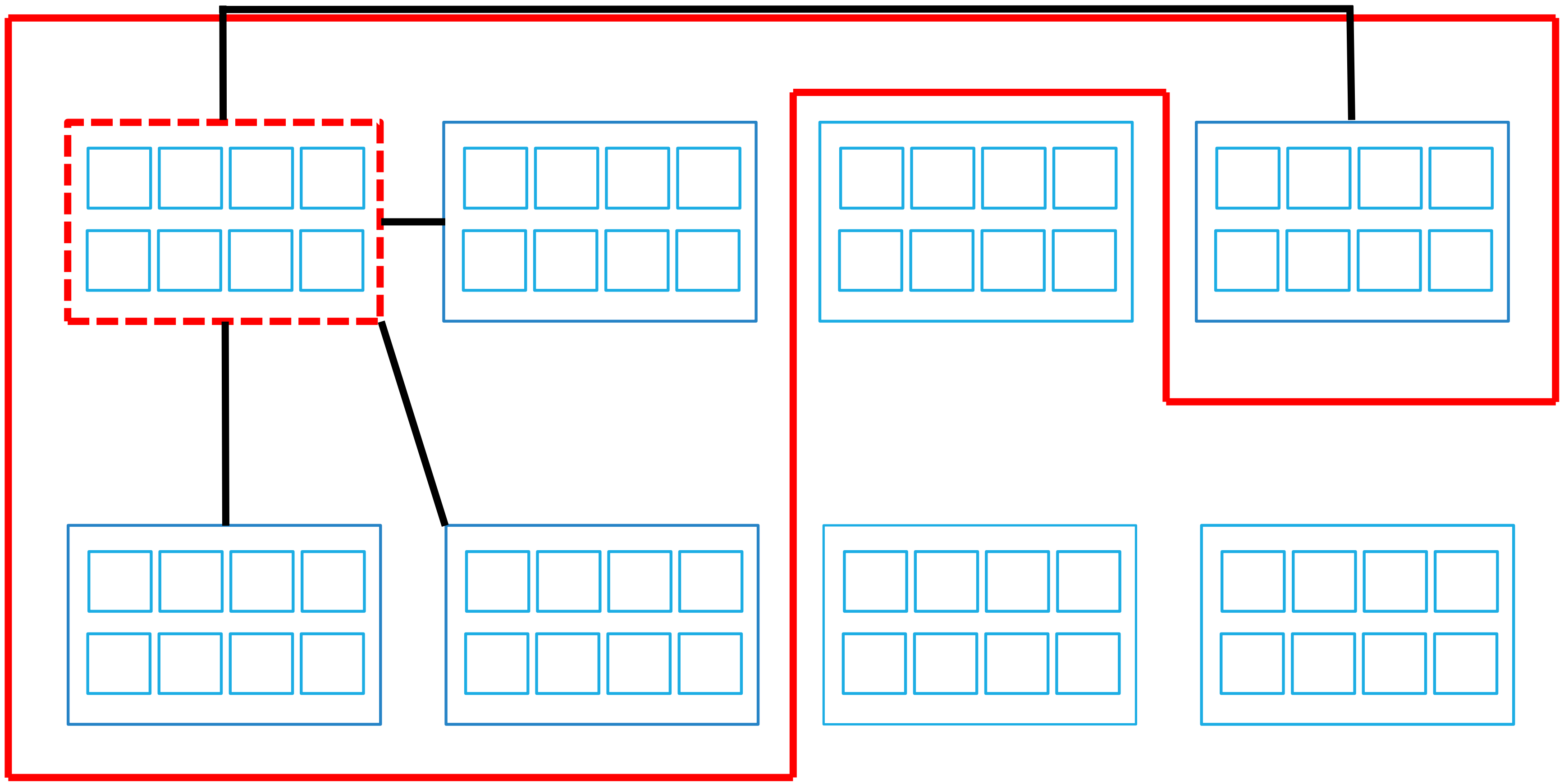
At the 3rd **level**, the **first CPU** balances load with **directly connected CPUS**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

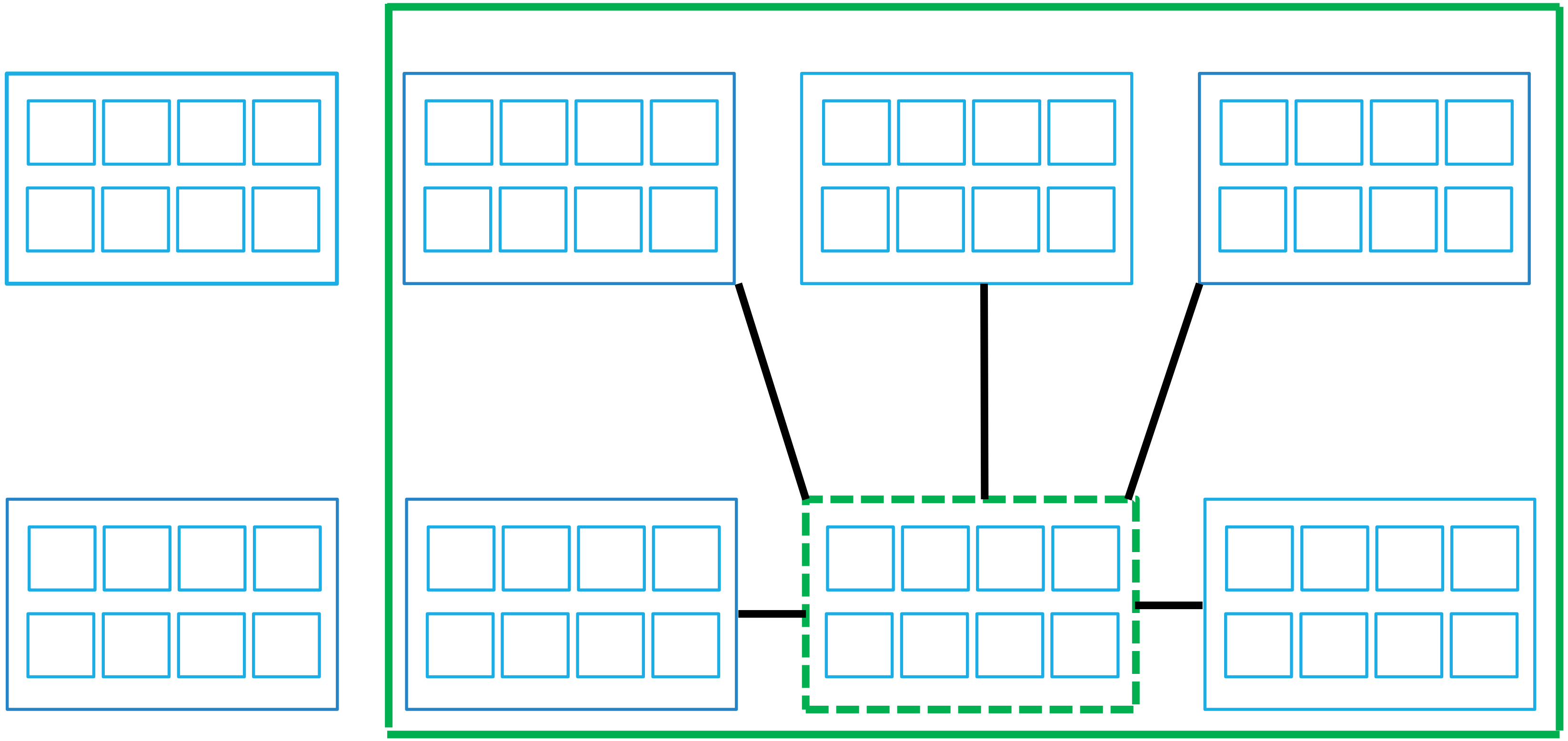
BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Groups of CPUs built by:

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

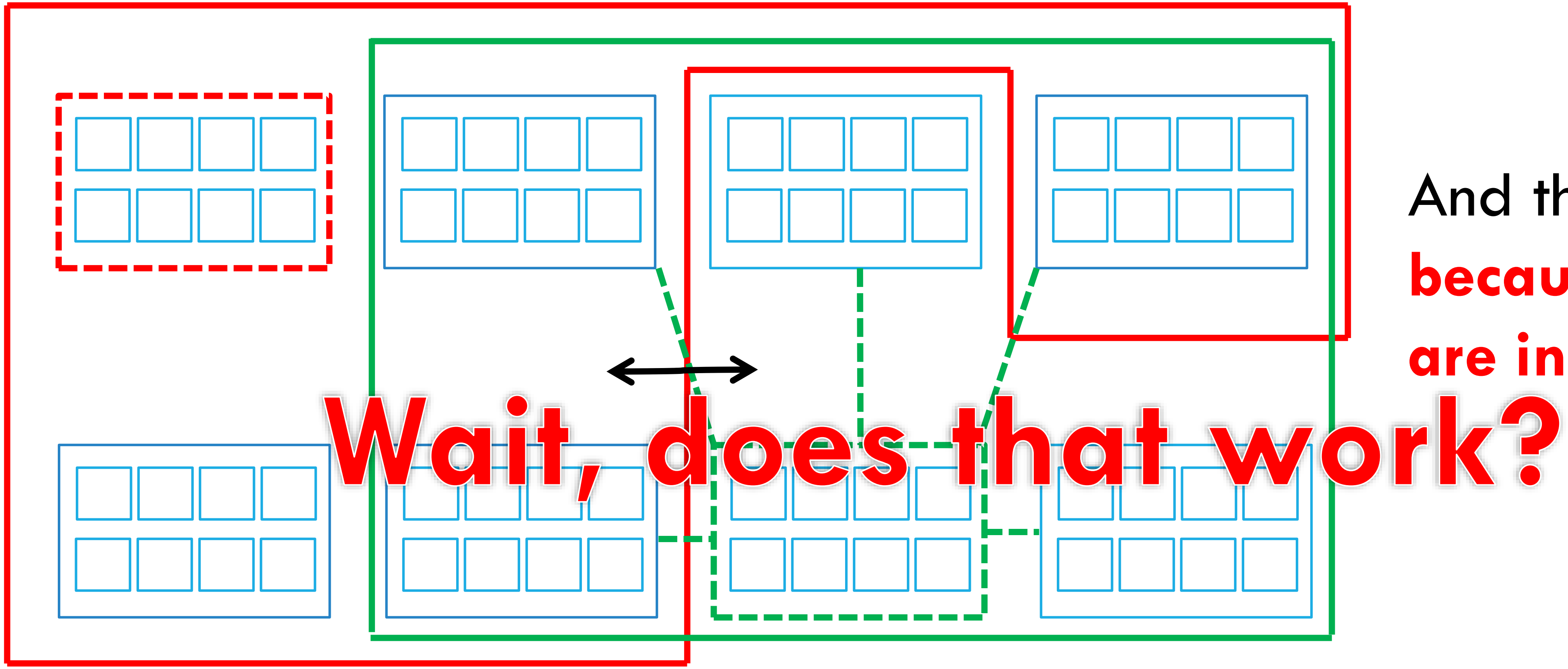
BUG 2/4: SCHEDULING GROUP CONSTRUCTION



Groups of CPUs built by:

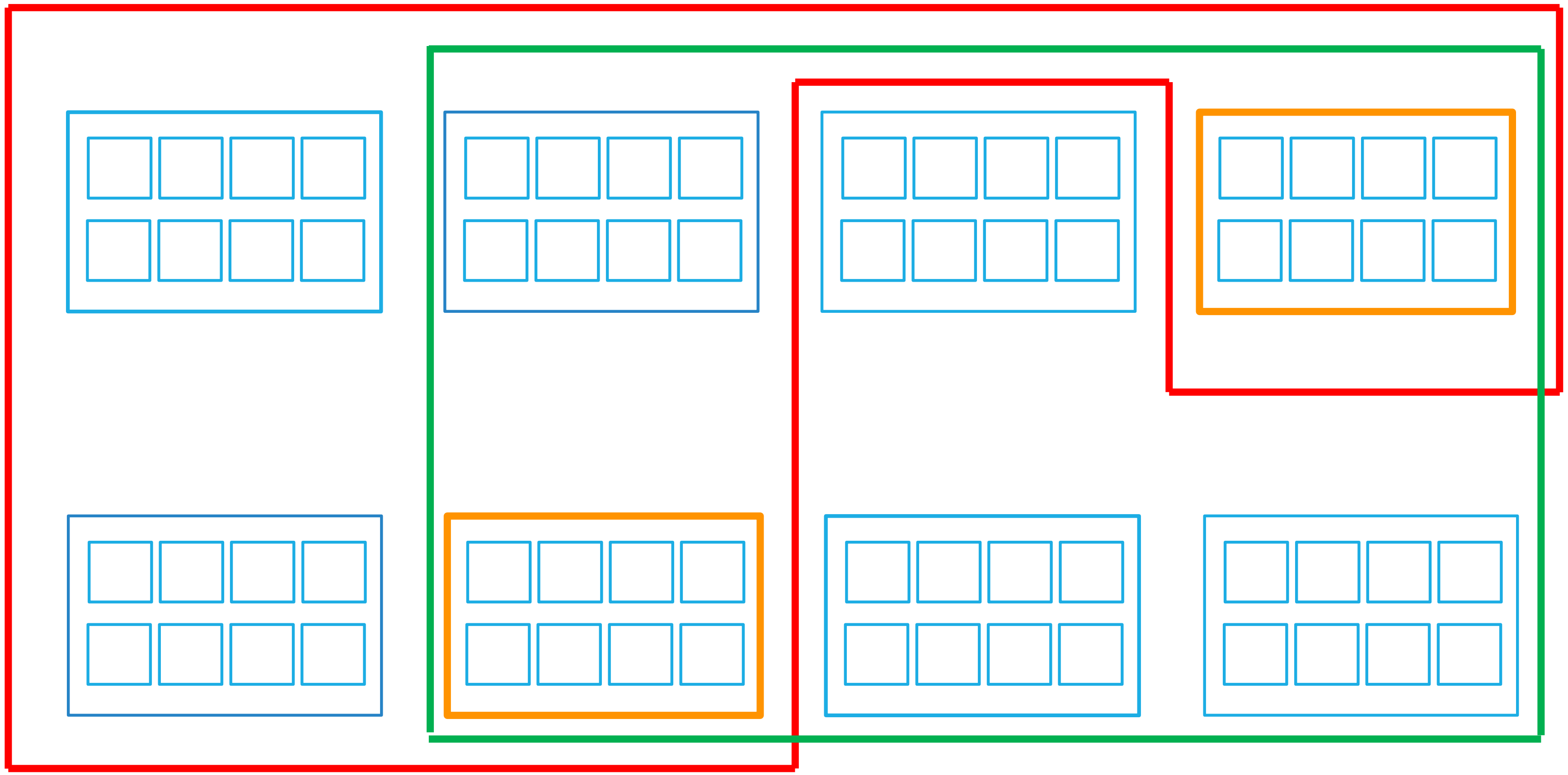
(2) picking first CPU not in a group and looking for all directly connected CPUs

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



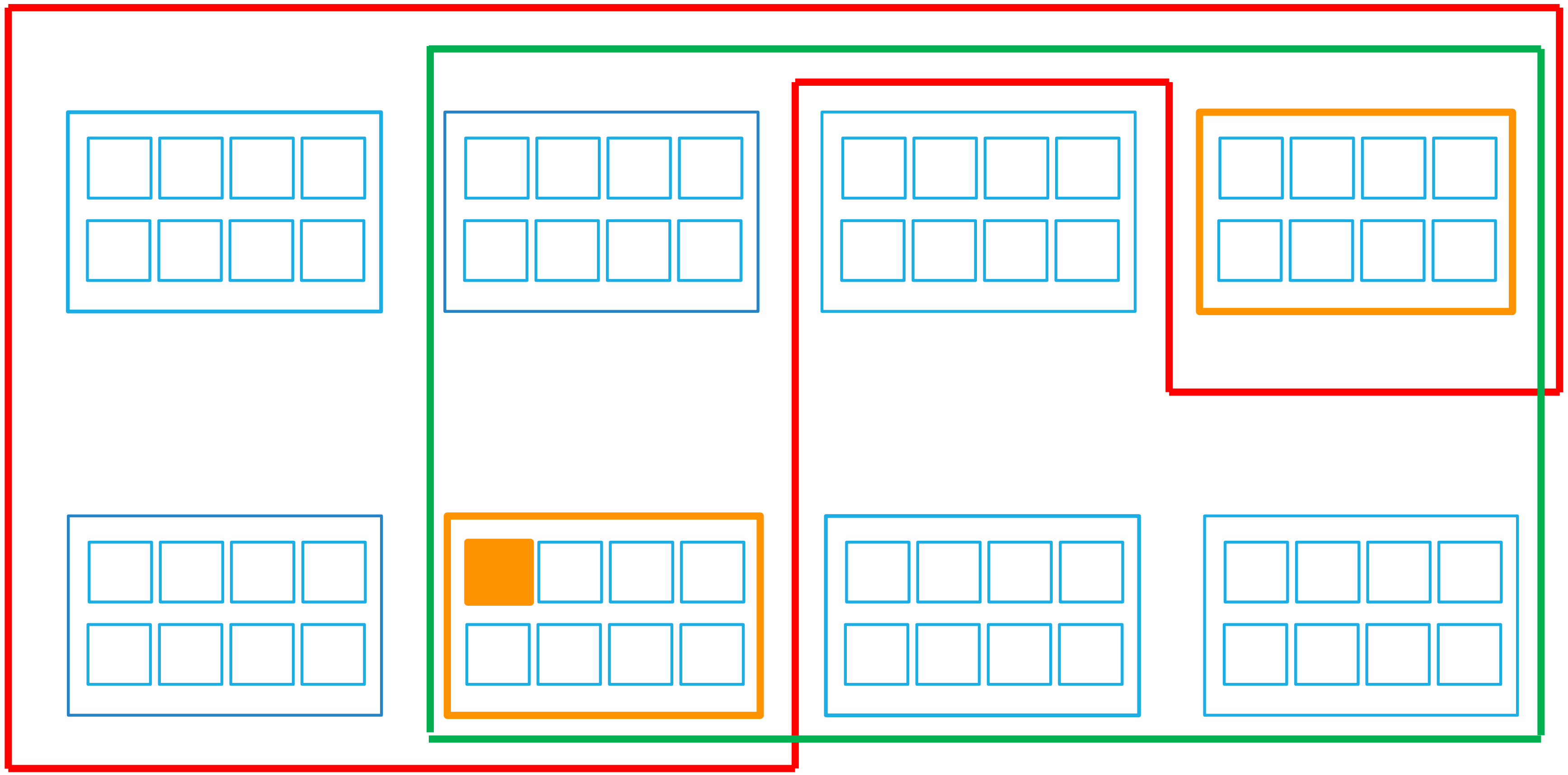
And then stop,
because all CPUs are in a group

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



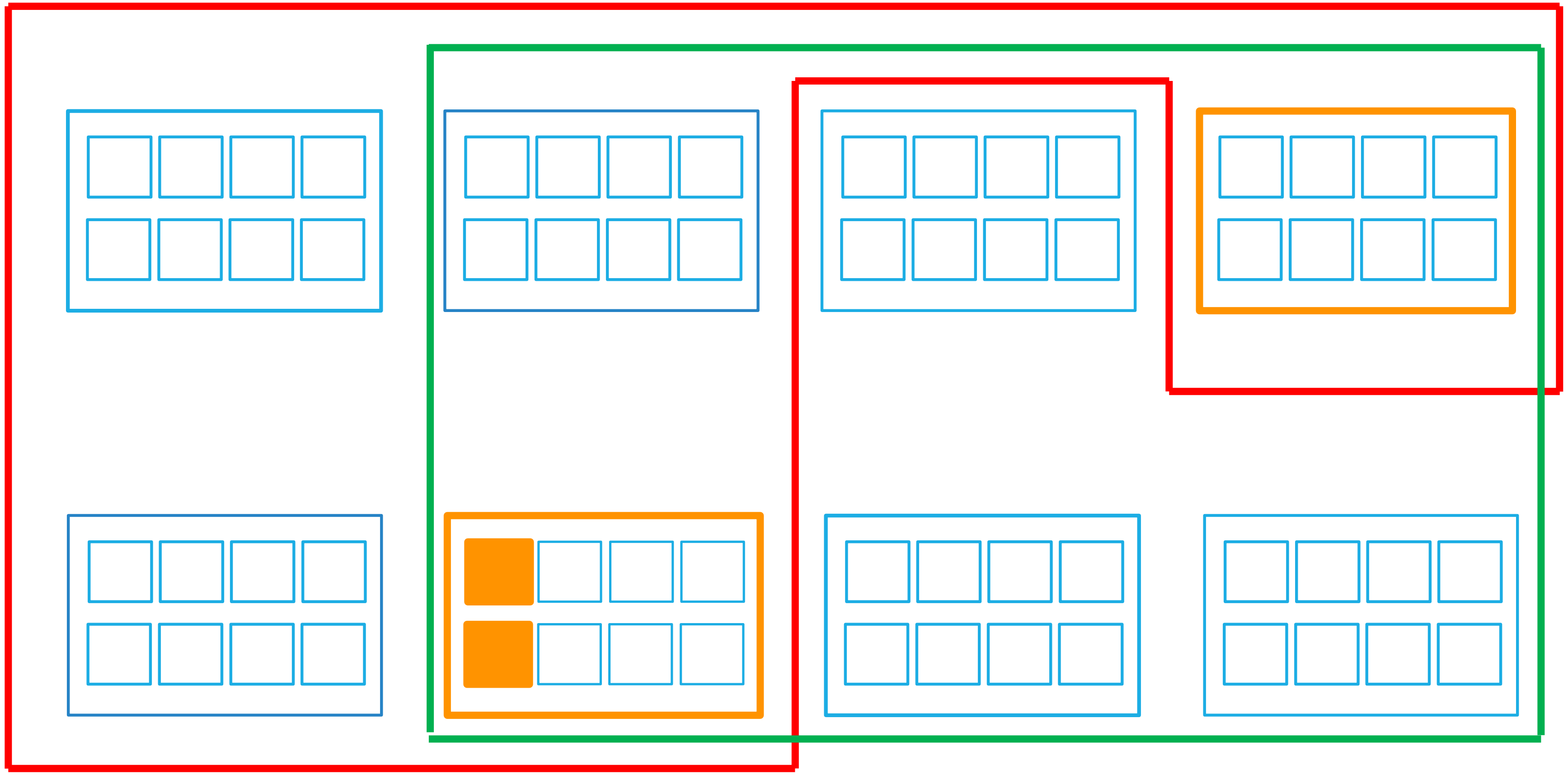
Suppose we taskset an application on **these two CPUs,** two hops apart (16 threads)

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



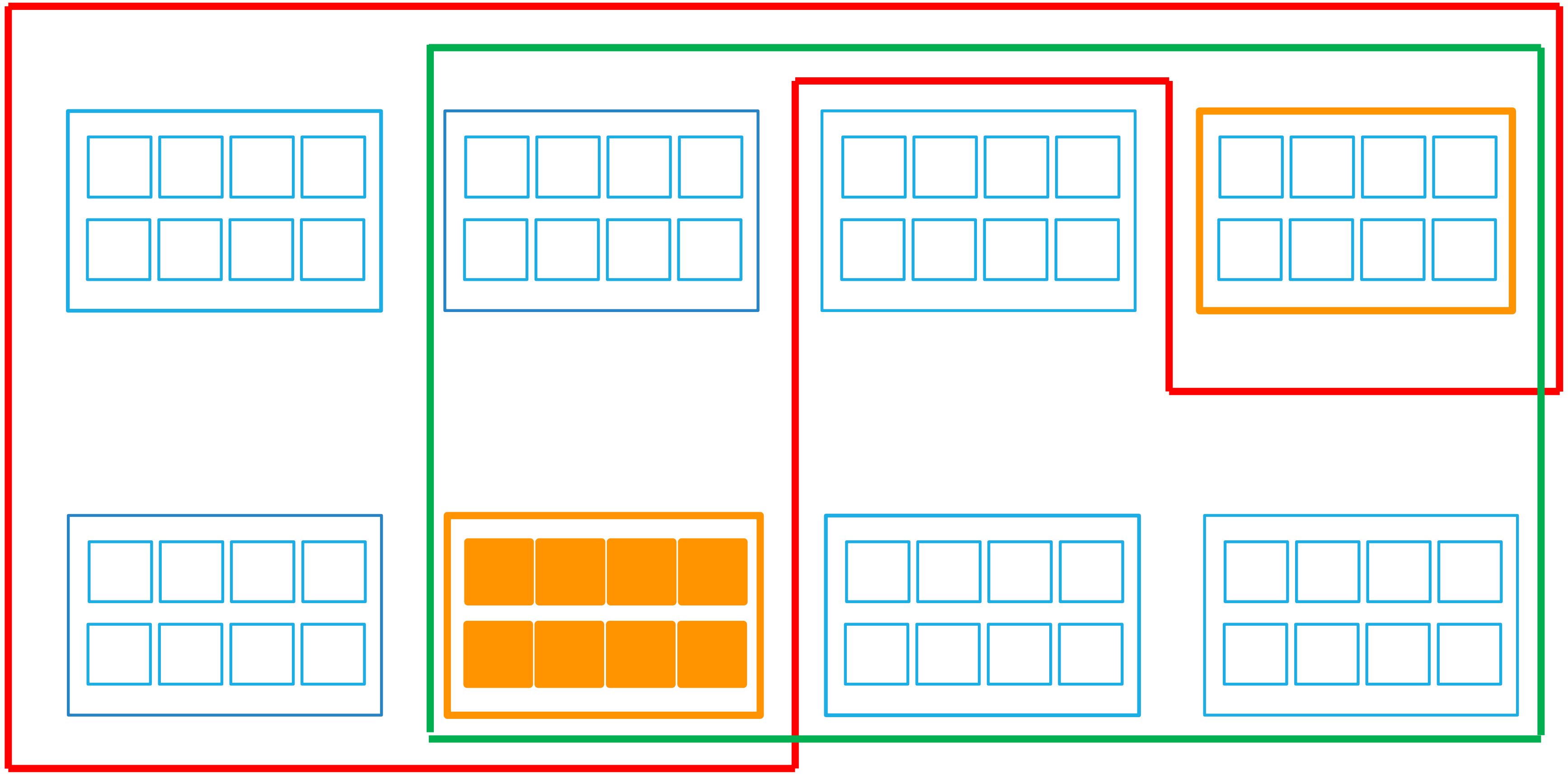
And threads are created **on this core**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



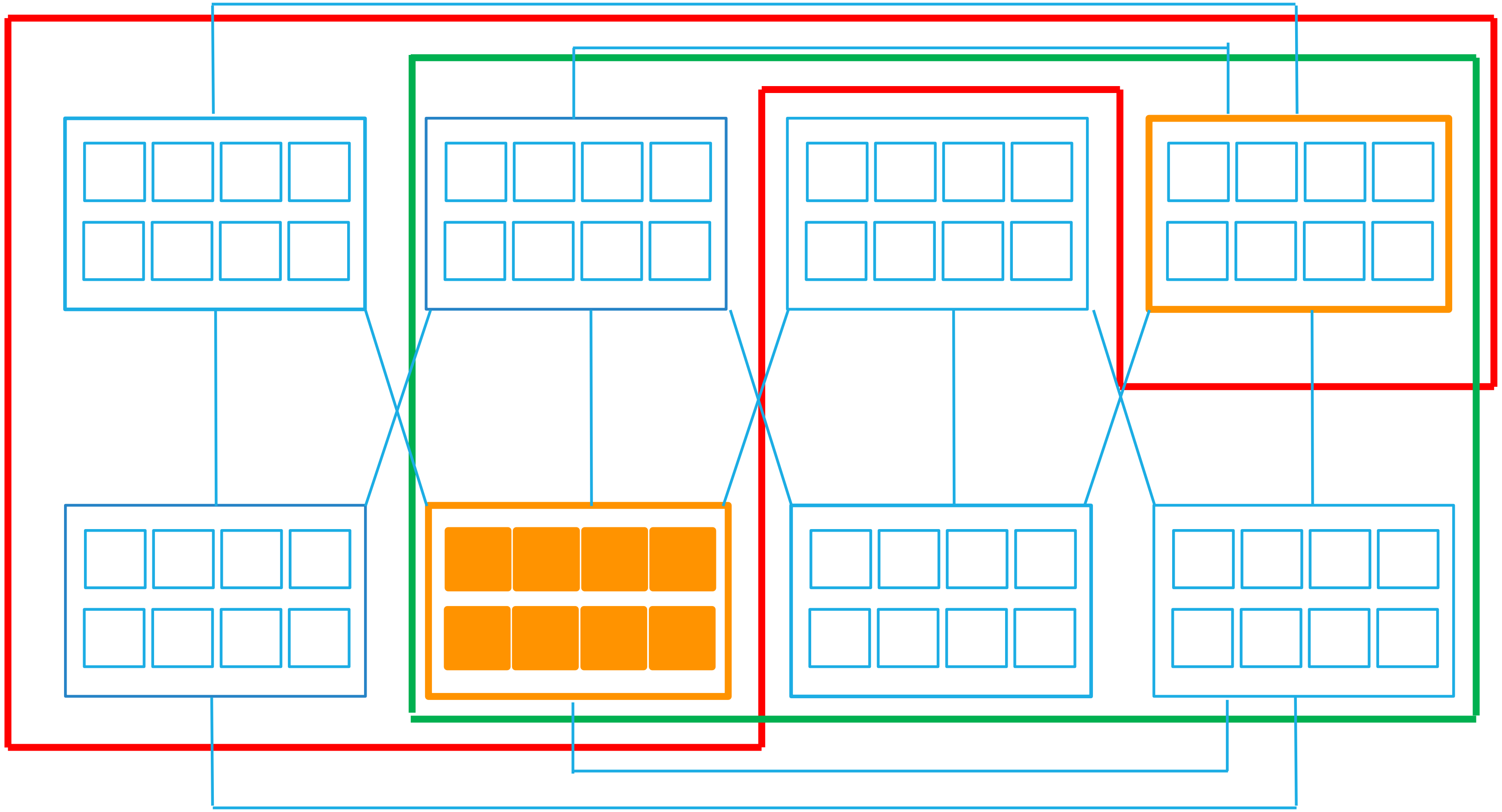
Load gets correctly balanced **on the pair of cores**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



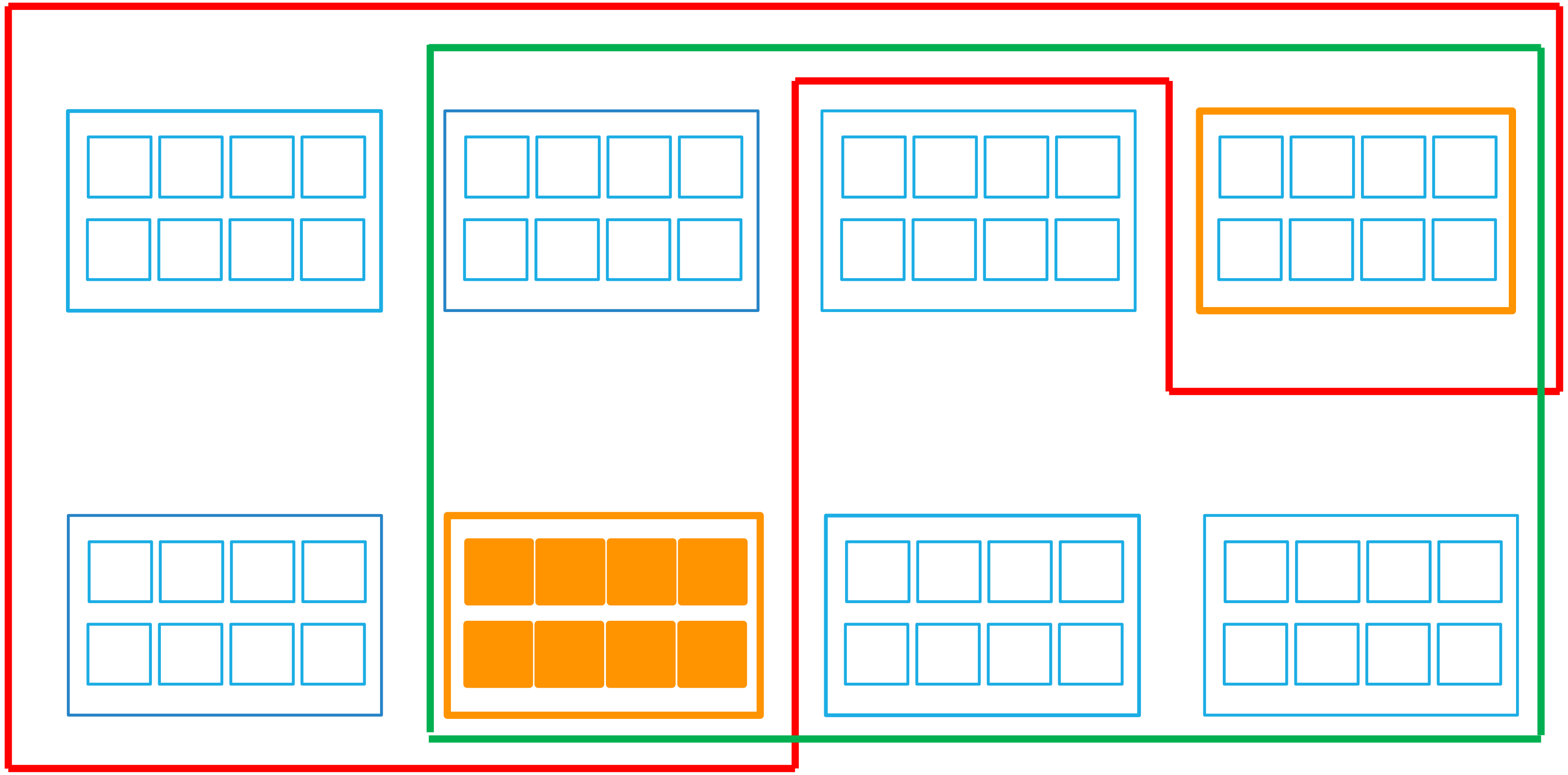
Load gets correctly balanced **on the CPU**

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

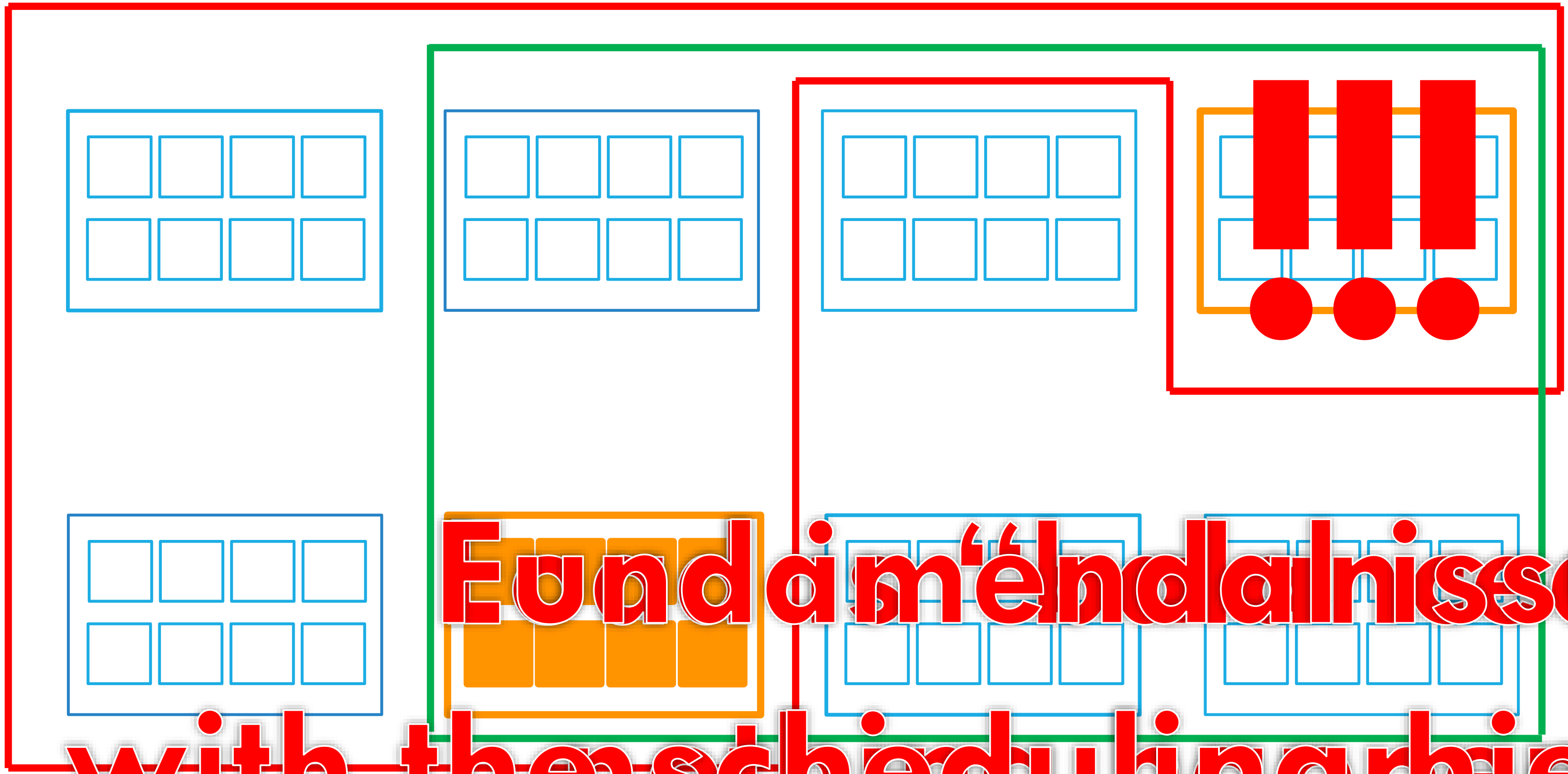
BUG 2/4: SCHEDULING GROUP CONSTRUCTION



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

Overloaded node in both groups!

BUG 2/4: SCHEDULING GROUP CONSTRUCTION



load(red) =
16 * load(thread)

load(green) =
16 * load(thread)

Fundamental issue:
with the scheduling hierarchy !

BUG 2/4: SCHEDULING GROUP CONSTRUCTION

- **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
- Performance improvement of NAS applications on two nodes :

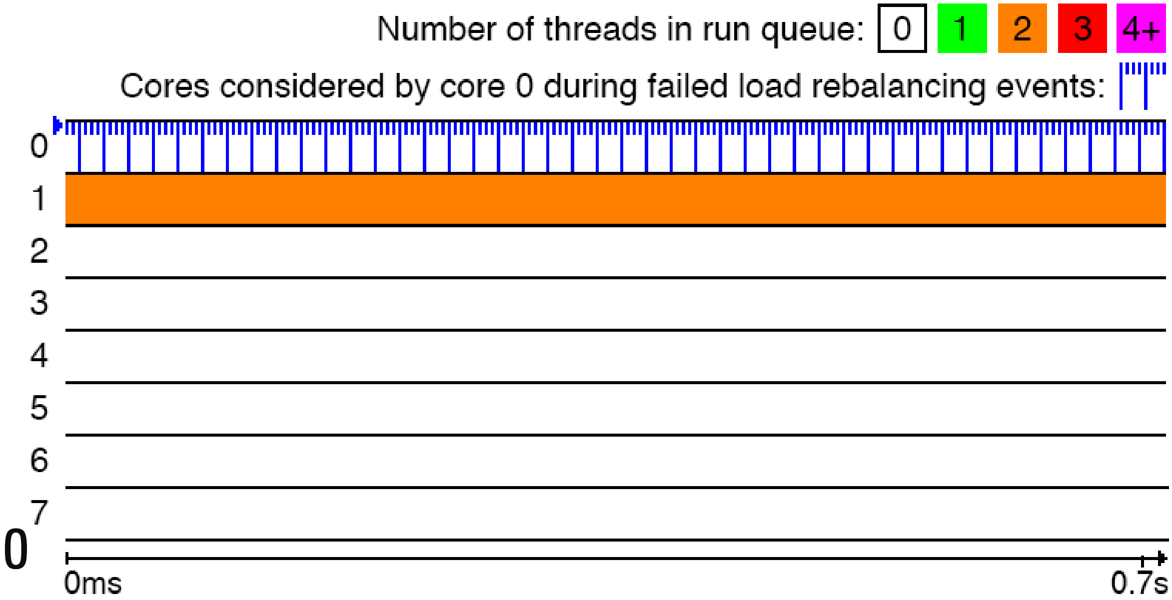
Application	With bug	After fix	Improvement
BT	99	56	1.75x
CG	42	15	2.73x
EP	73	36	2x
LU	1040	38	27x

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

BUG 3/4: MISSING SCHEDULING DOMAINS

- **In addition to this, when domains re-built, levels 3 and 4 not re-built...**
  - I.e., no balancing between directly connected or 1-hop CPUs (i.e. any CPU)
  - Happens for instance when disabling and re-enabling a core
- **Launch an application, first thread created on CPU 1**
  - First thread will stay on CPU 1, next threads will be created on CPU 1 (default Linux)
  - All the threads will be on CPU 1 forever!

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



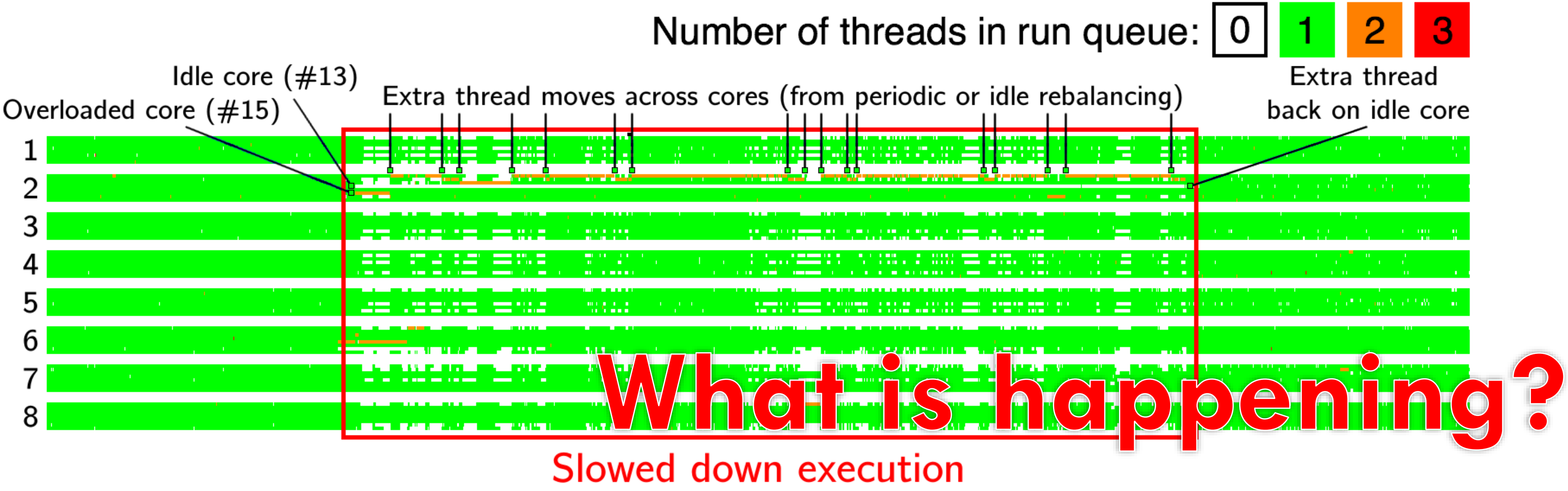
BUG 4/4: OVERLOAD-ON-WAKEUP

- **Until now, we analyzed the behavior of the the periodic, (buggy) hierarchical load balancing that uses (buggy) scheduling domains**
- **But there is another way load is balanced:** threads get to pick on which core they get woken up when they are done blocking (after a lock acquisition, an I/O)…
- **Here is how it works:** when a thread wakes up, it looks for non-busy cores on the same CPU in order to decide on which core it should wake up.
- **Only cores that are on the same CPU, in order to improve data locality…**

Wait, does that work?

BUG 4/4: OVERLOAD-ON-WAKEUP

- **Commercial DB with TPC-H, 64 threads on 64 cores, nothing else on the machine.**
- With threads pinned to cores, works fine. **With Linux scheduling, execution much slower, phases with overloaded cores while there are long-term idle cores!**



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%)

- Begin…
- Occa… ared during…
- **Now,** … ws down all exe… ywhere…
- **Barri… up on idle core, because waking up algorithm only considers local CPU!**
- **Periodic rebalancing can't rebalance load most of the time because many idle cores**
  ⇒ Hard to see an imbalance between 9-thread and 7-thread CPU…
- **"Solution":** wake up on core idle for the longest time (not great for energy)

WHERE DO WE GO FROM HERE?

- Load balancing on a multicore machine usually considered a solved problem
- **To recap, on Linux, load balancing works that way:**
  - Hierarchical rebalancing uses a metric named ***load,***

  ↑ **Found fundamental issue here**
  - to periodically balance threads between ***scheduling domains.***

  ↑ **Found fundamental issue here**
  - In addition to this, threads balance load by ***selecting core where to wake up.***

  ↑ **Found fundamental issue here**

Wait, was anything working at all? ☺

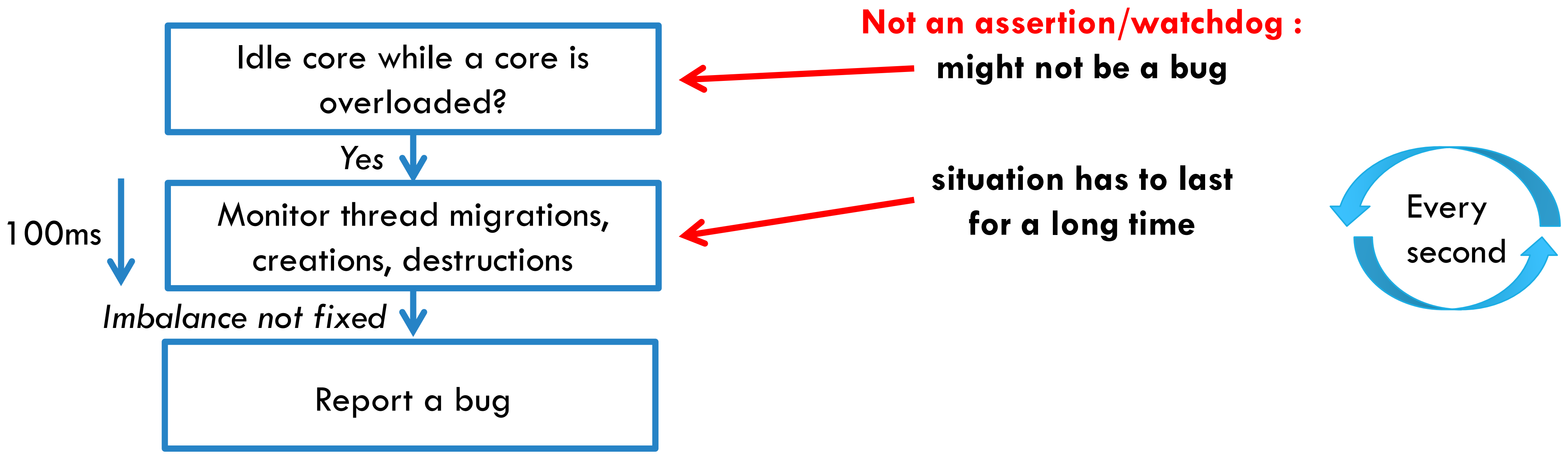
WHERE DO WE GO FROM HERE?

Many major issues went unnoticed for years in the scheduler…
How can we prevent this from happening again?

- **Code testing**
  - No clear fault (no crash, no deadlock, etc.)
  - Existing tools don't target these bugs
- **Performance regression**
  - Usually done with 1 app on a machine to avoid interactions
  - Insufficient coverage
- **Model checking, formal proofs**
  - Complex, parallel code: so far, nobody knows how to do it…

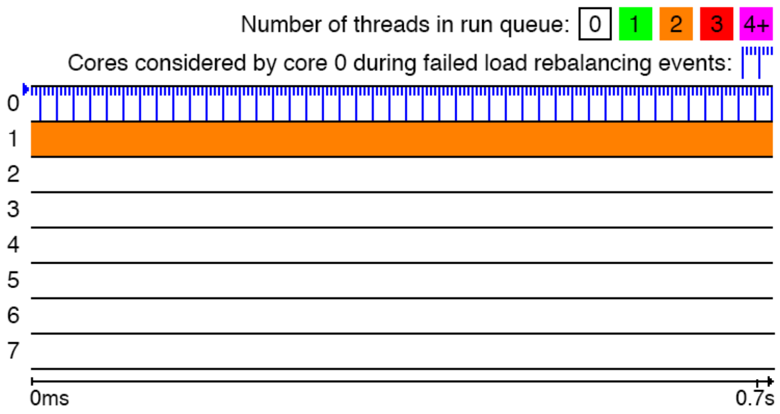
WHERE DO WE GO FROM HERE?

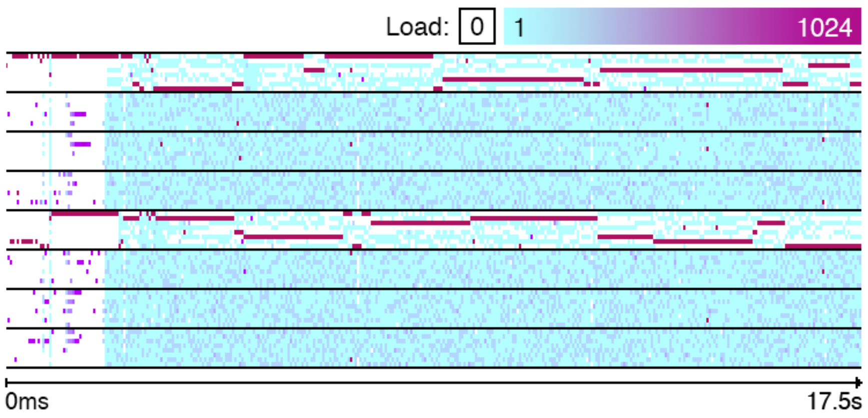
- **Idea 1:** short-term hack — implemented a sanity checker



WHERE DO WE GO FROM HERE?

- **Idea 2:** fine-grained tracers!
  - Built a simple one, turned out to be the only way to really understand what happens
  - Aggregate metrics (CPI, cache misses, etc.) not precise enough





  - **Could really be improved!**

WHERE DO WE GO FROM HERE?

- **Idea 3:** produce a dedicated profiler!
  - Lack of tools!

  - Possible to detect if slowdown comes from scheduler or application?
  - Would avoid a lot of wasted time!

  - Follow threads, and see if often on overloaded cores when shouldn't have?
  - Detect if threads unnecessarily moved to core/node that leads to many cache misses?

WHERE DO WE GO FROM HERE?

- **Idea 4:** produce good scheduler benchmarks!
  - Really needed, and virtually inexistent!

  - **Not an easy problem:** insane coverage needed!
  - **Using combination of many real applications:** configuration nightmare!

  - Simulated workloads?
    - Have to do **elaborate work:** spinning and sleeping not efficient
    - Have to be **representative of reality**, have to **cover corner cases**
      - *Use machine learning? Genetic algorithms?*

WHERE DO WE GO FROM HERE?

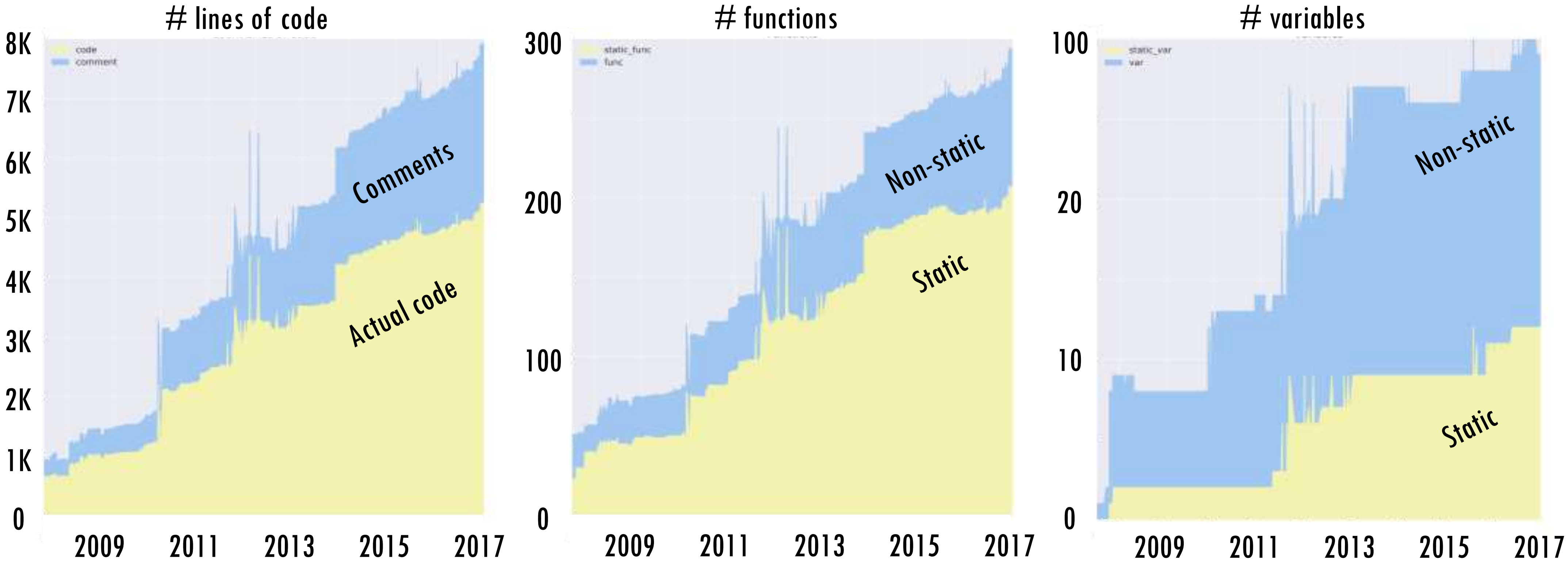
- **Idea 5:** switch to simpler schedulers, easier to reason about!

Let's take a step back: *why* did we end up in this situation?

- Linux used for many classes of applications (big data, n-tier, cloud, interactive, DB, HPC…)
- Multicore architectures increasingly diverse and complex!
- **Result:** very complex monolithic scheduler supposed to work in all situations!
  - Many heuristics interact in complex, unpredictable ways
  - Some features greatly complexify, e.g., load balancing (tasksets, cgroups/autogroups…)
- Keeps getting worse!
  - **E.g., task_struct:** 163 fields in Linux 3.0 (07/2011), 215 fields in 4.6 (05/2016)
  - **20,000 lines of C!**

WHERE DO WE GO FROM HERE?

- **Idea 5:** switch to simpler schedulers, easier to reason about!



WHERE DO WE GO FROM HERE?

- **Idea 5:** switch to simpler schedulers, easier to reason about!

- **Proving the scheduler implementation correct: not doable!**
  - Way too much code for current technology
  - We'd need to detect high-level abstractions from low-level C: a challenge!
  - Even if we managed that, how do we keep up with updates?
    - *Code keeps evolving with new architectures and application needs…*

  - *We need another approach…*

WHERE DO WE GO FROM HERE?

Towards Proving Optimistic Multicore Schedulers

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WiP!

- **Idea 5:** switch to simpler schedulers, easier to reason about!
- **Write simple, schedulers with proven properties !**
  - A scheduler is tailored to a (class of) parallel application(s)
  - Specific thread election criterion, load balancing criterion, state machine with events…
  - **Machine partitioned into sets of cores that run ≠ schedulers**
  - Scheduler deployed together with (an) application(s) on a partition
- **Through a DSL, for two reasons:**
  - Much easier, safer and less bug-prone than writing low-level C kernel code !
  - Clear abstractions, possible to reason about them and prove properties
    - *Work conservation, load balancing live and in finite # or rounds, valid hierarchy…*

WHERE DO WE GO FROM HERE?

- **Idea 6: ???**
- Any other ideas?

CONCLUSION

- Scheduling (as in dividing CPU cycles among theads) was thought to be a solved problem.
- **Analysis:** fundamental issues in the load metric, scheduling domains, scheduling choices…
- Very bug-prone implementation following years of adapting to hardware
- **Can't ensure simple "invariant": no idle cores while overloaded cores**
- **Proposed fixes:** not always satisfactory
- **What can we do?** Many things to explore!

- **Our takeaway:** ***more research must be directed towards implementing efficient and reliable schedulers for multicore architectures!***

Your turn!