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SOUTENANCE D'HABILITATION À DIRIGER DES RECHERCHES

EFFICIENT TASK SCHEDULING, SYNCHRONIZATION, AND GRAPH ANALYTICS ON MULTICORE ARCHITECTURES

Jean-Pierre Lozi
Inria, Paris, France

Overview

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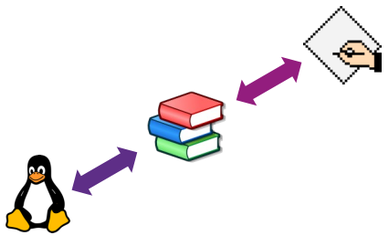

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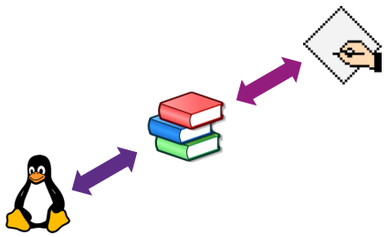
- **The hard truth:** Improving real-world software stacks is messy!
- **Bottlenecks in all layers:** In the kernel, libraries, and applications
- **No silver bullet !**
  - Some optimization techniques shared
  - But custom solutions needed for each bottleneck



Bottlenecks Across the Software Stack

Task Scheduling

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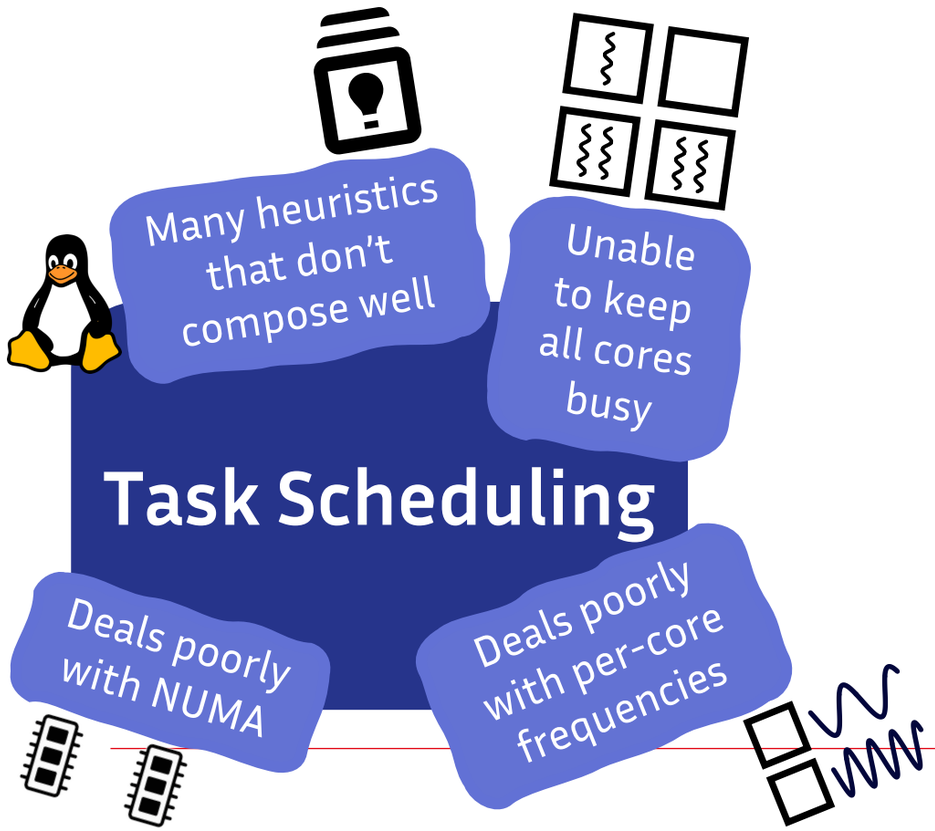

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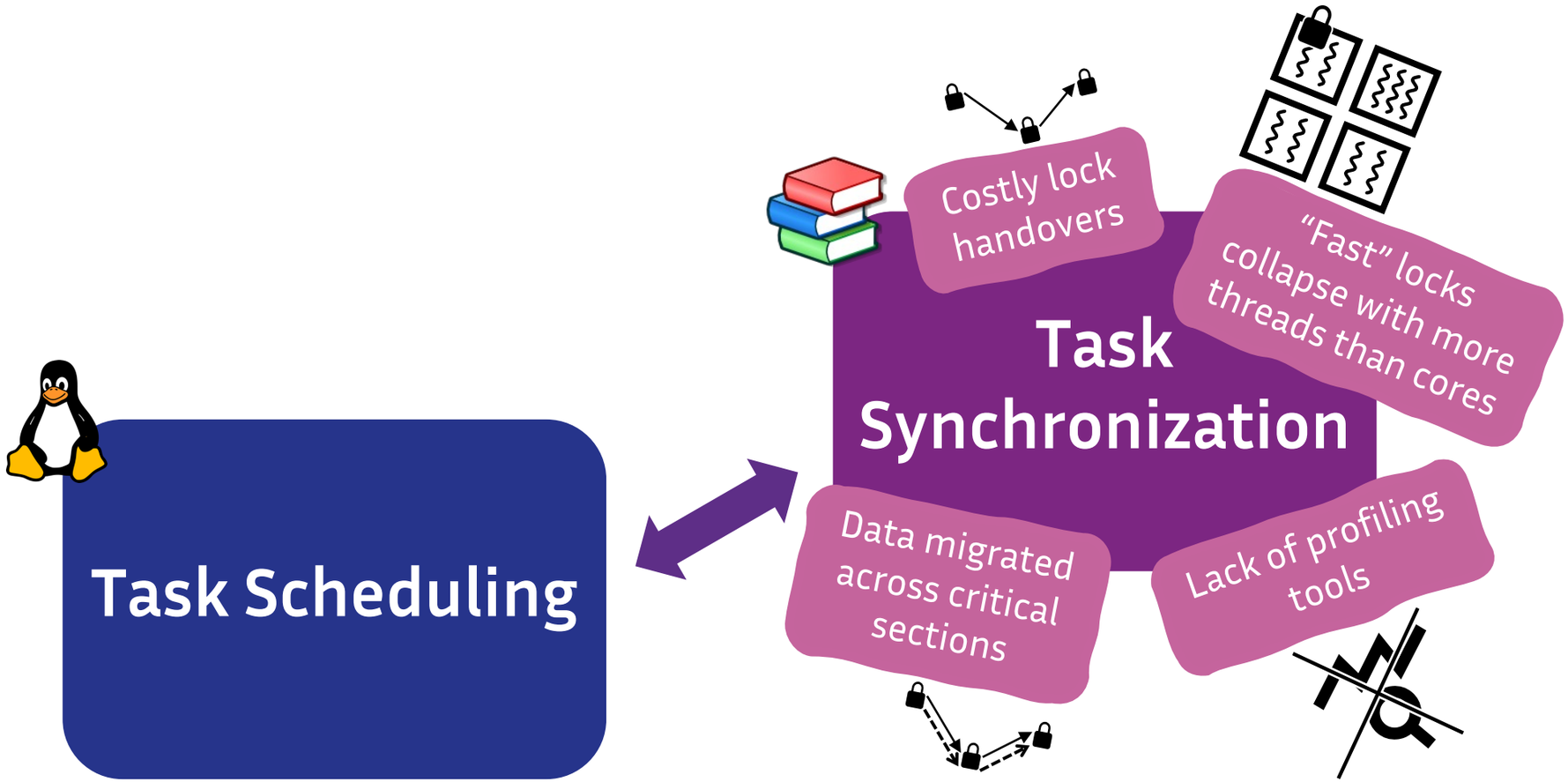

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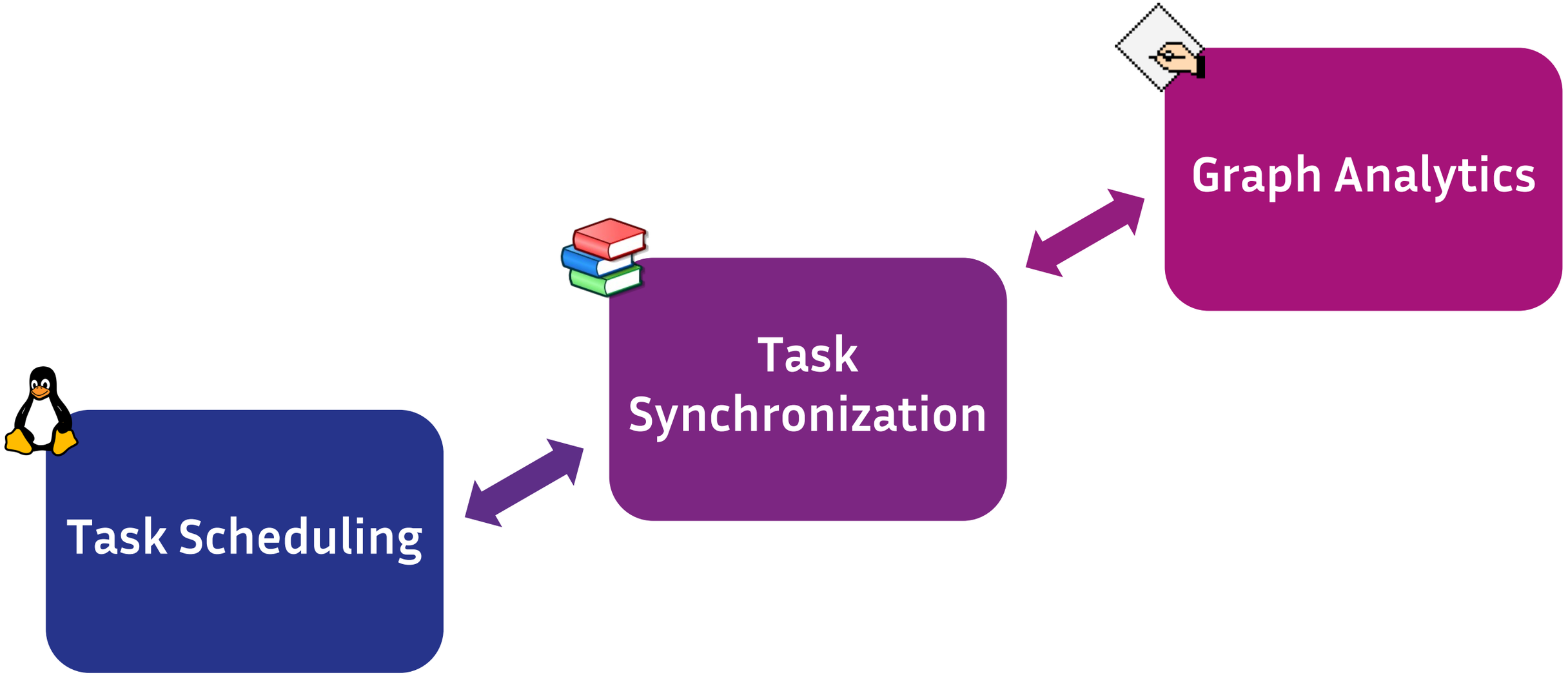

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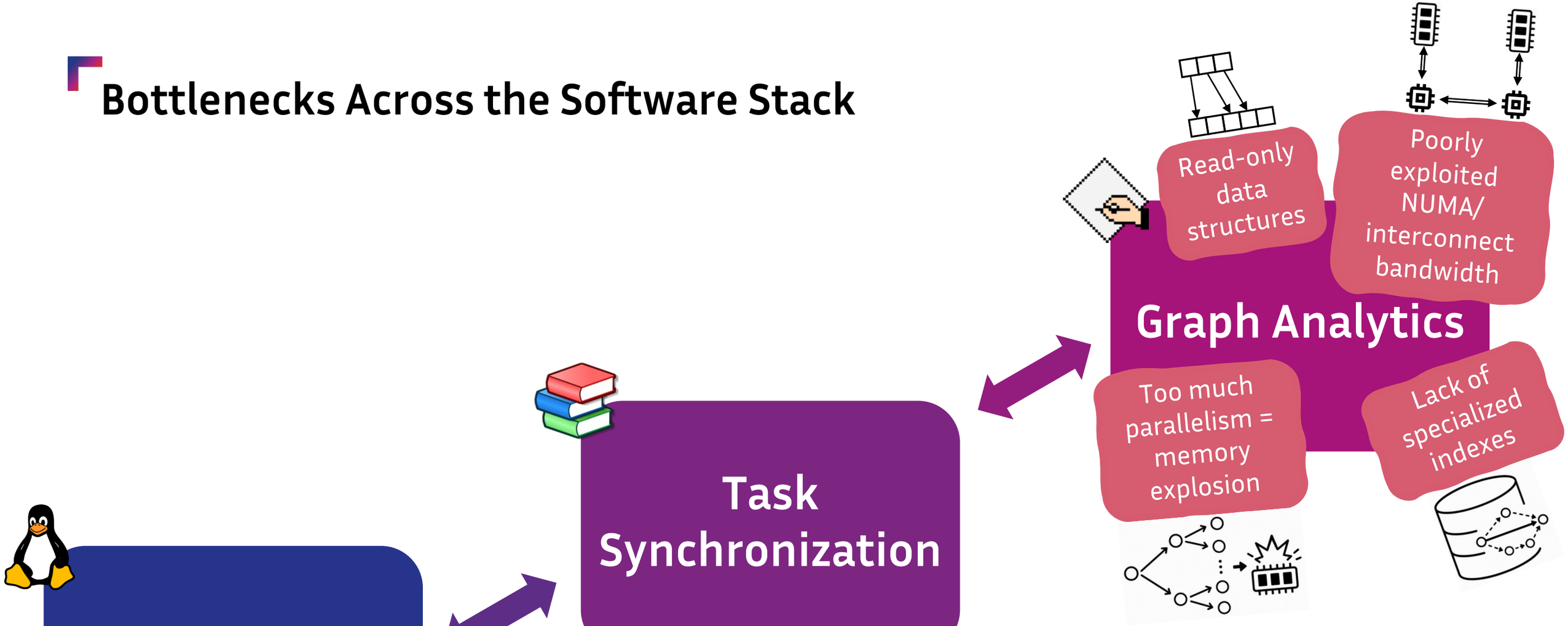

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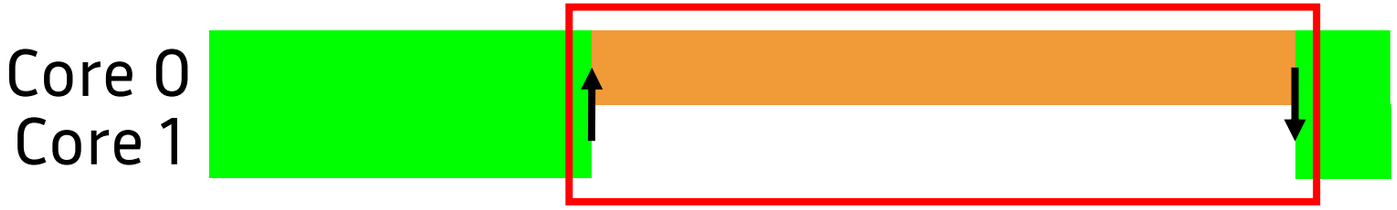

Unfortunate task migration = work conservation not maintained ☹

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  - More adjustments for new hardware (e.g., NUMA) and use cases (e.g., containers)
  - These heuristics/adjustments often don't compose well!

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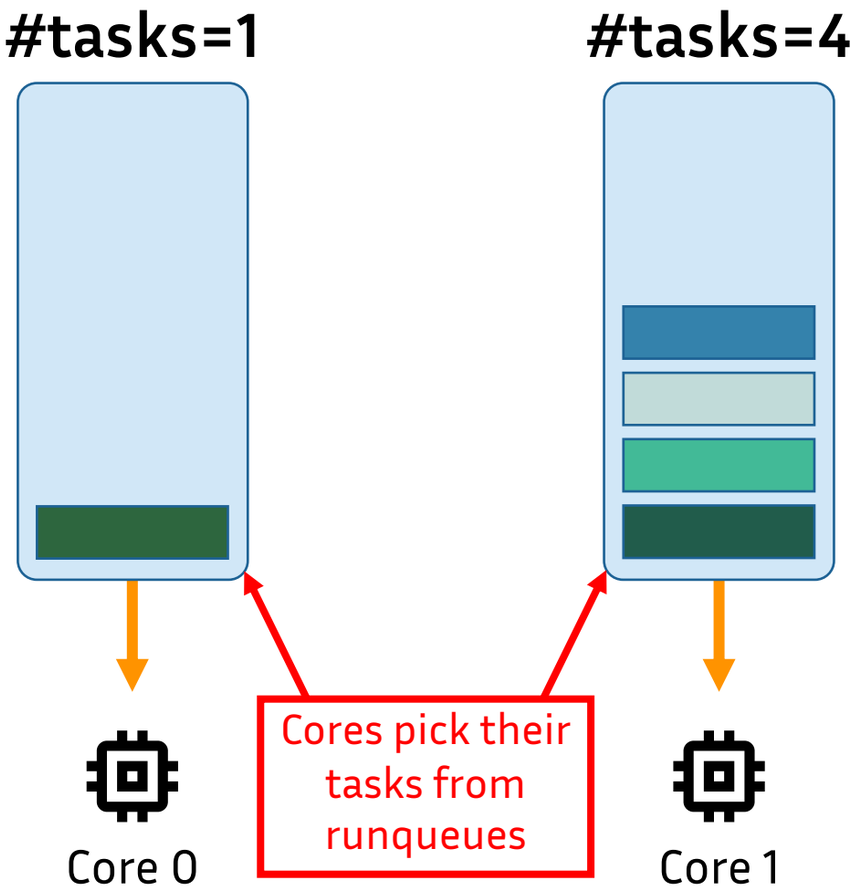
Background: Load balancing in Linux (2016, simplified)



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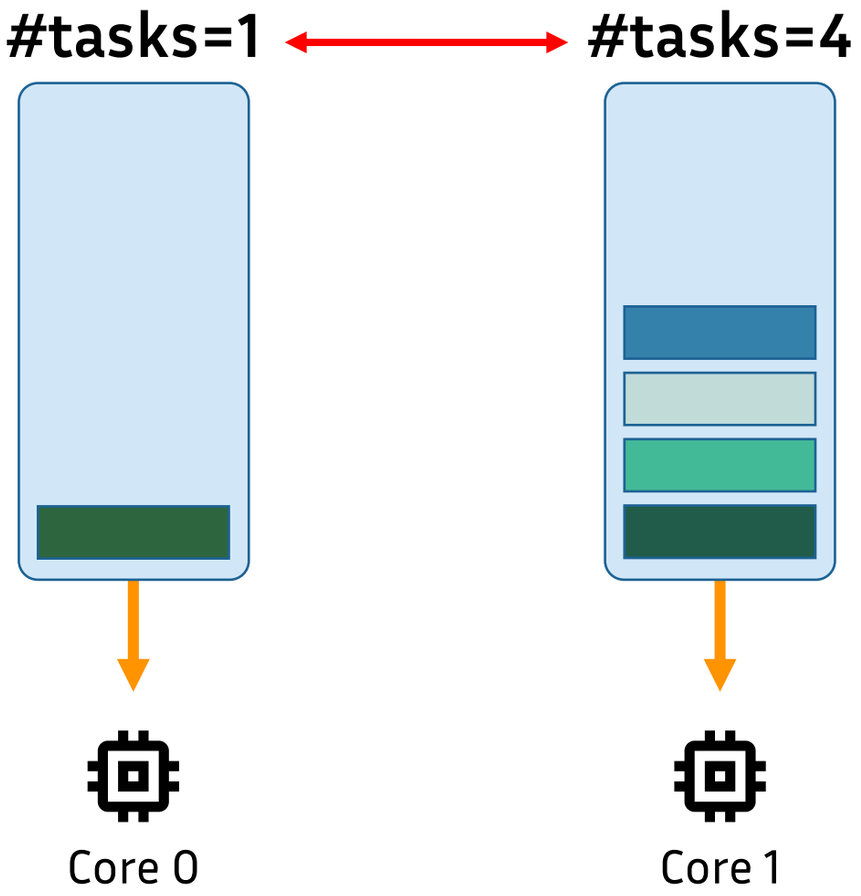

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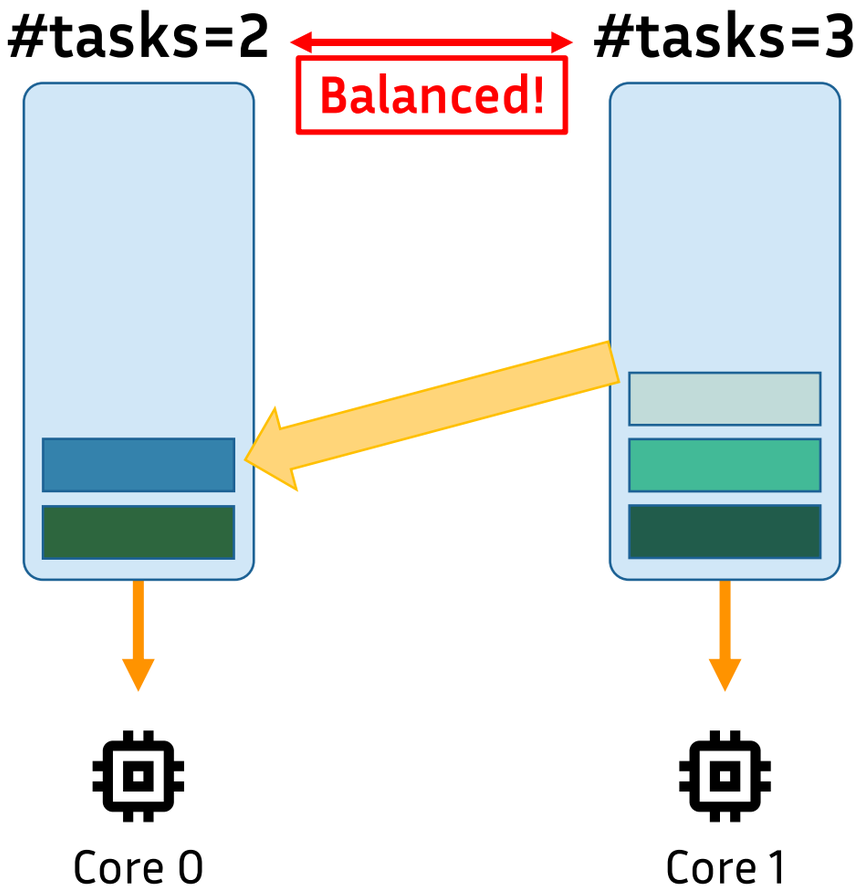

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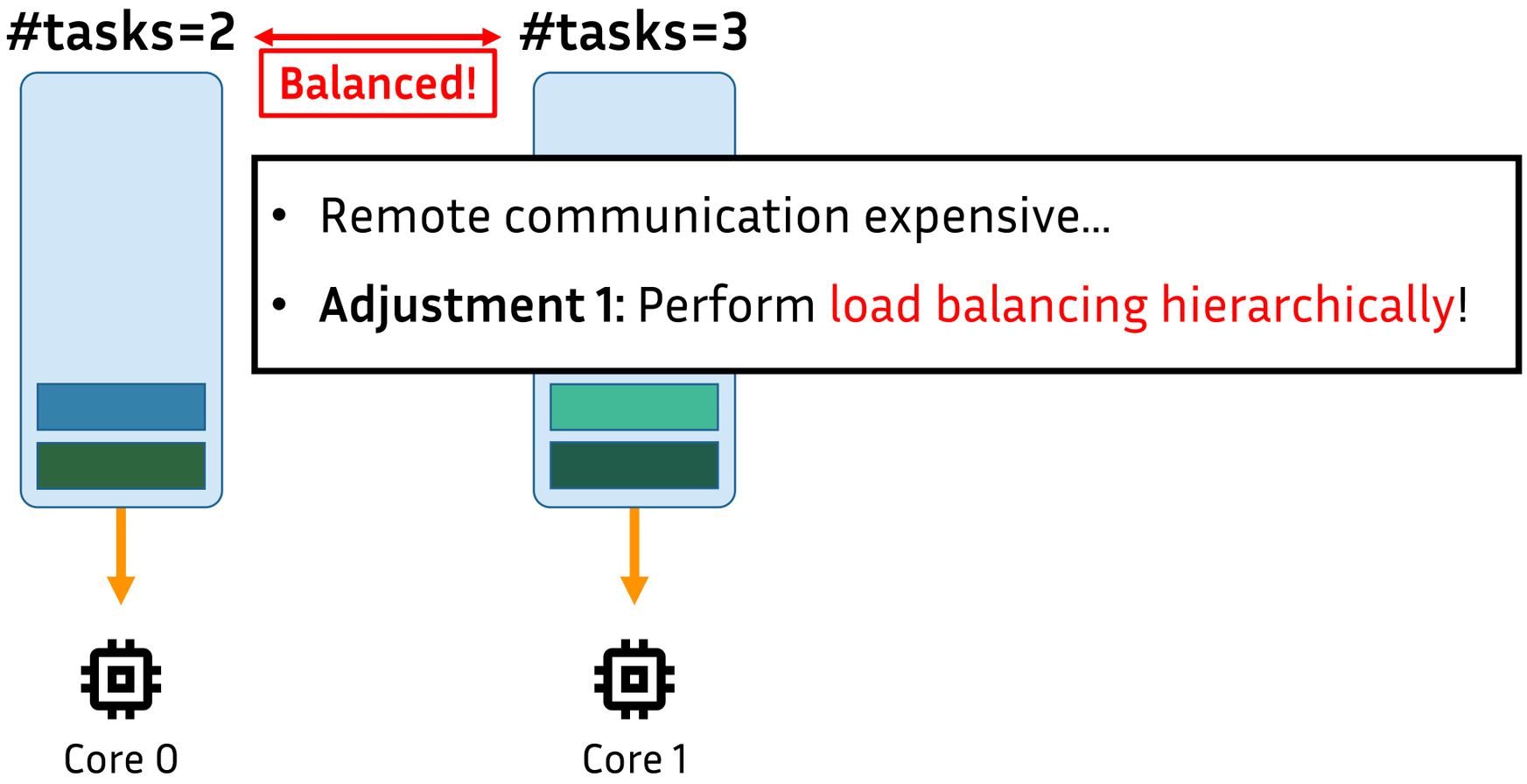

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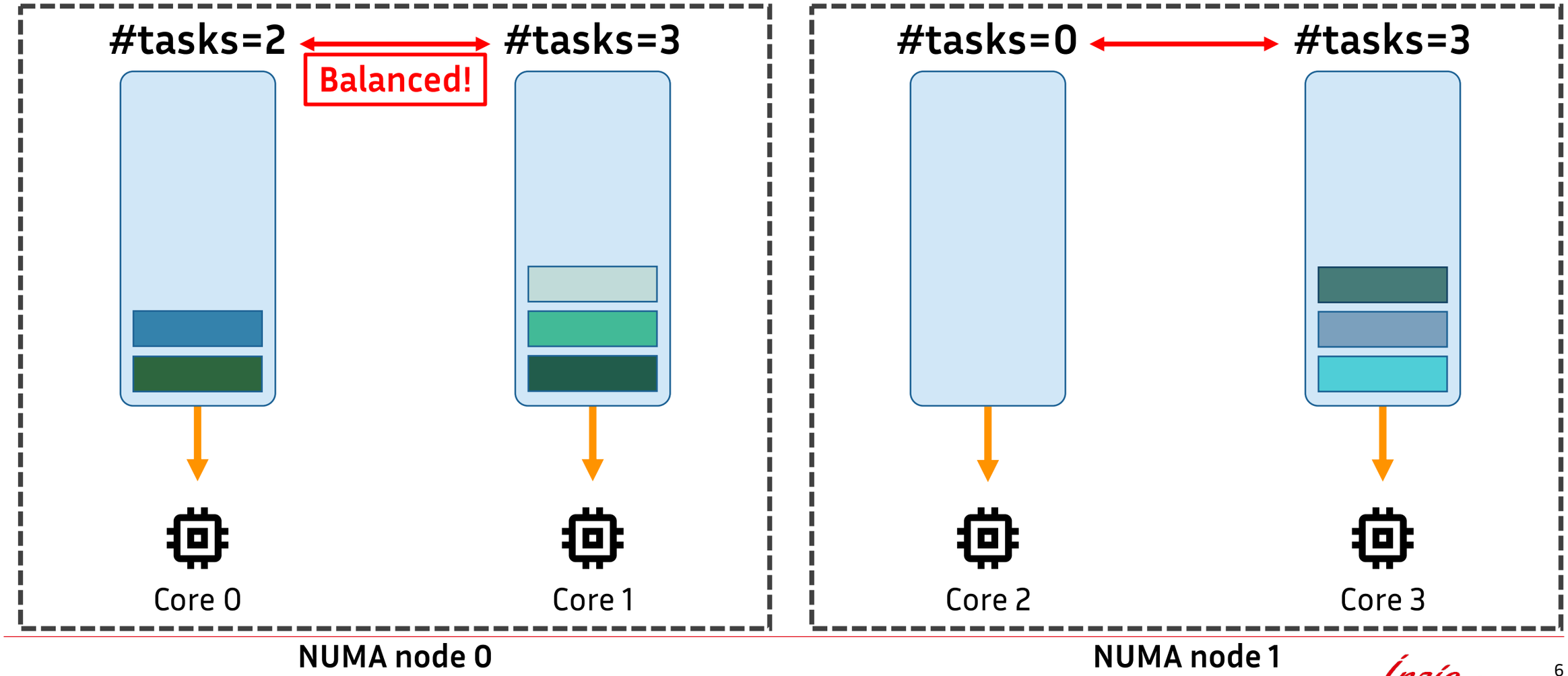

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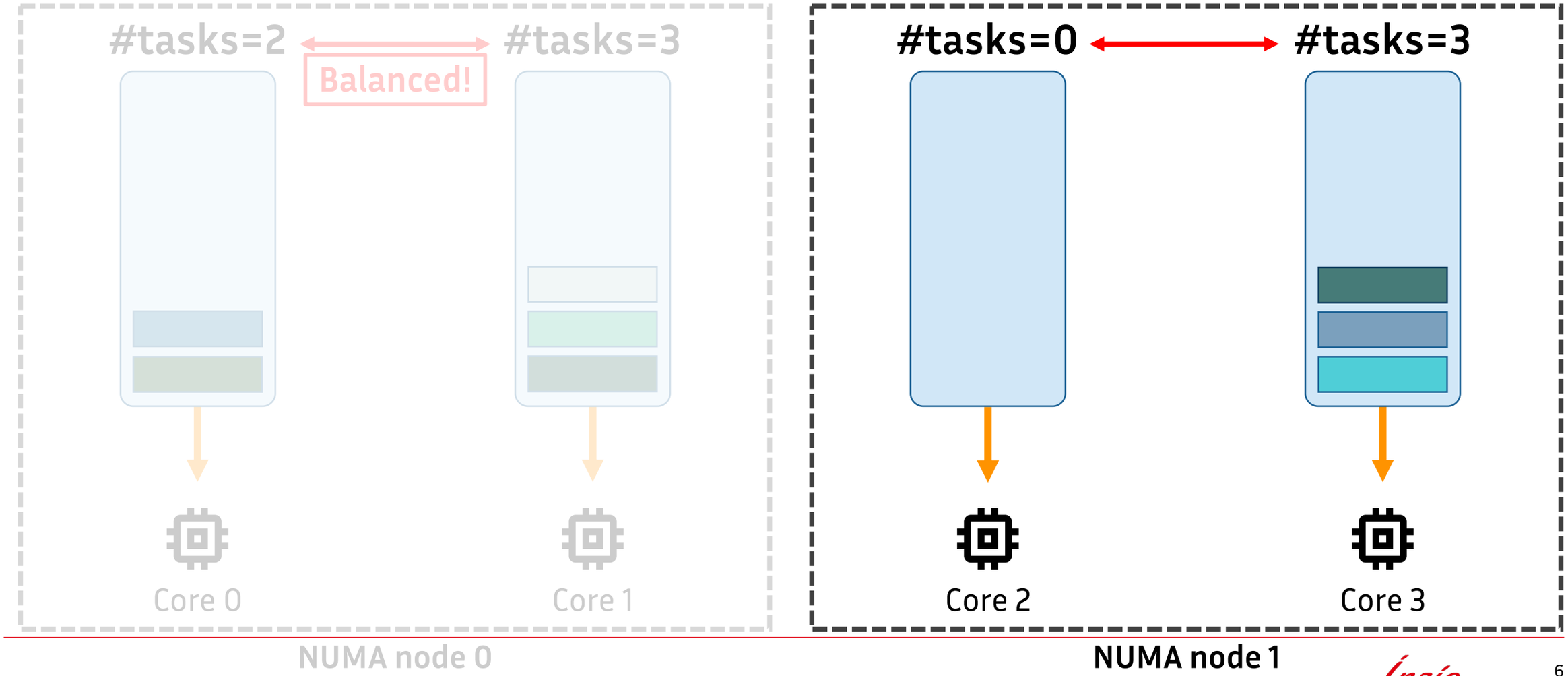

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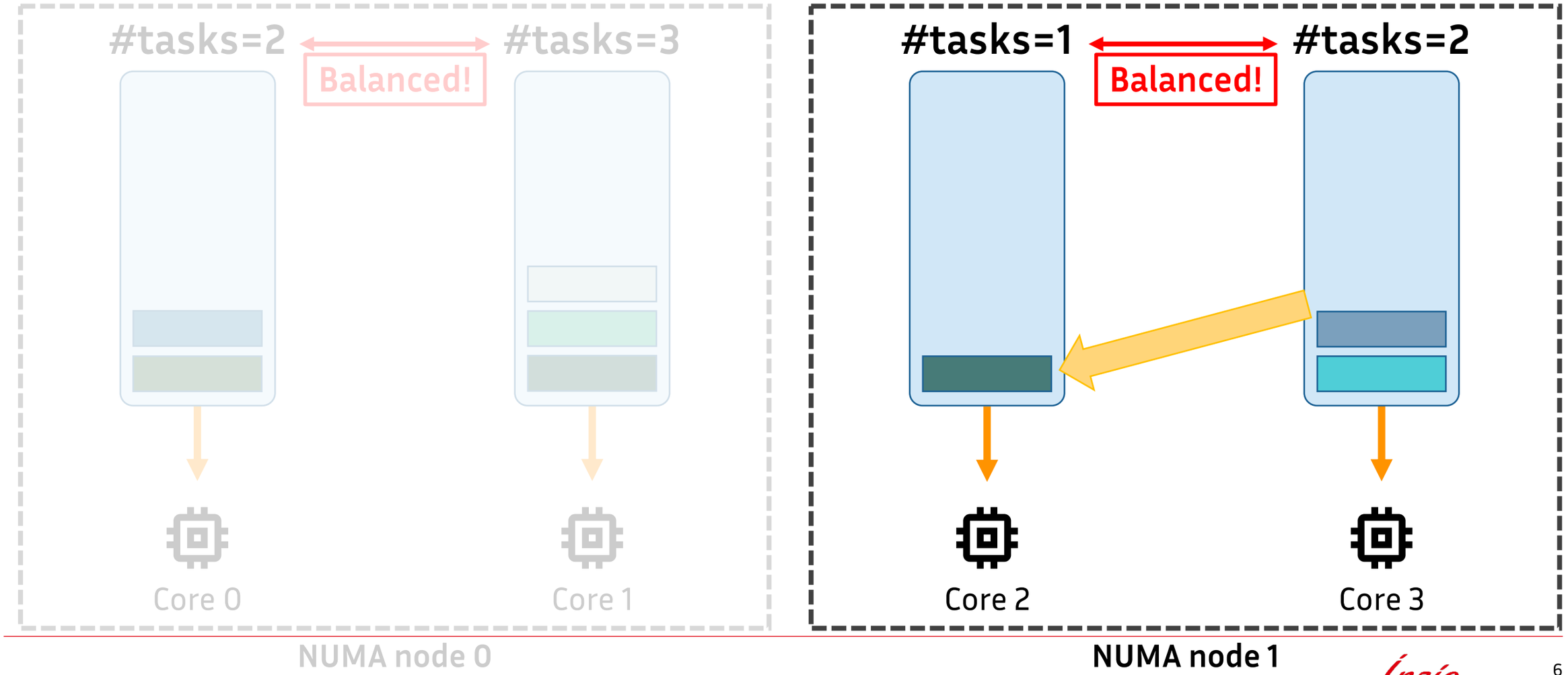

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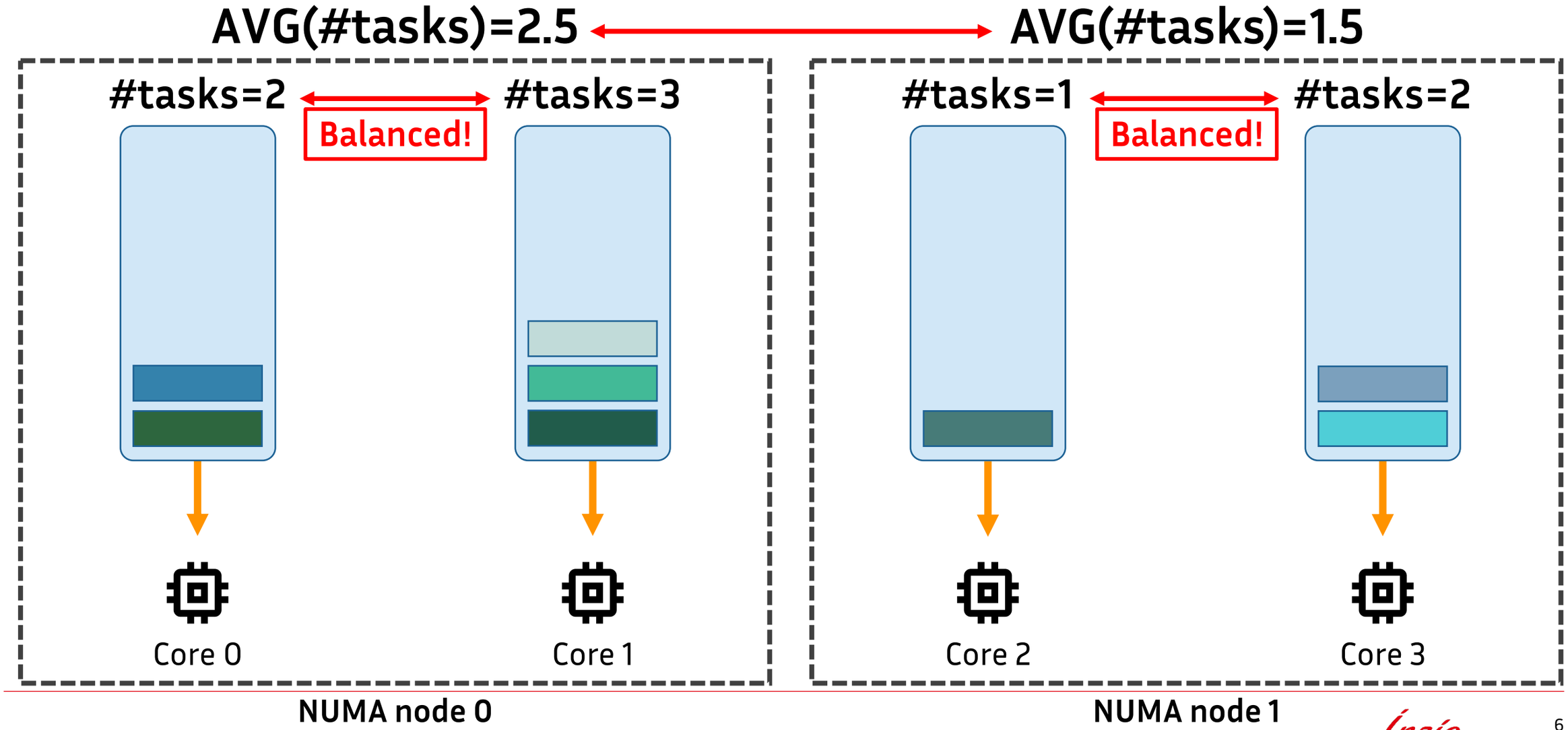

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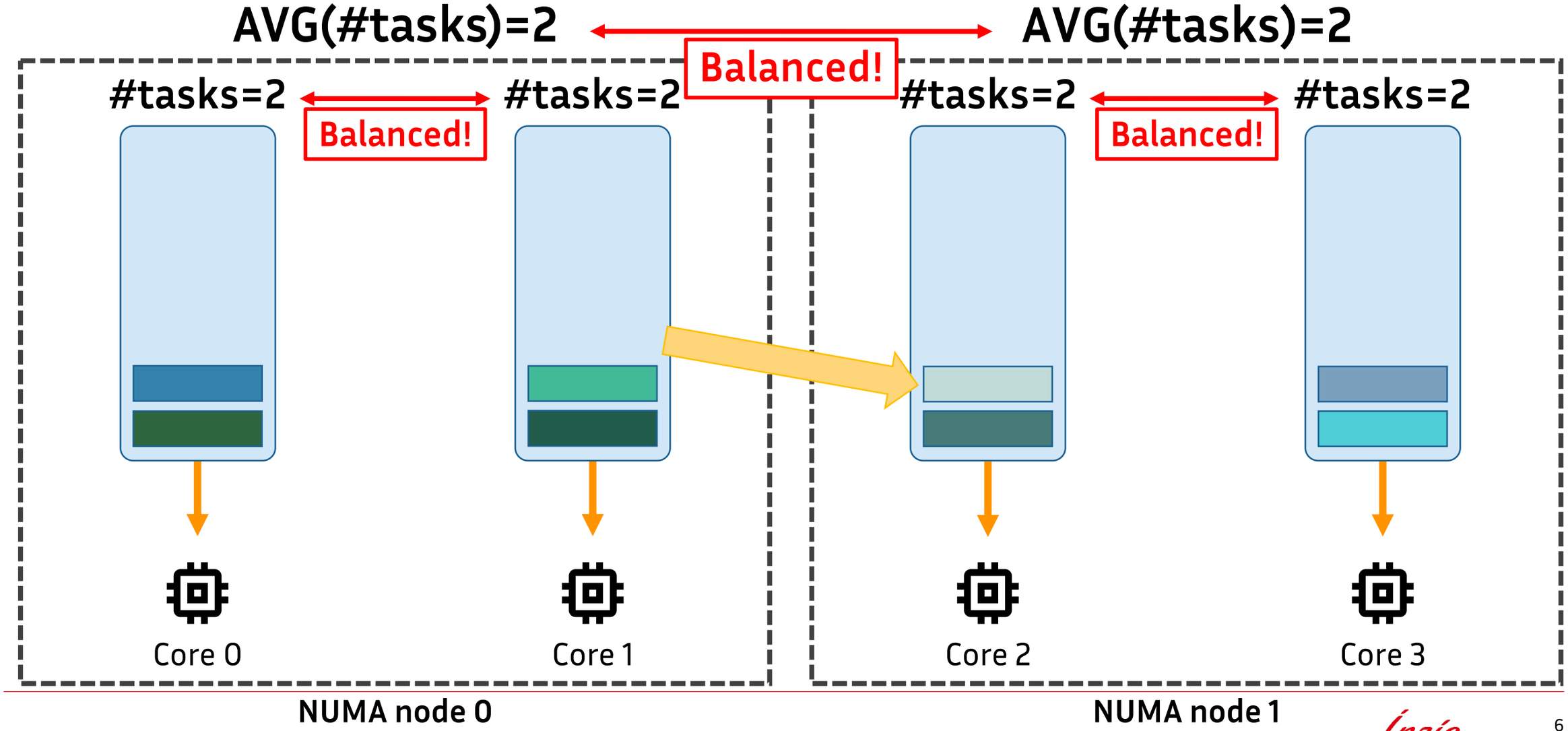

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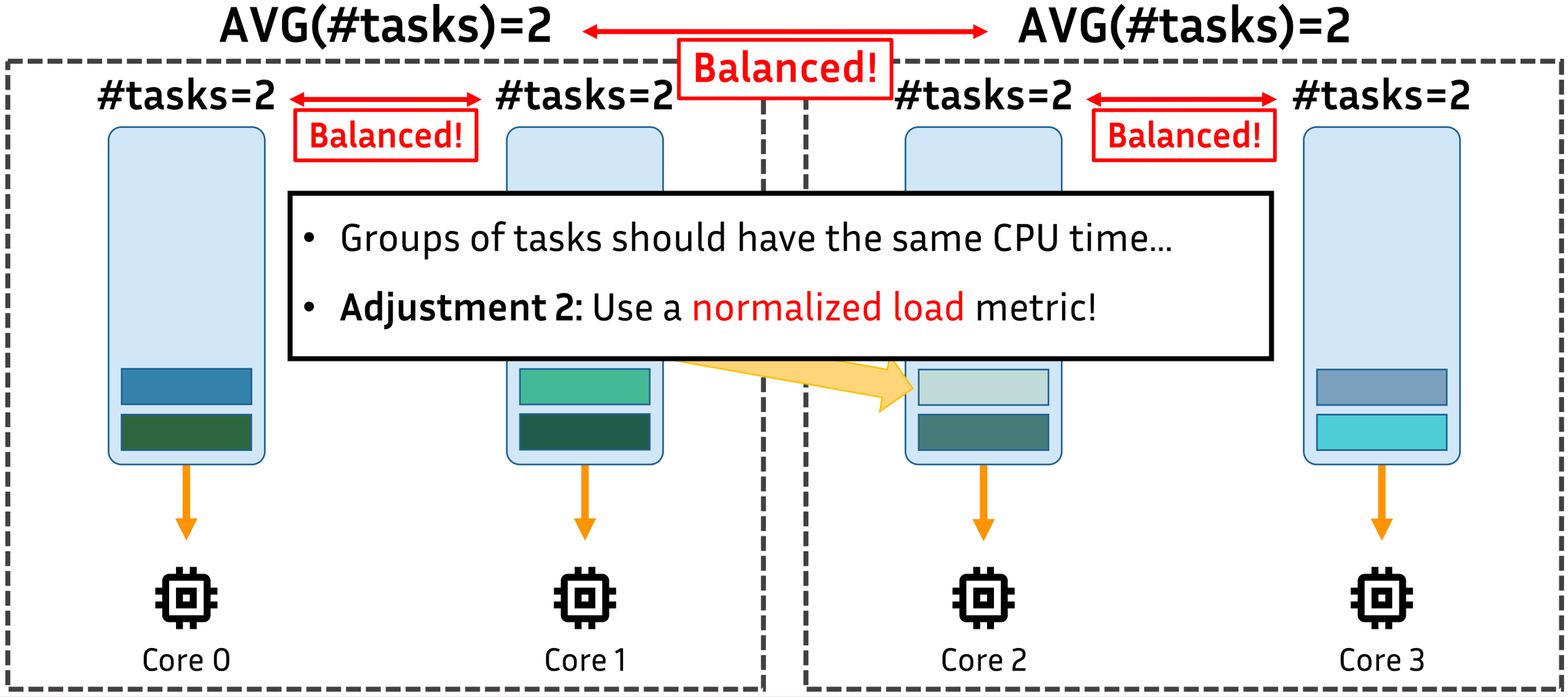

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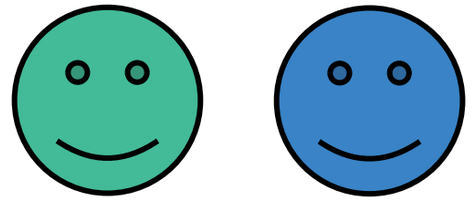

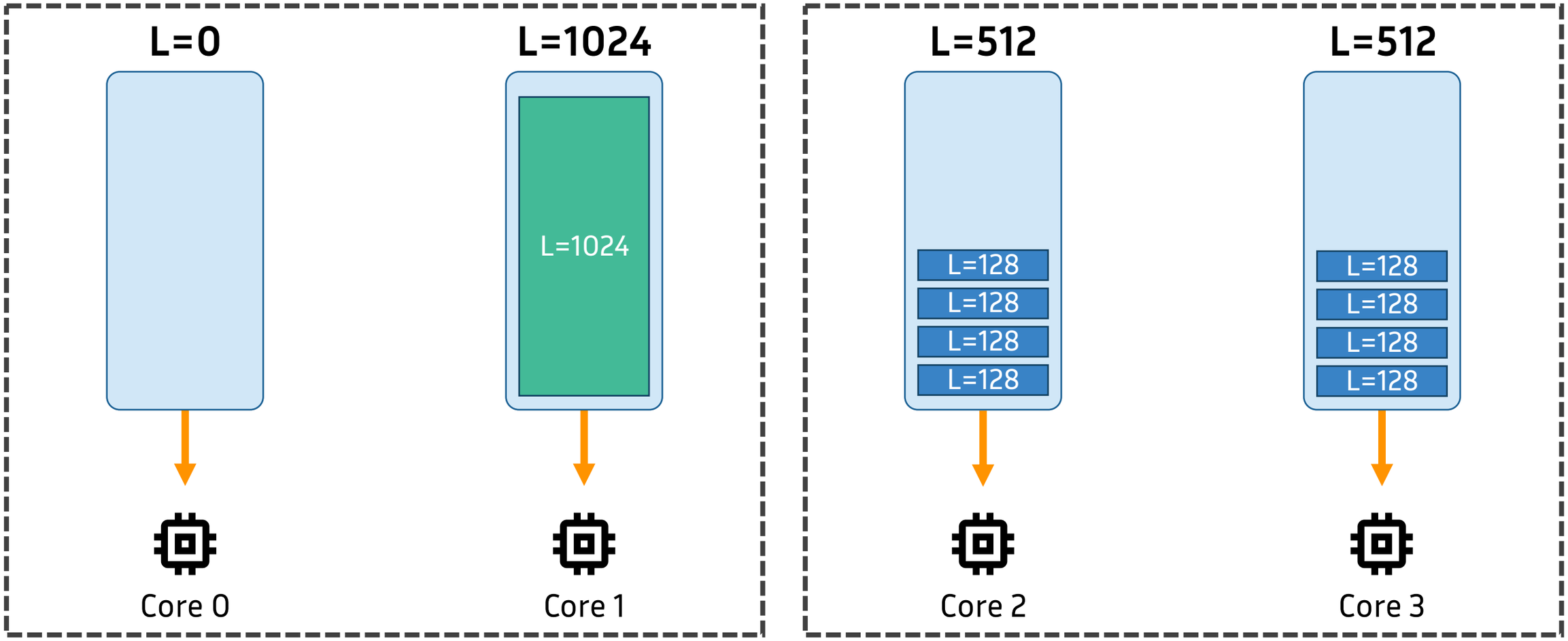

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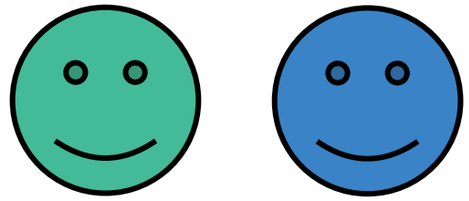

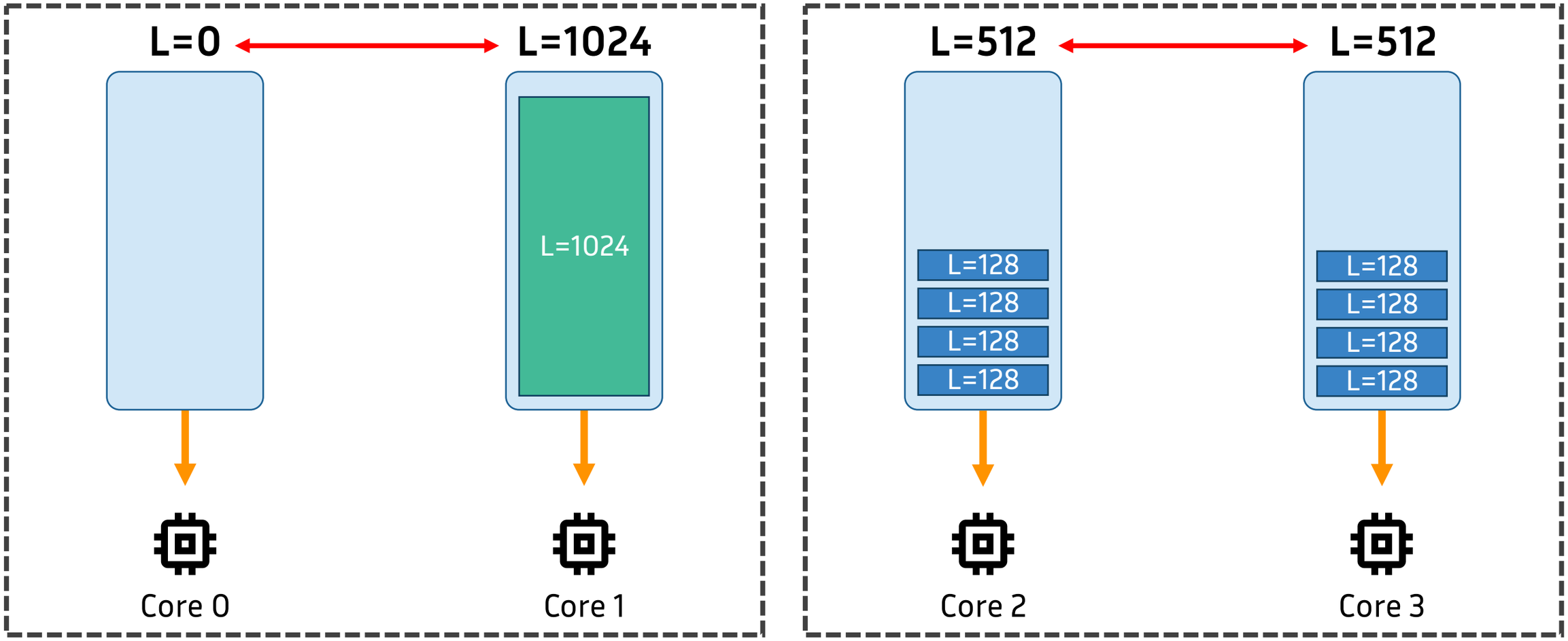

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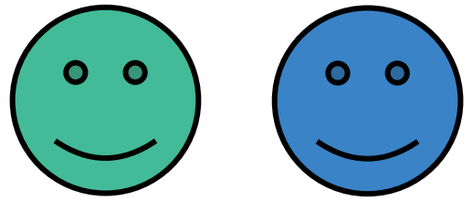

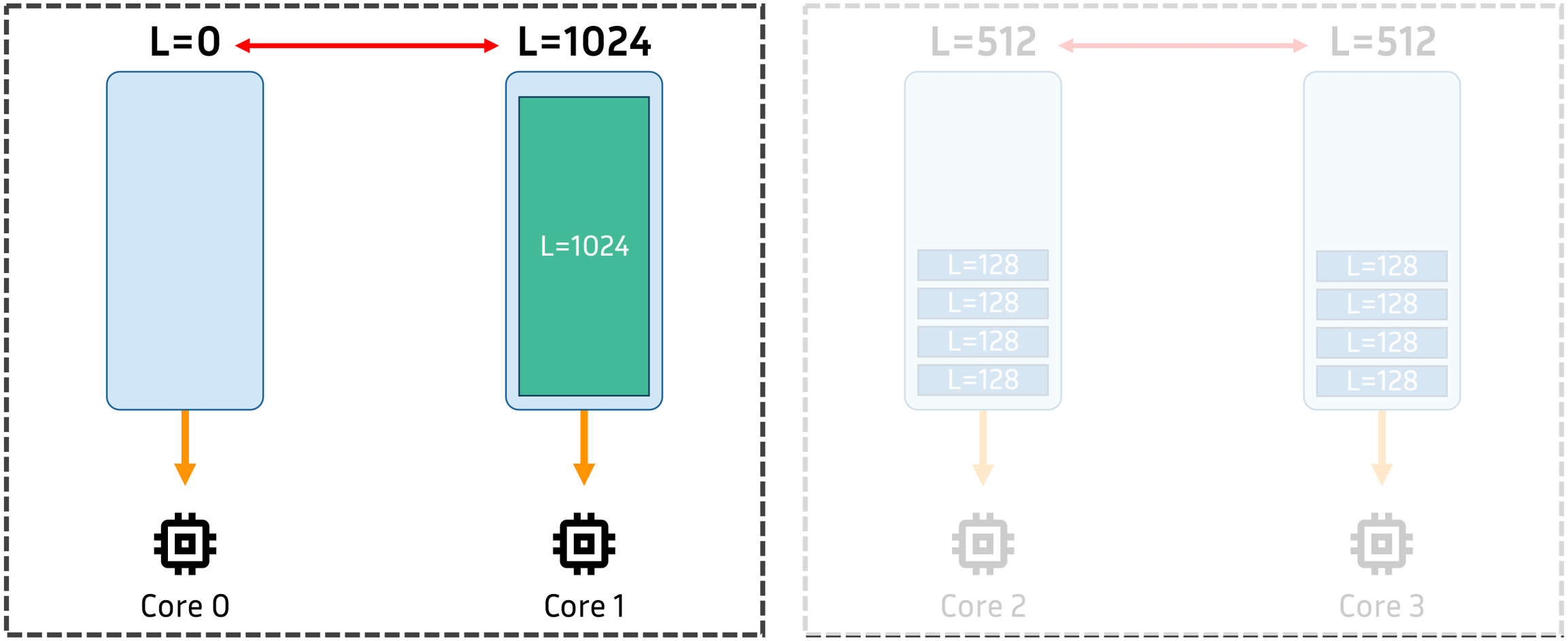

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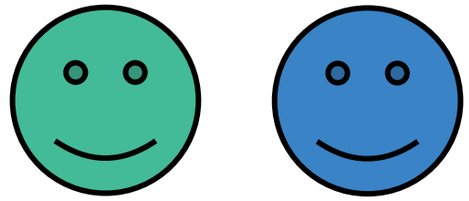

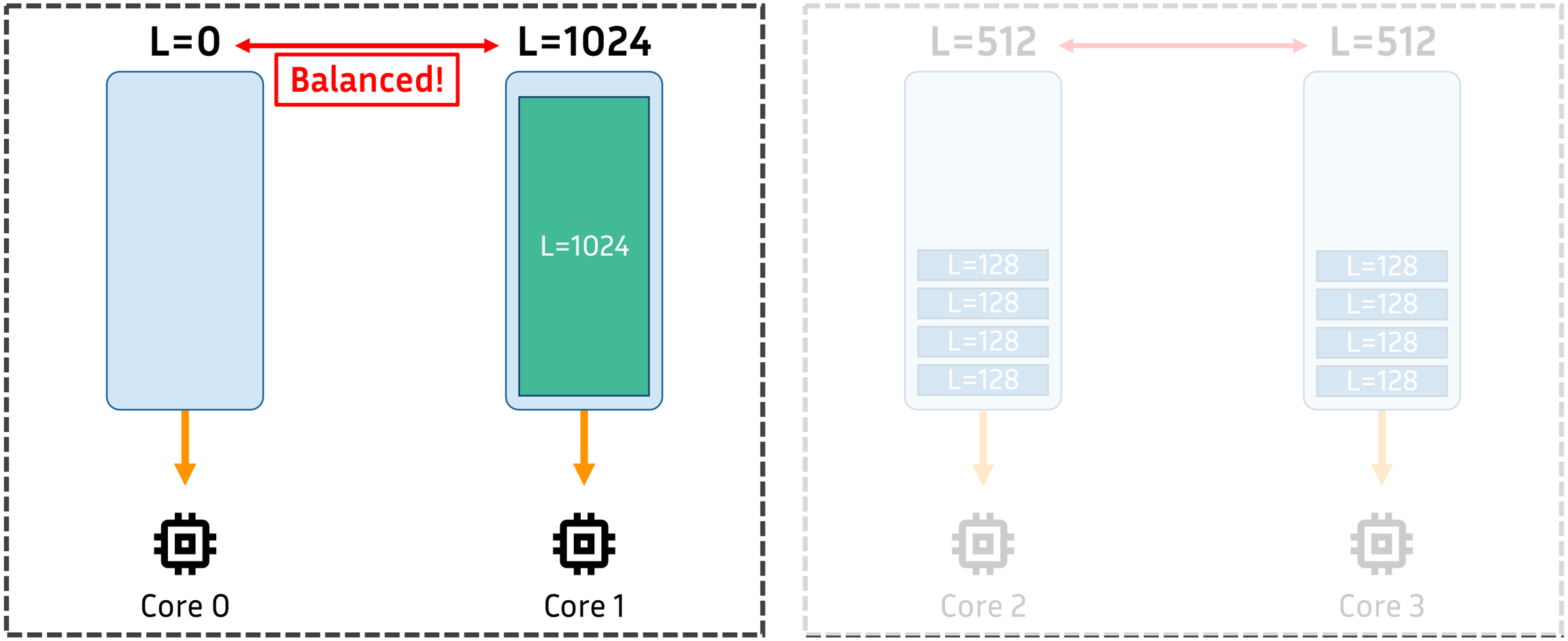

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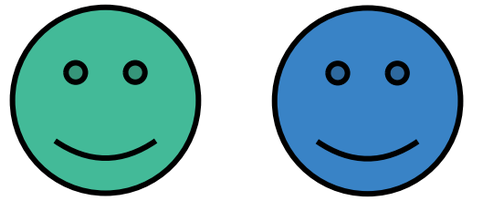

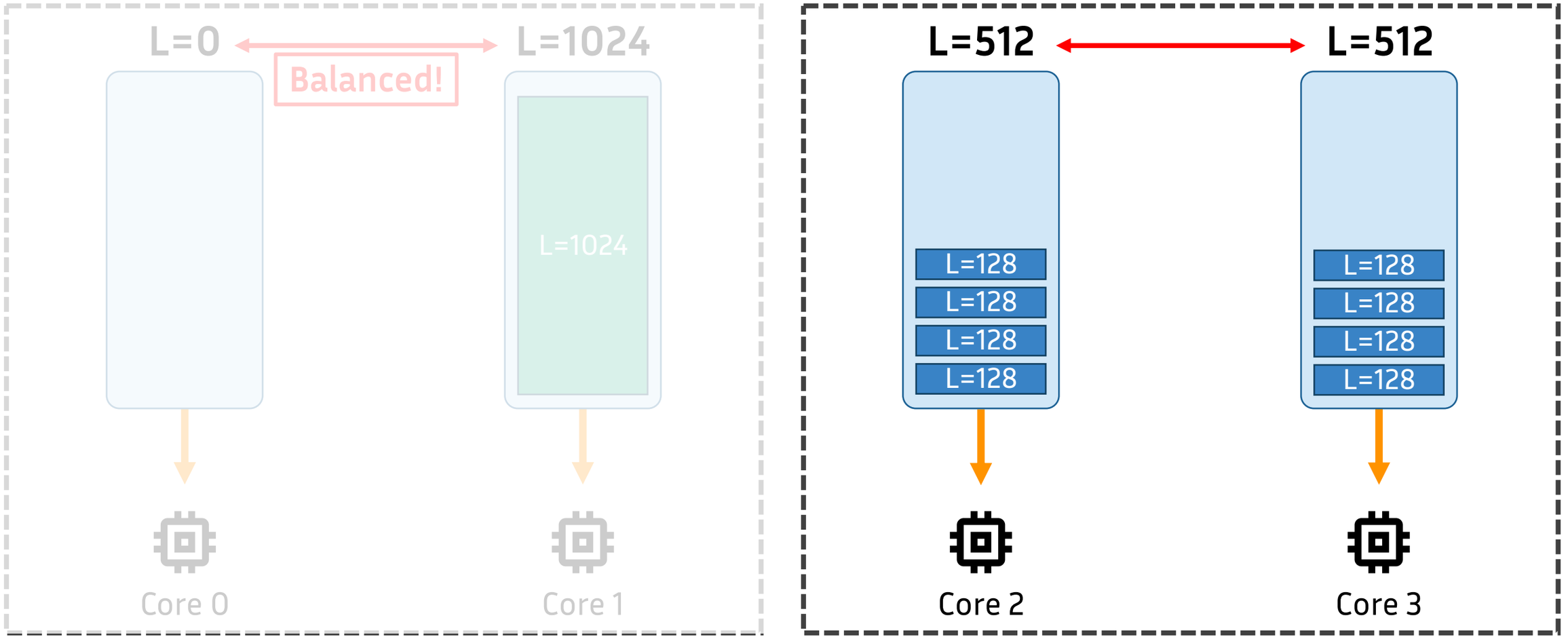

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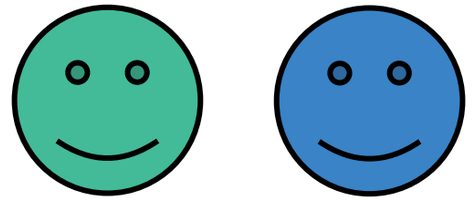

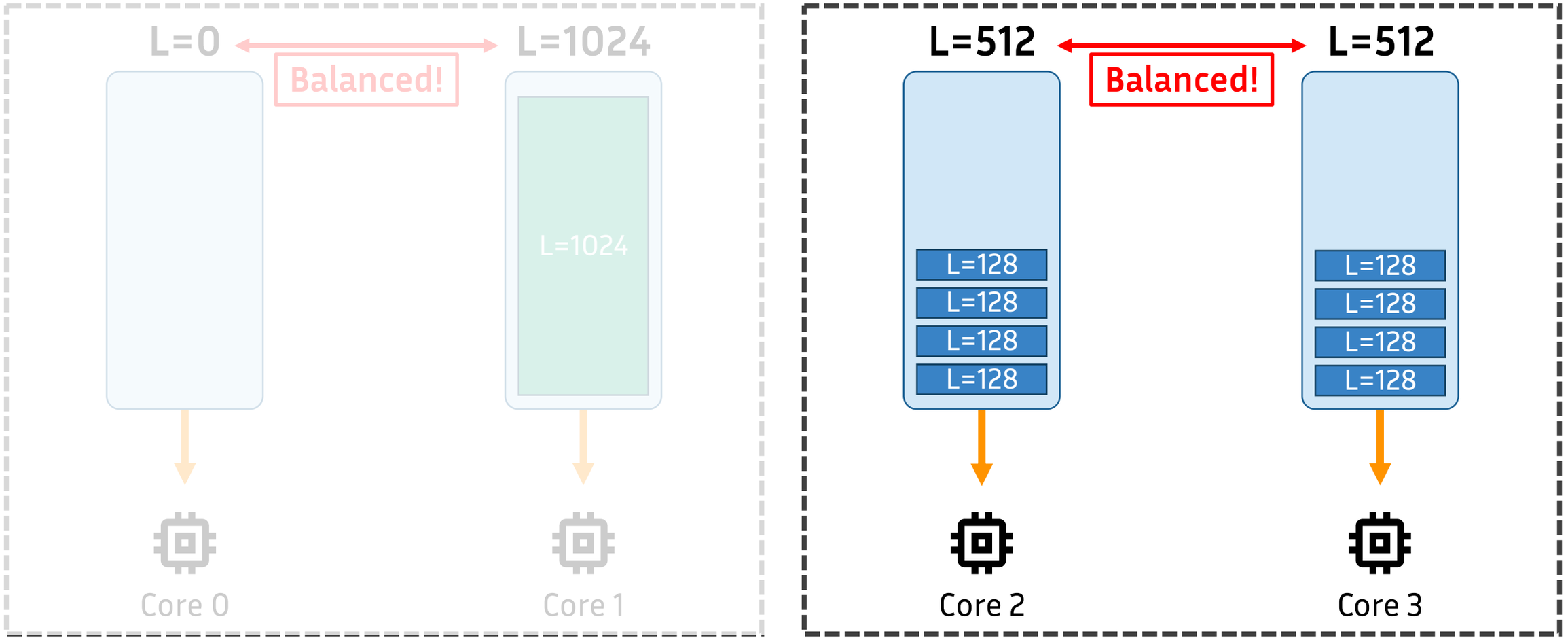

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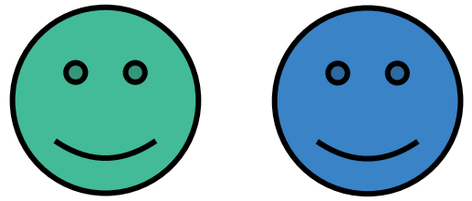

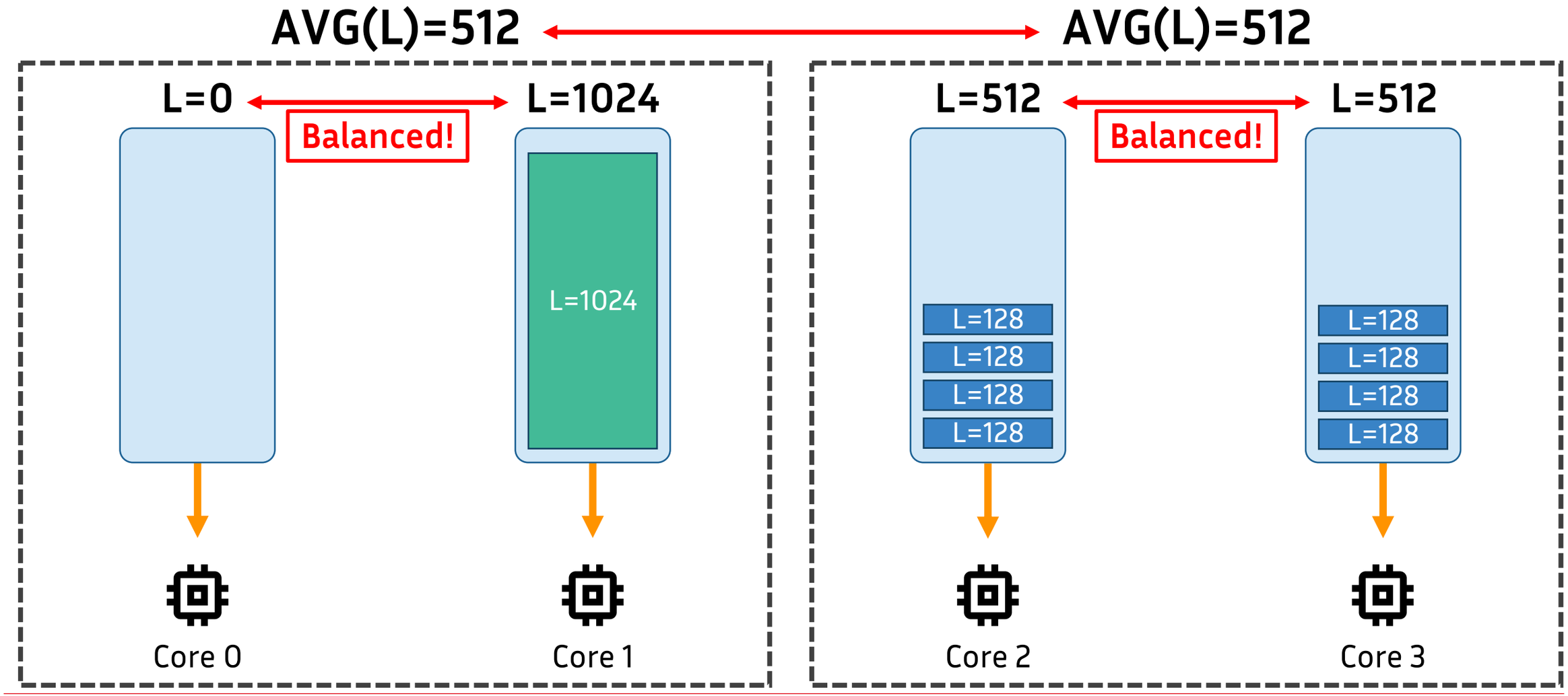

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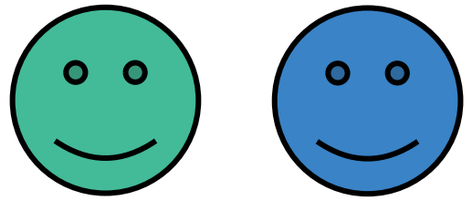

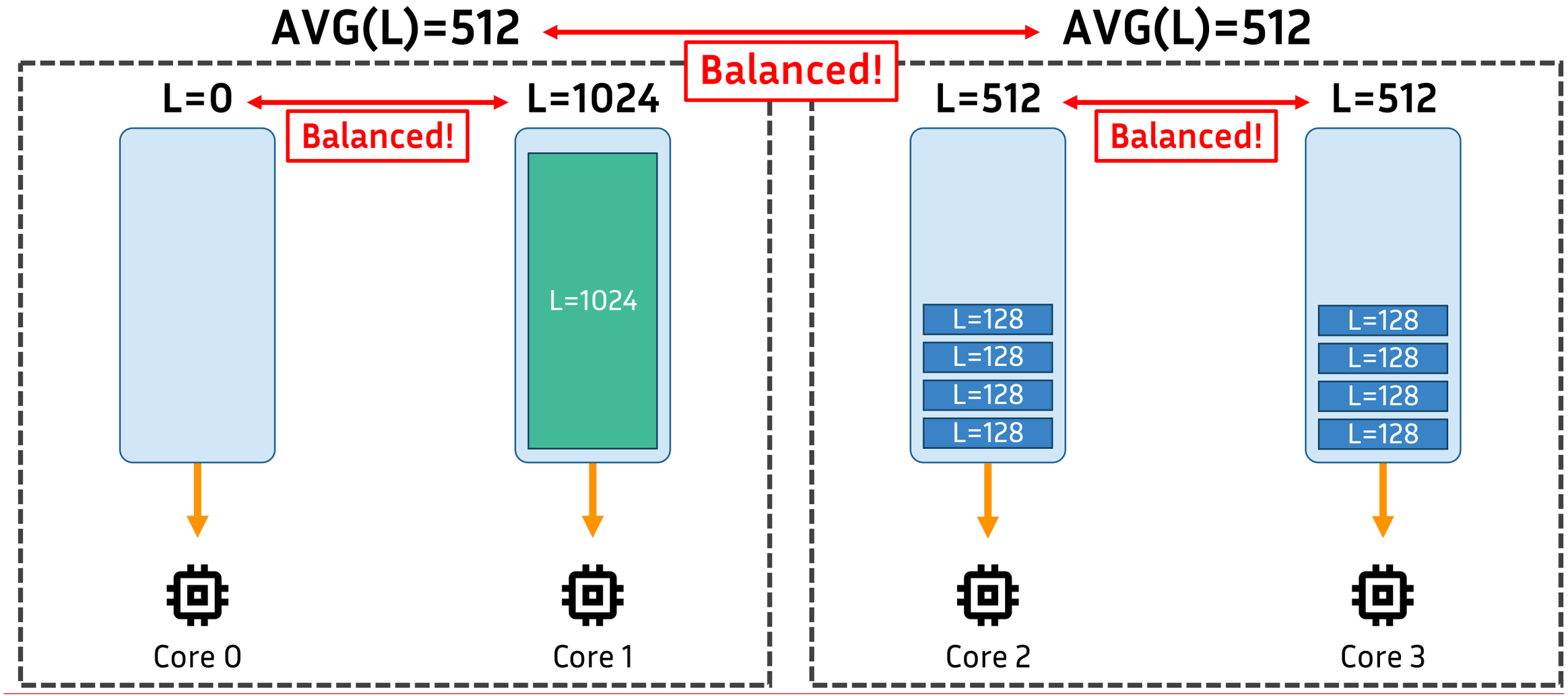

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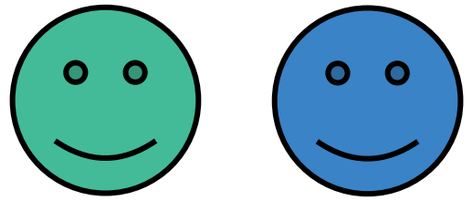

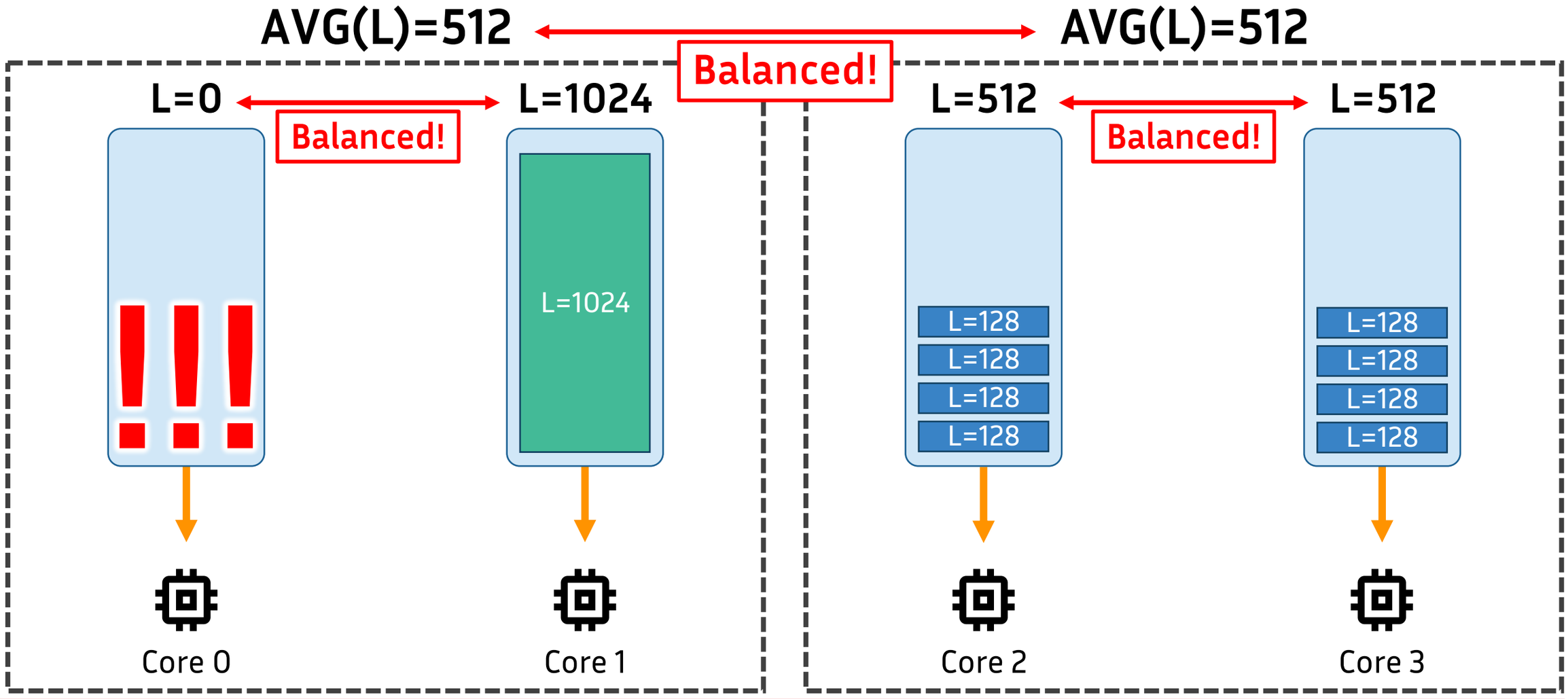

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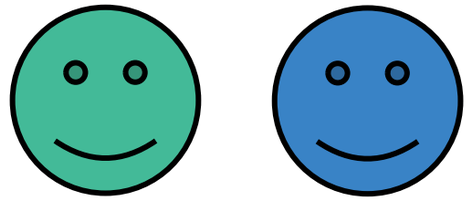

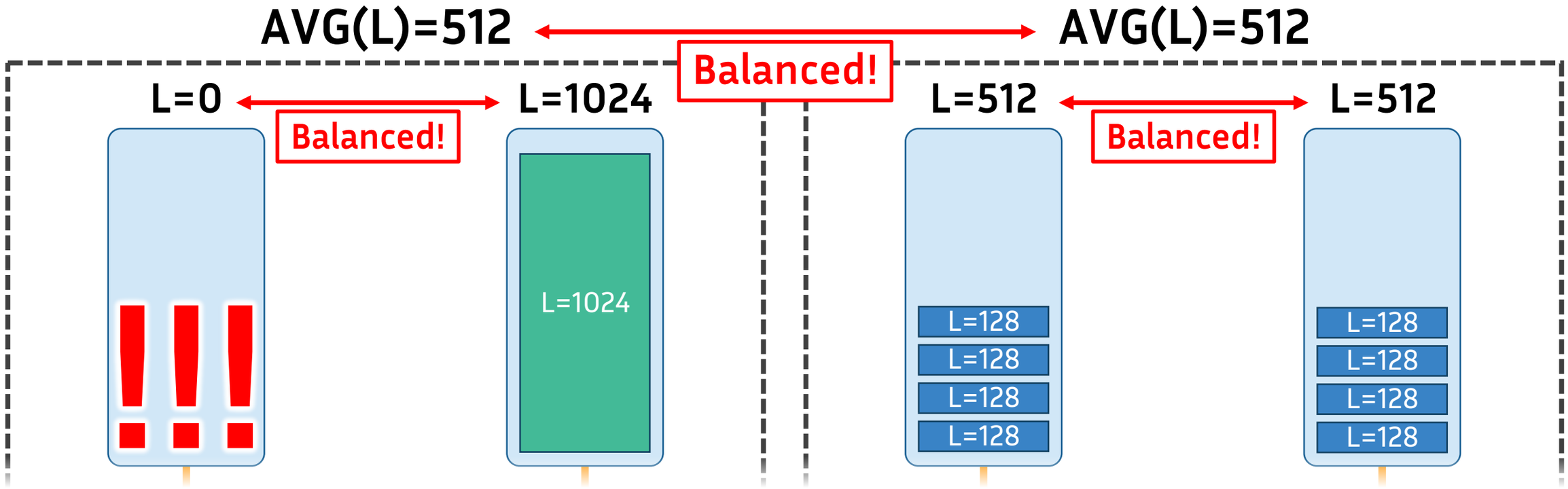

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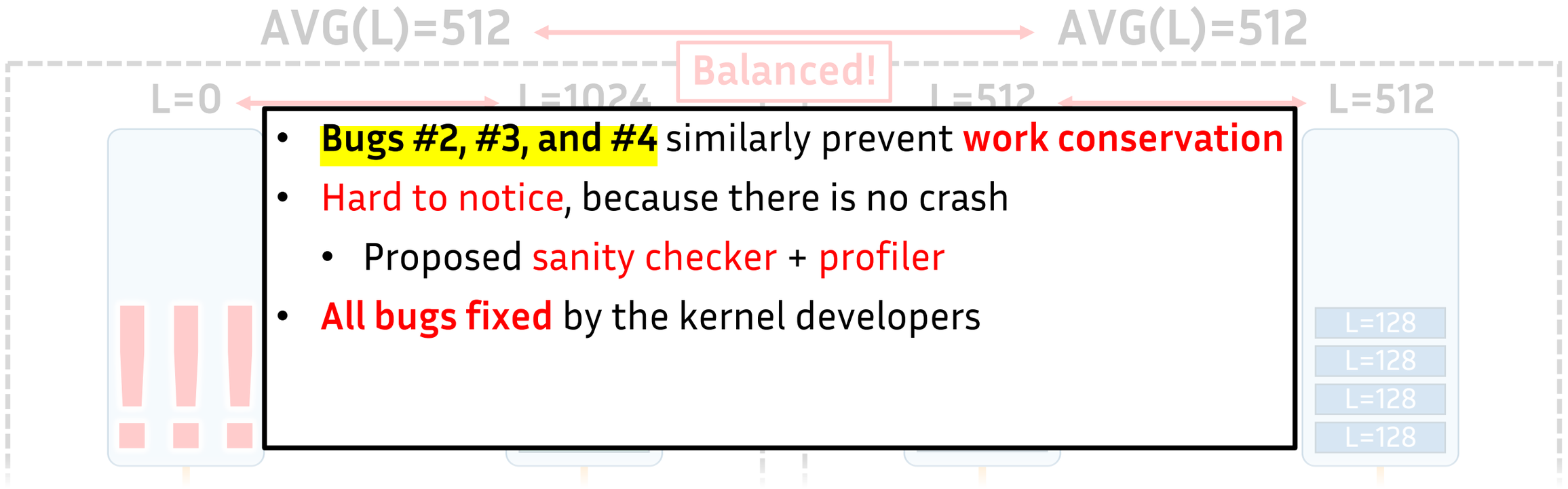

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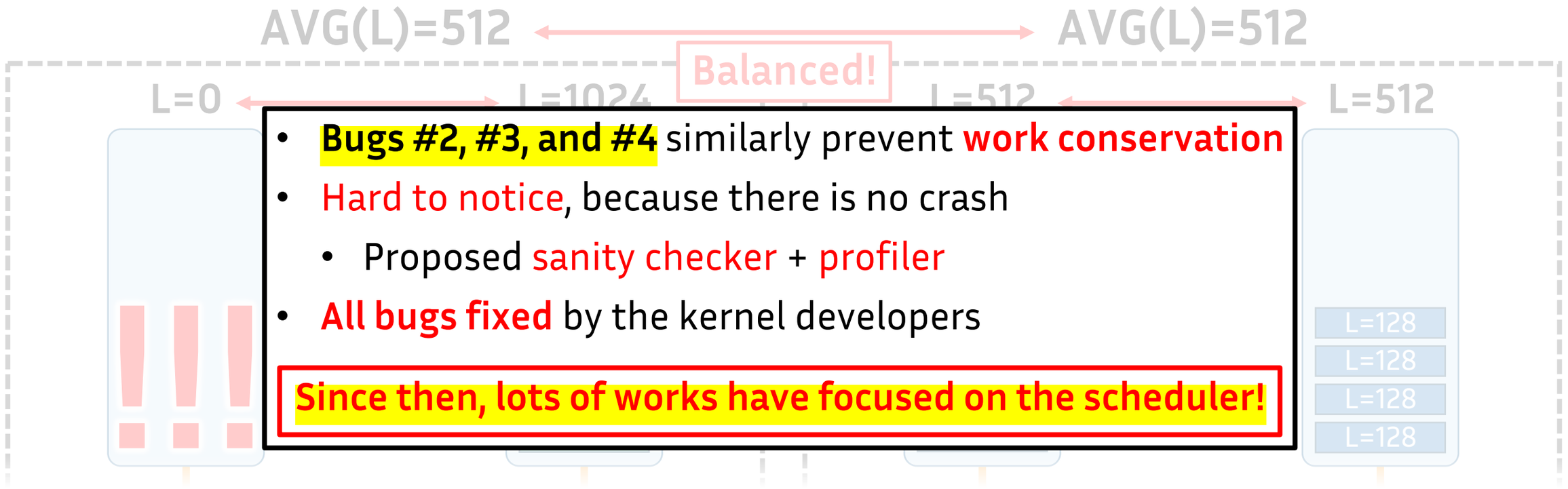

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Since then, lots of works have focused on the scheduler!

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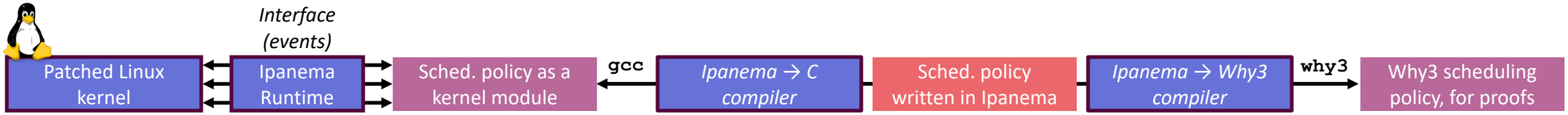

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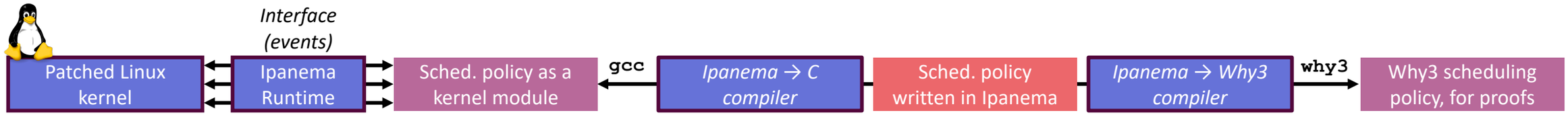

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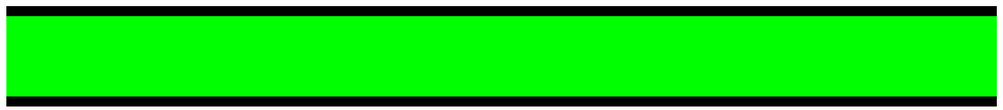
- **Problem:** full work conservation is too strong a property



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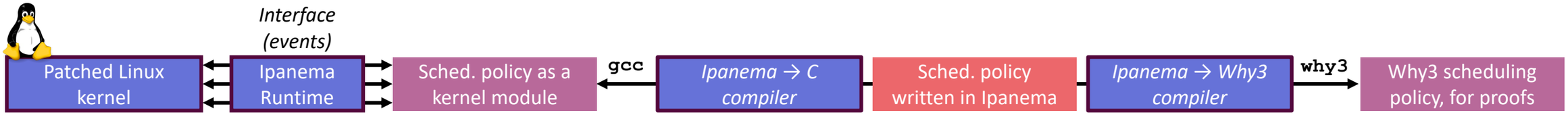

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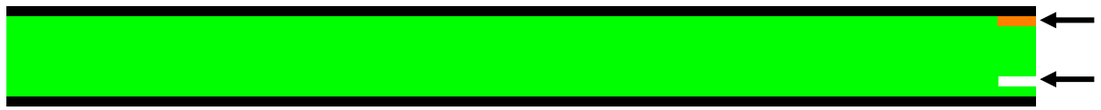

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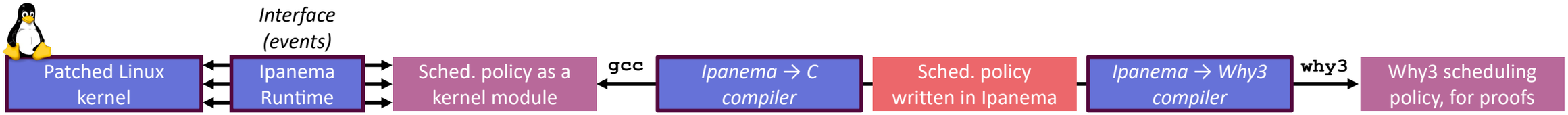

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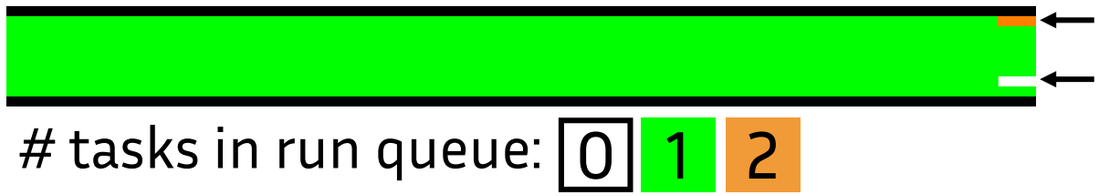

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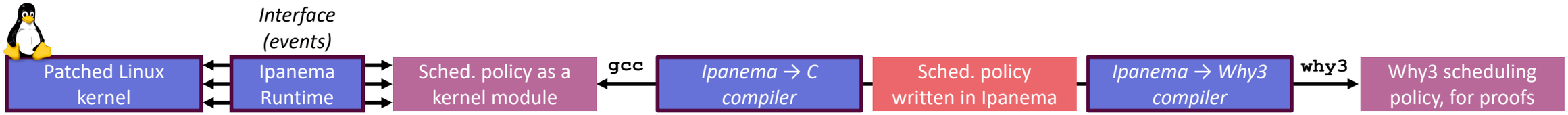

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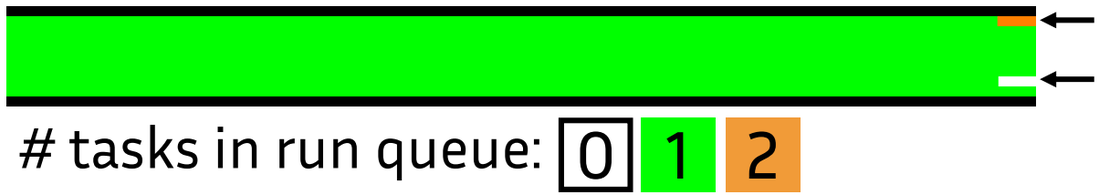

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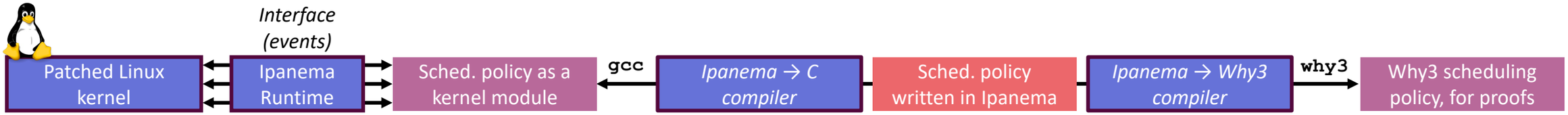

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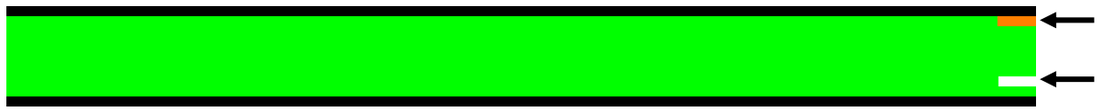

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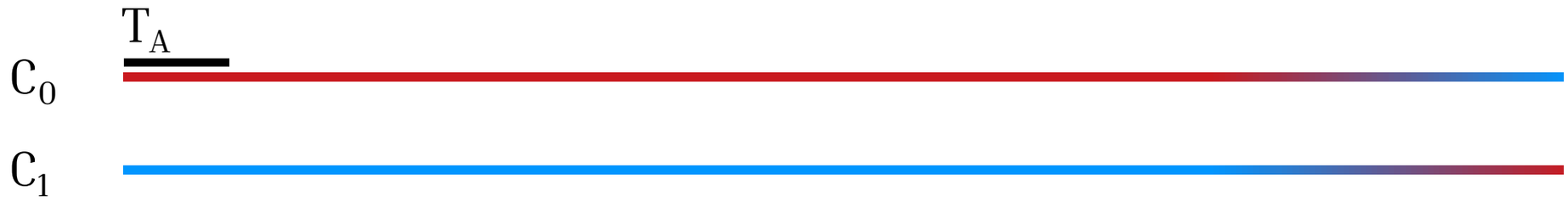

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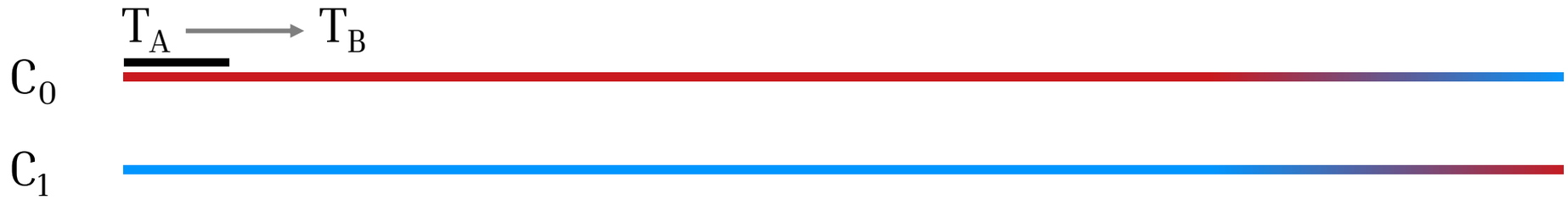

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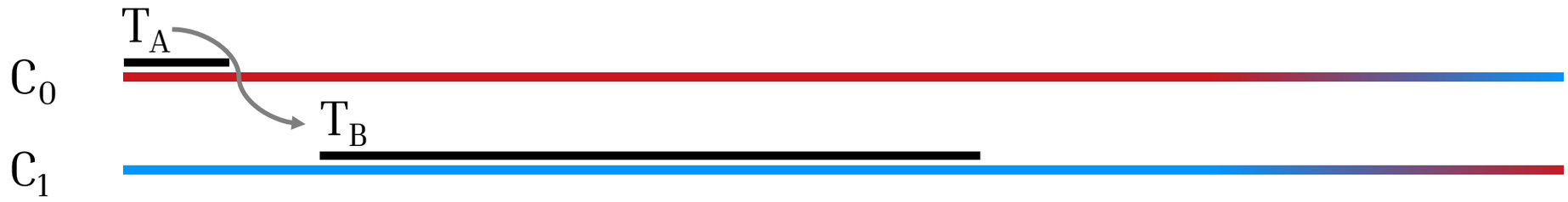

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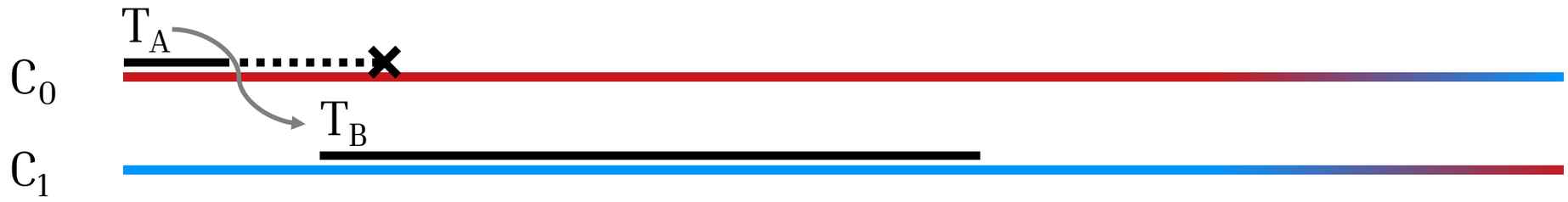

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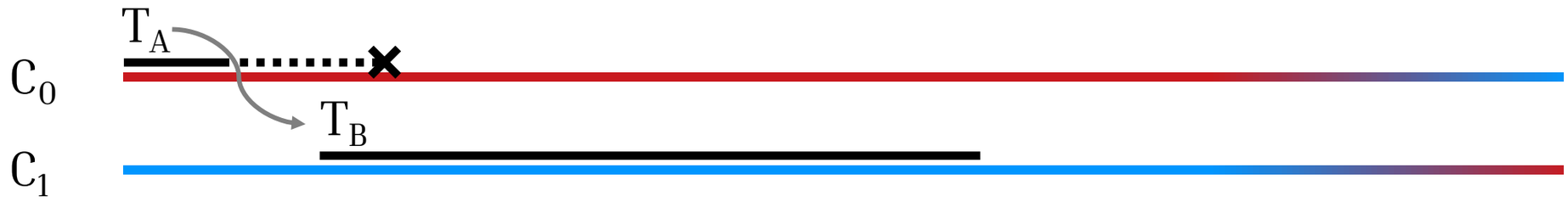

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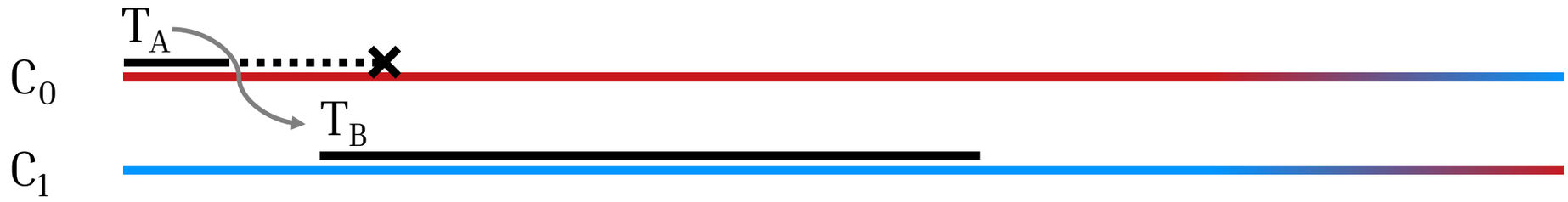

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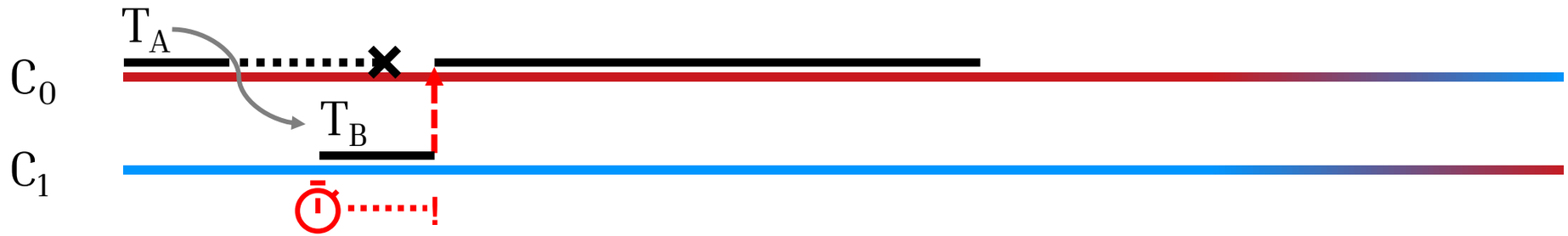

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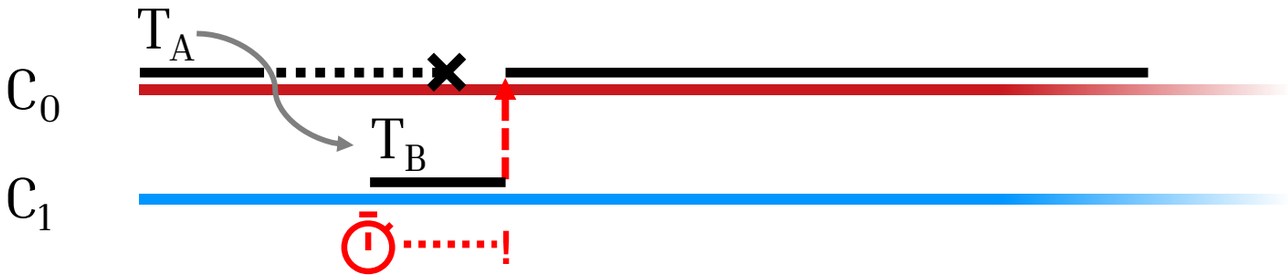

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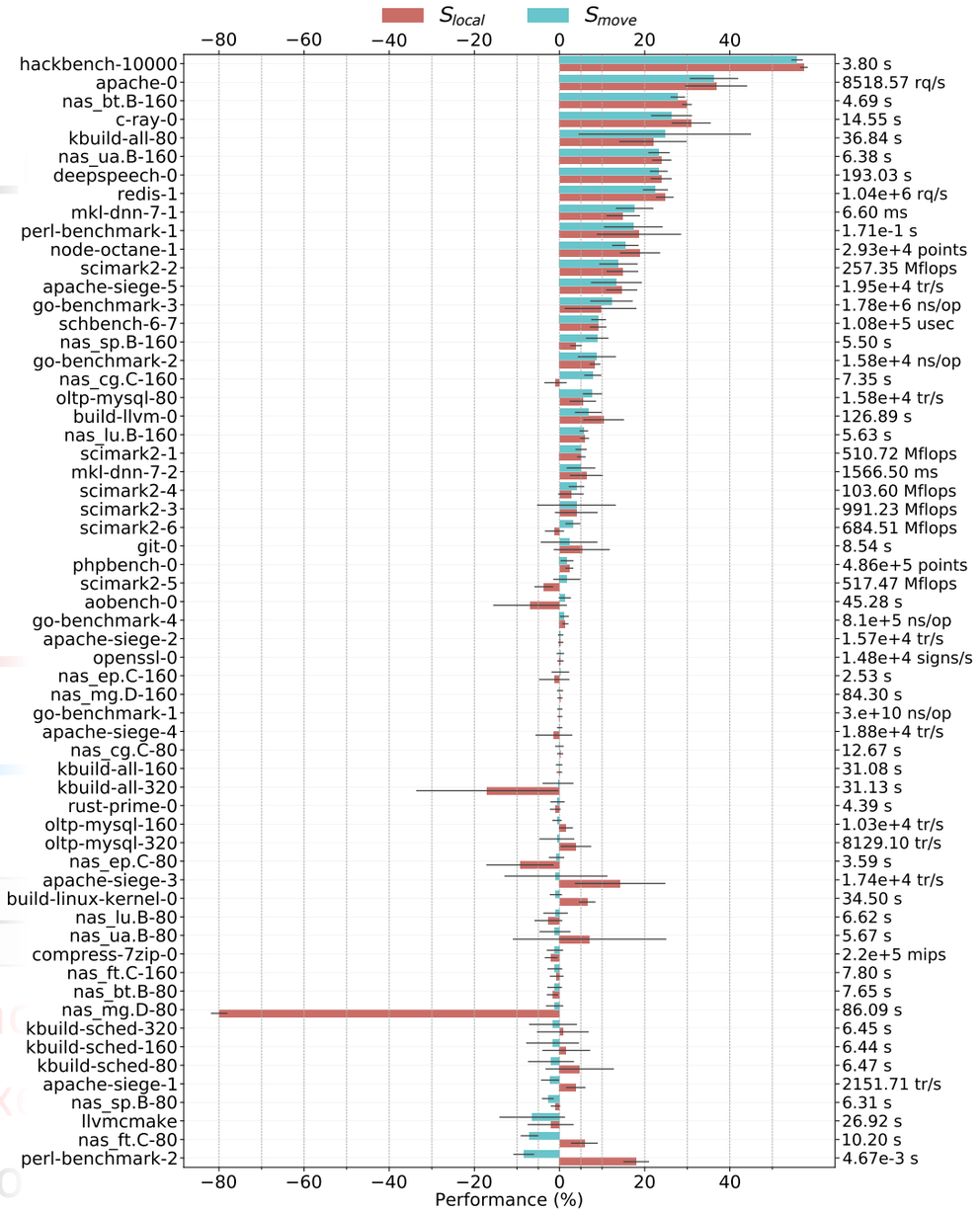

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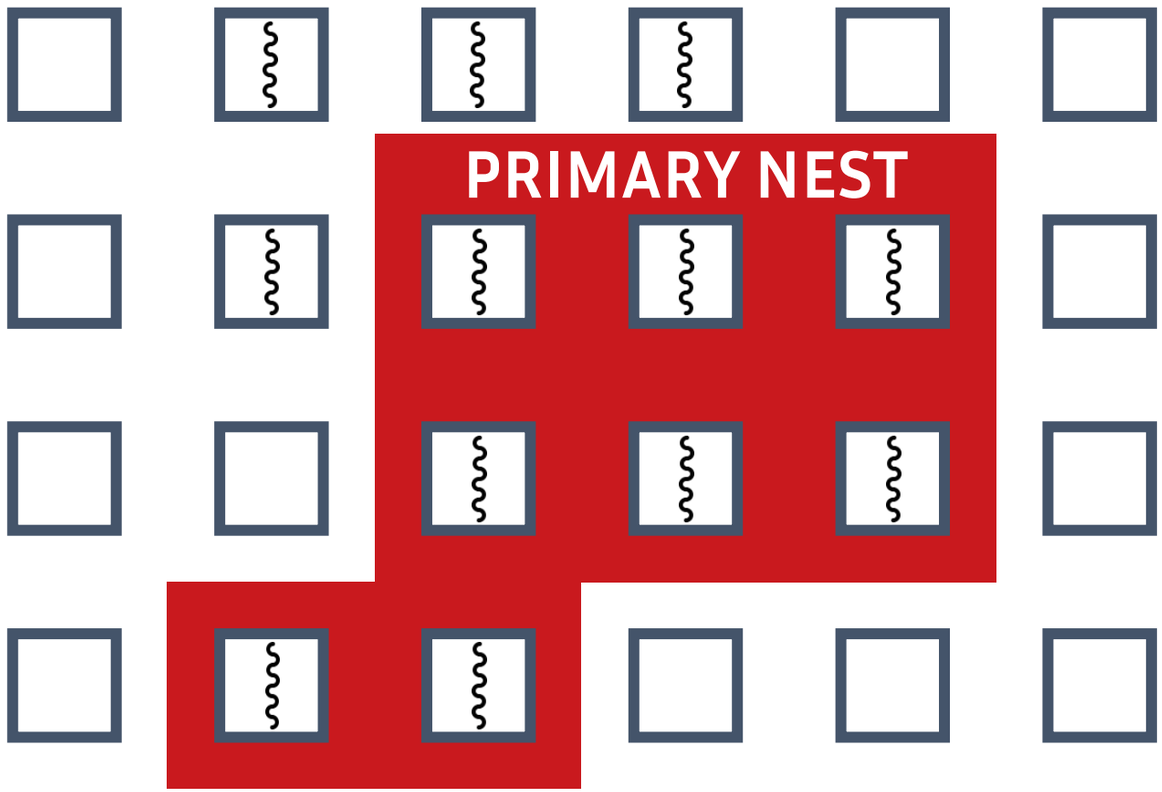

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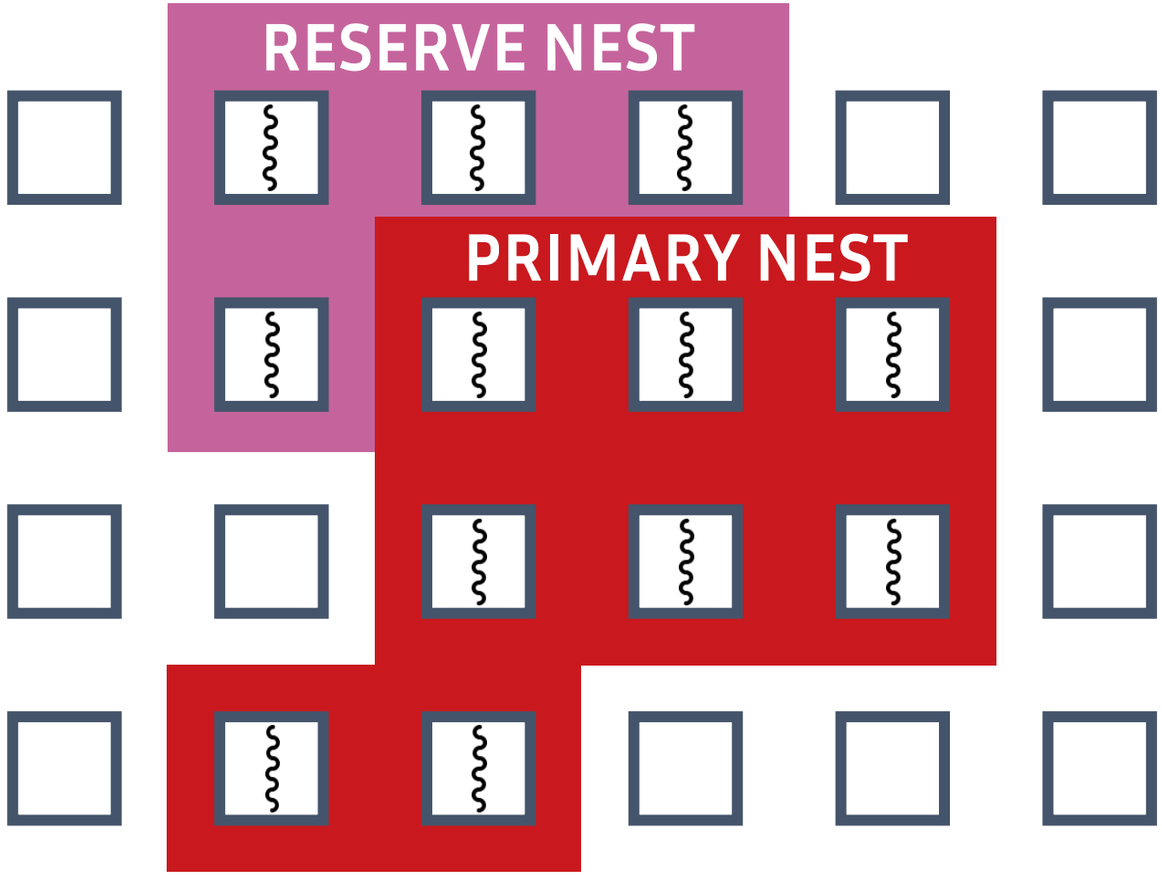

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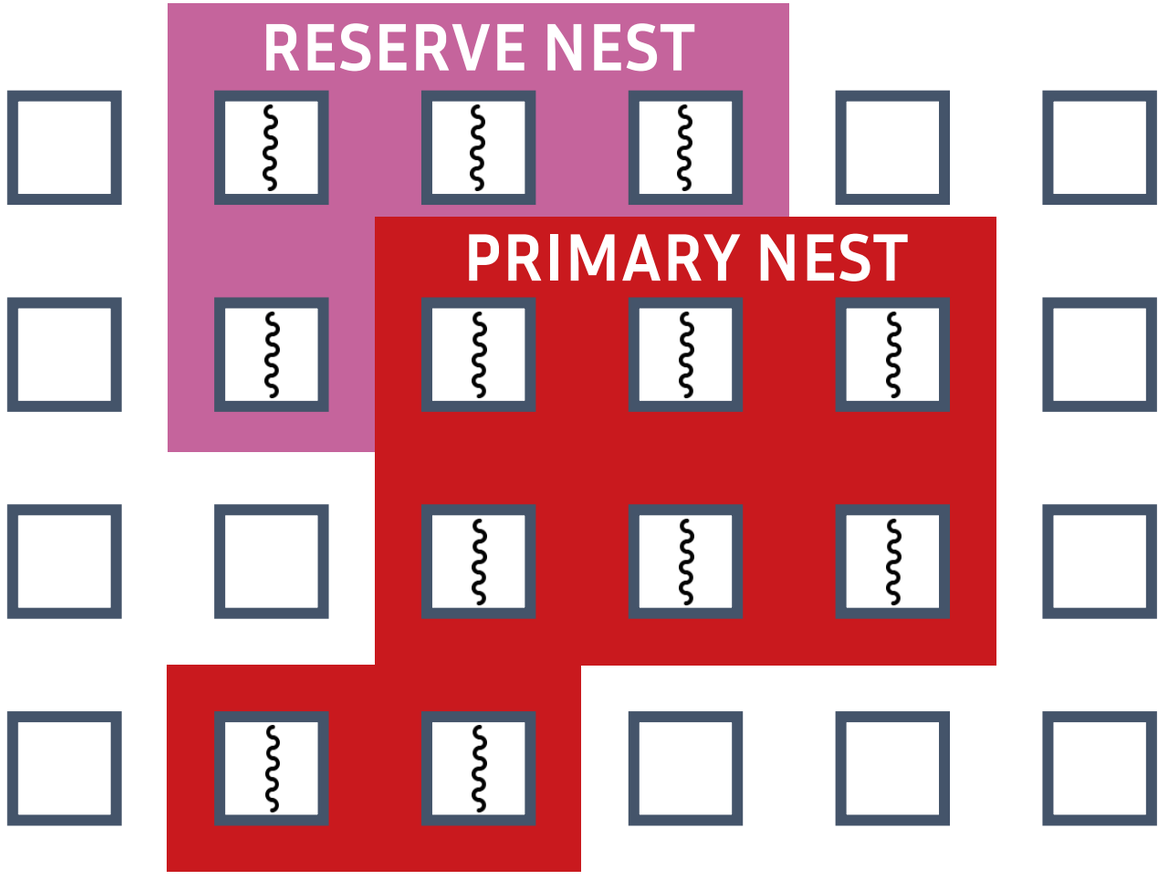

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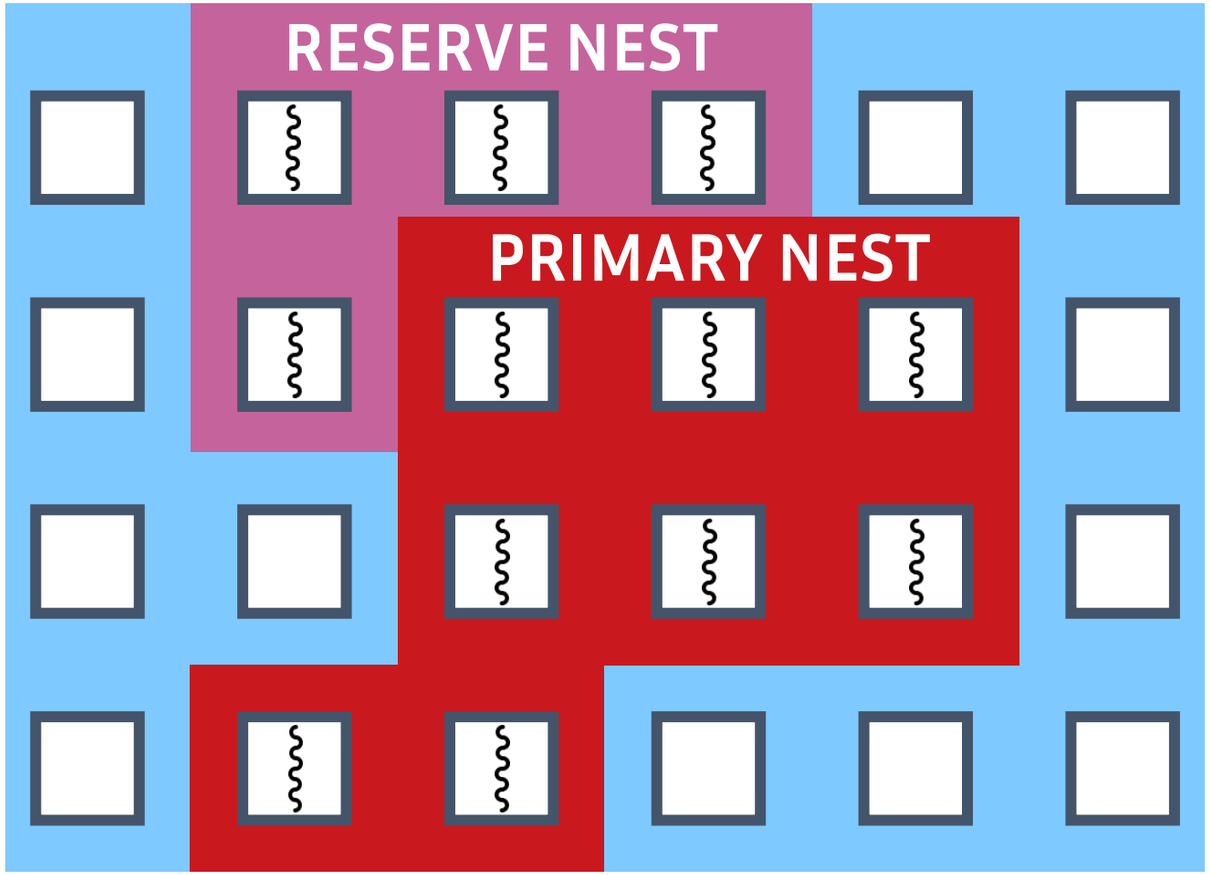

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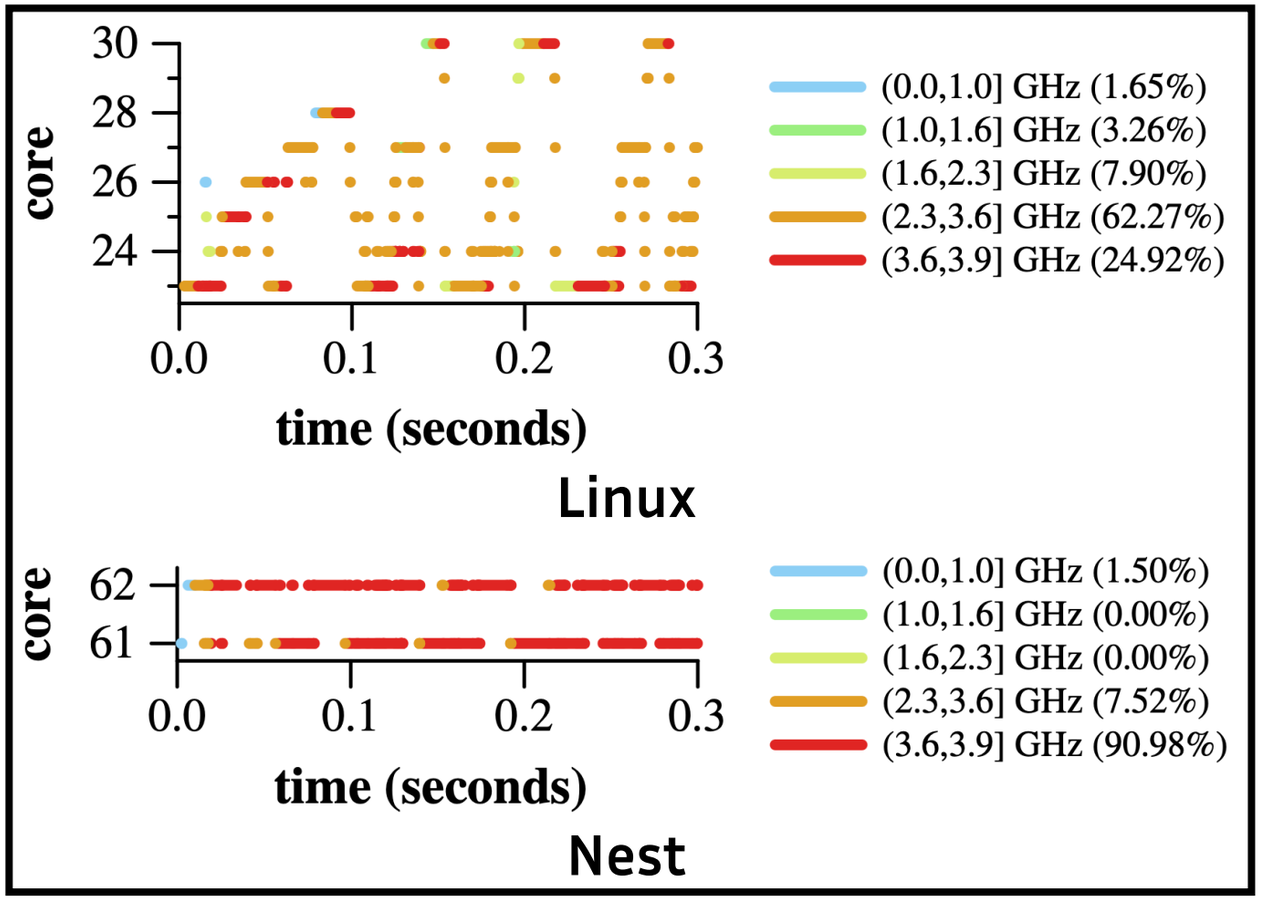

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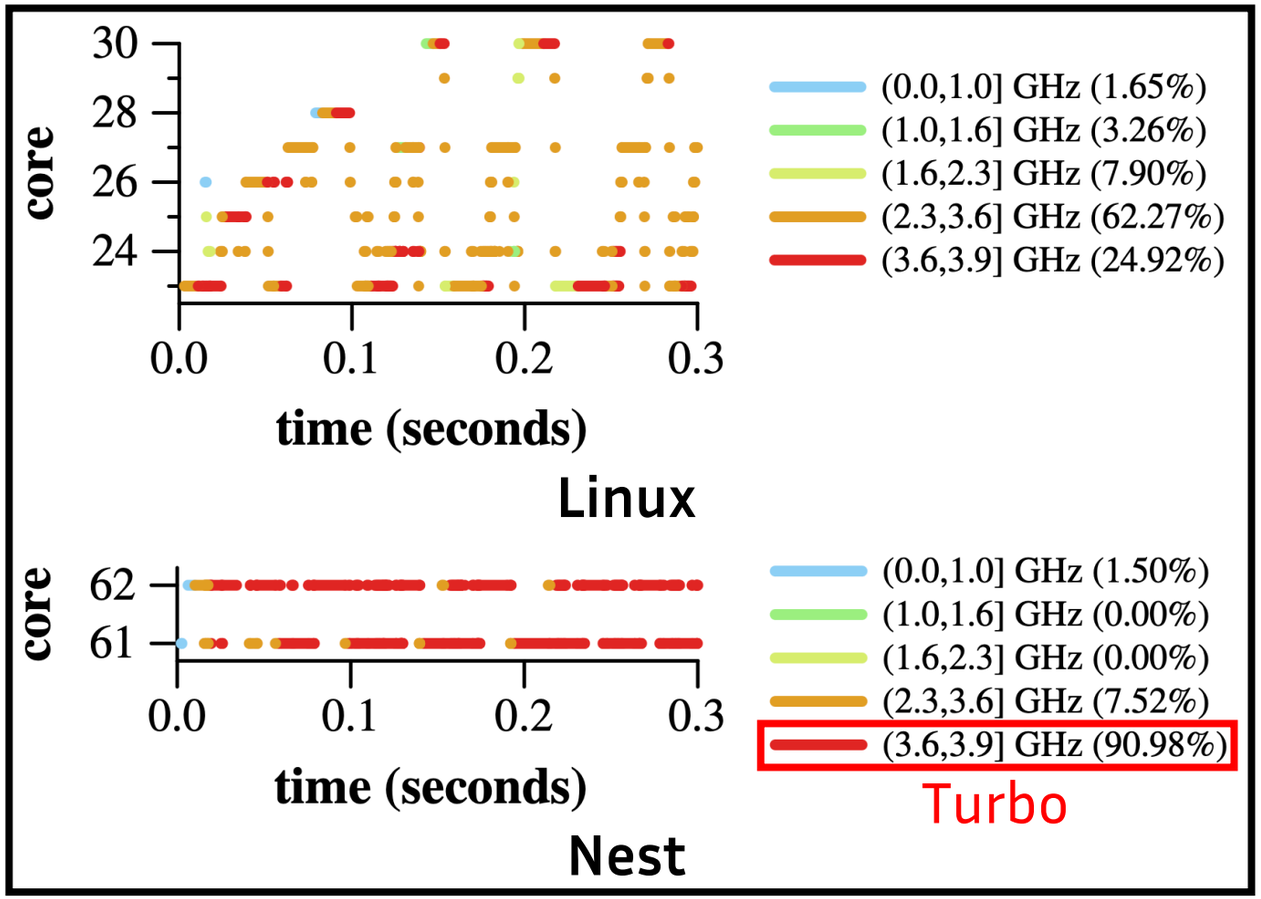

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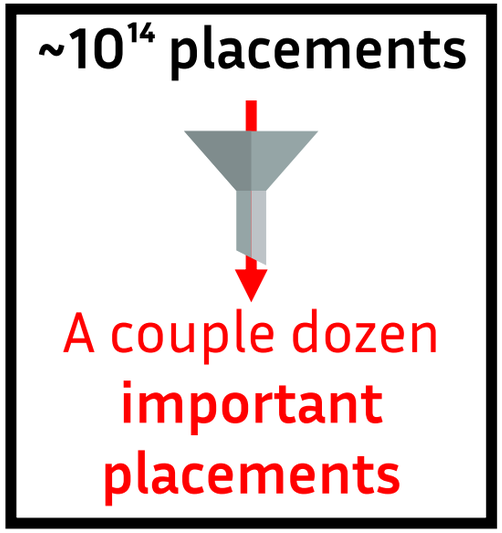

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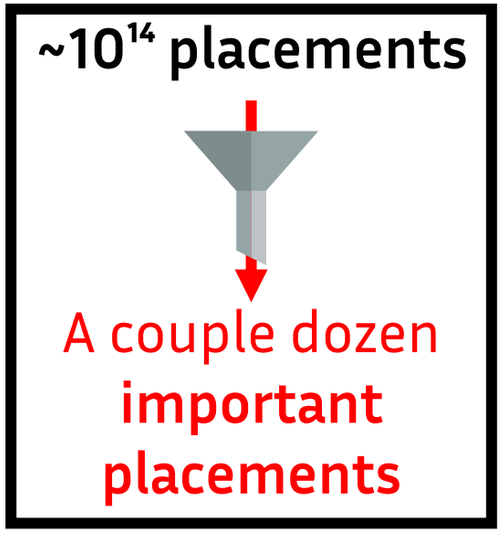

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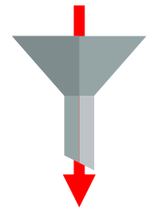

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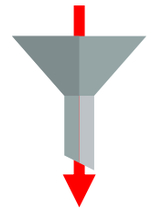

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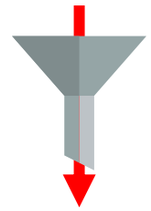

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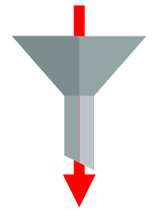

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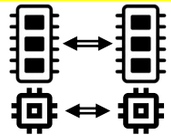

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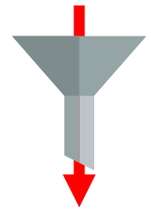

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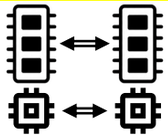

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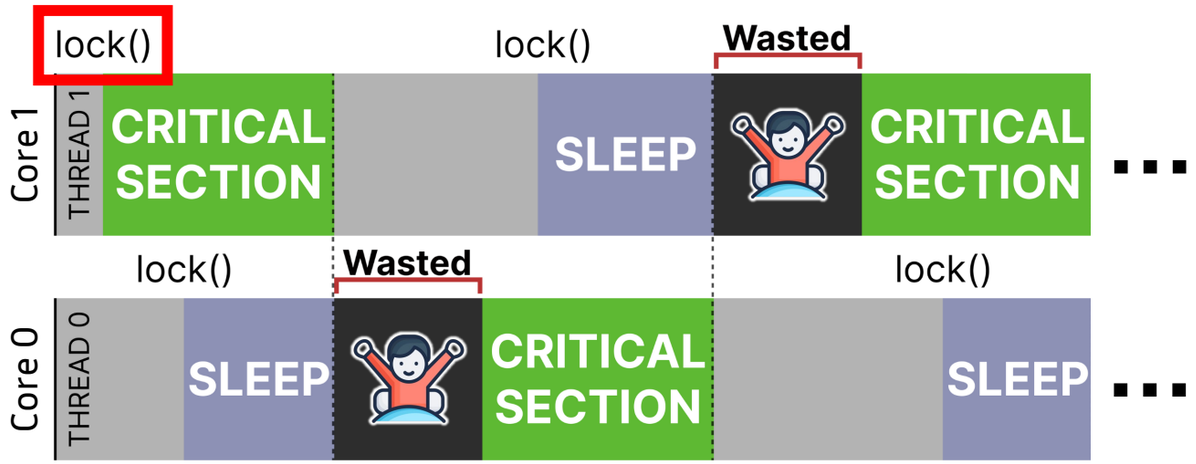

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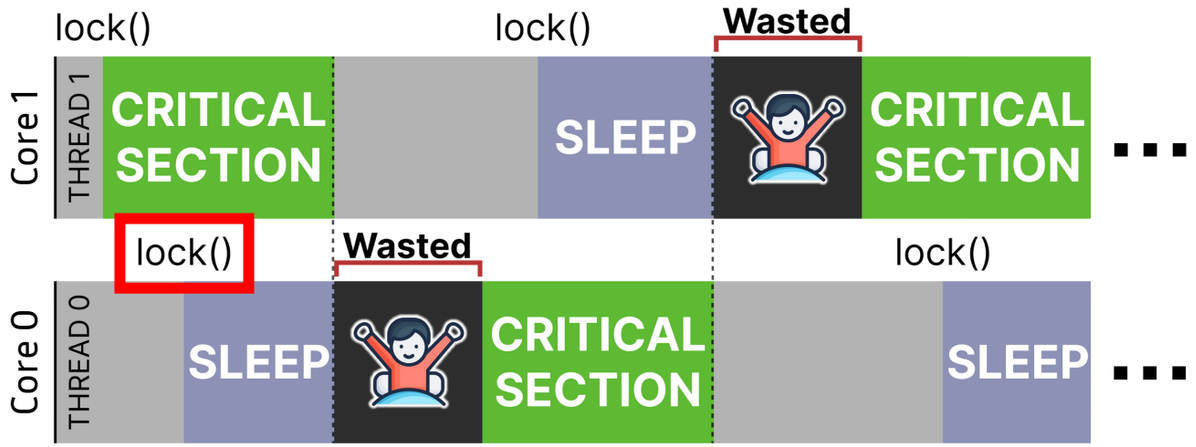

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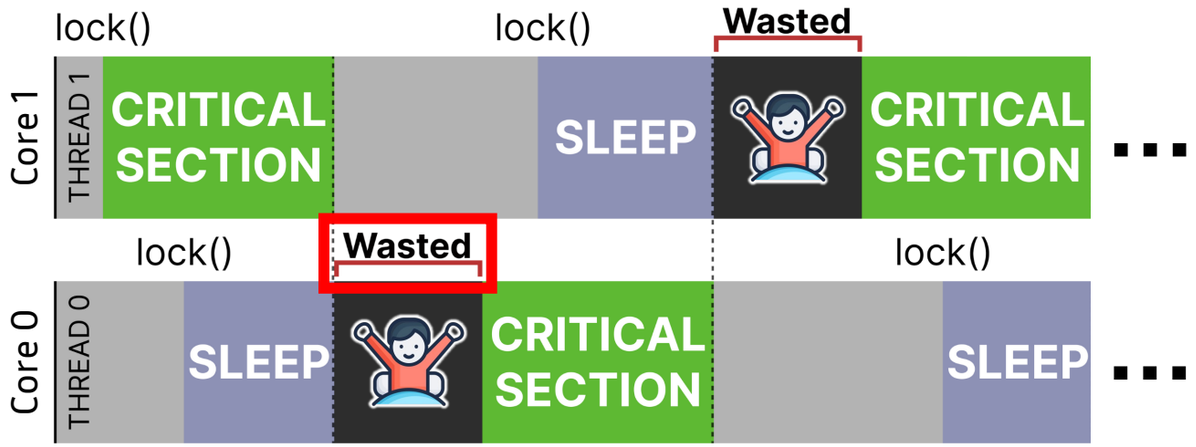

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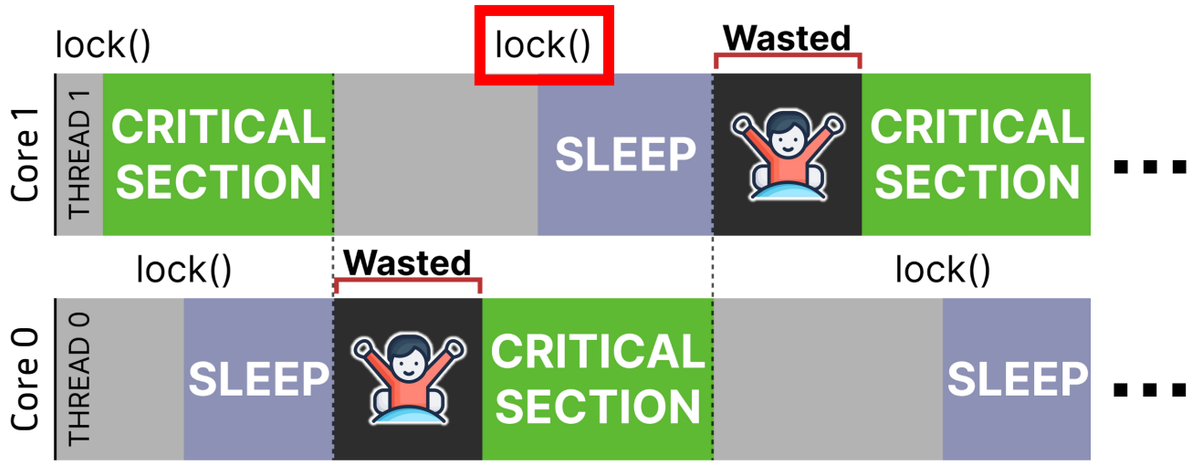

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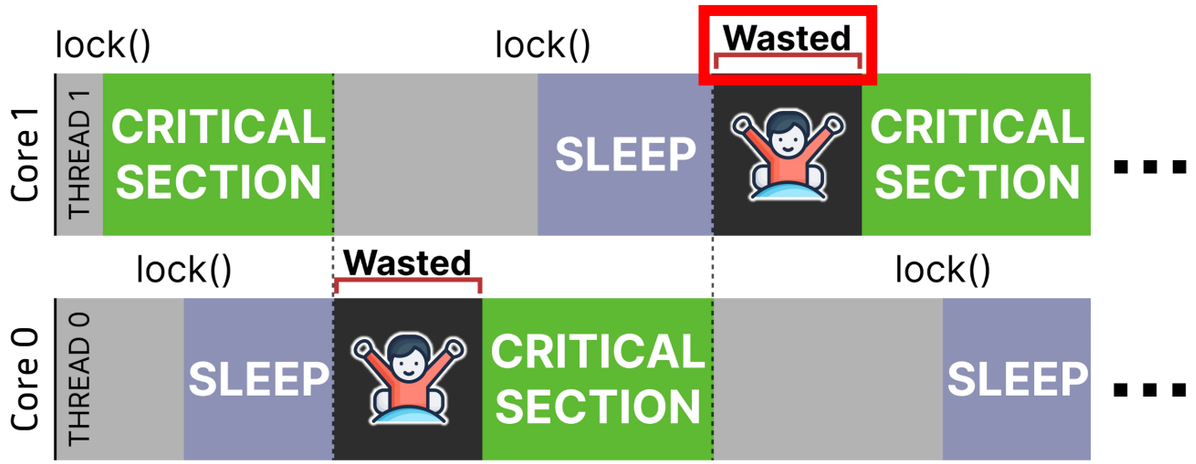

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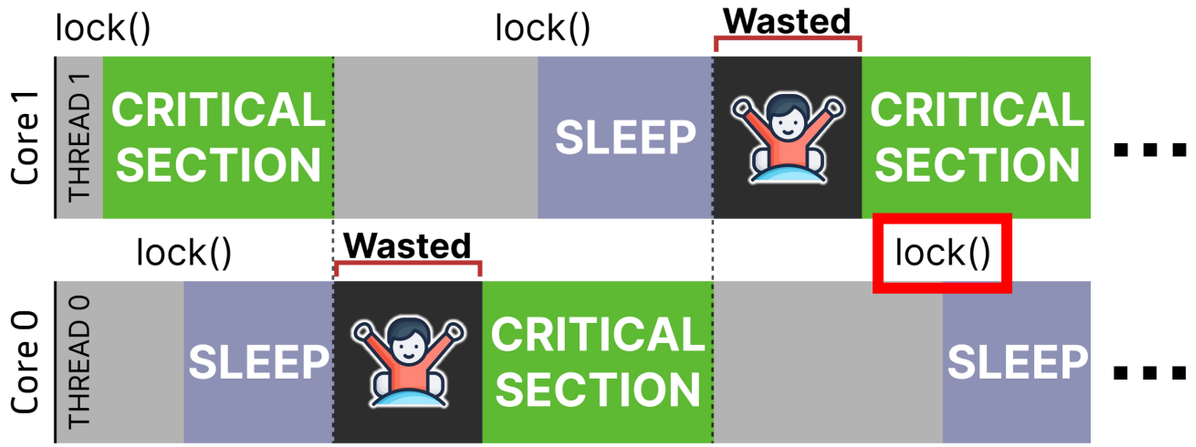

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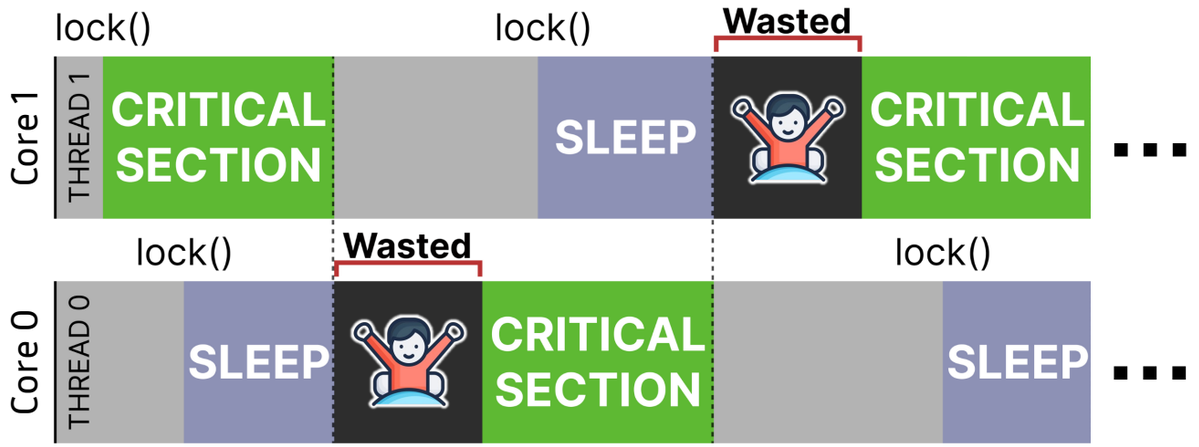

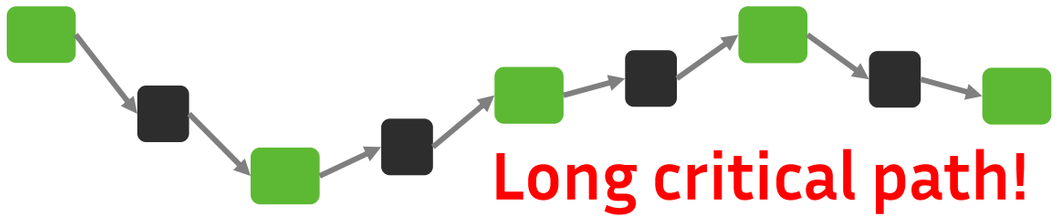

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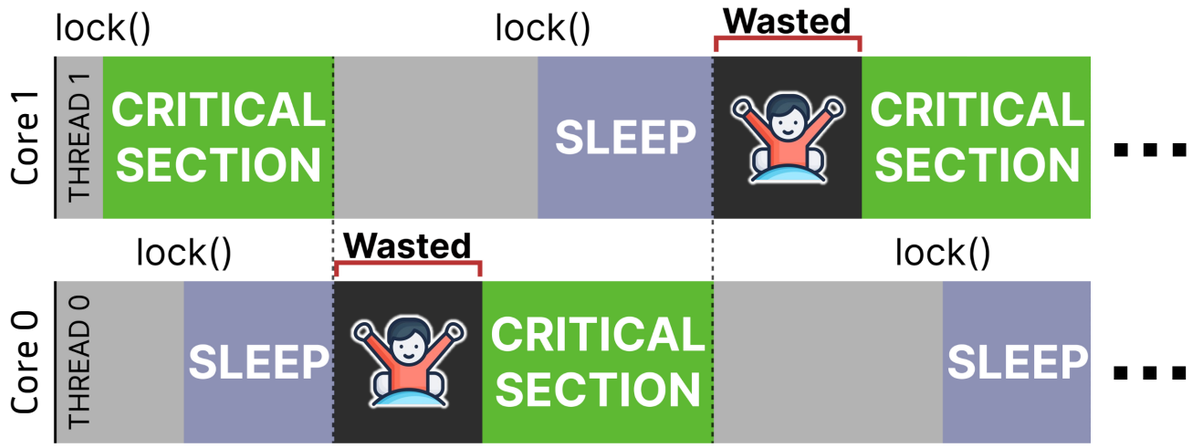

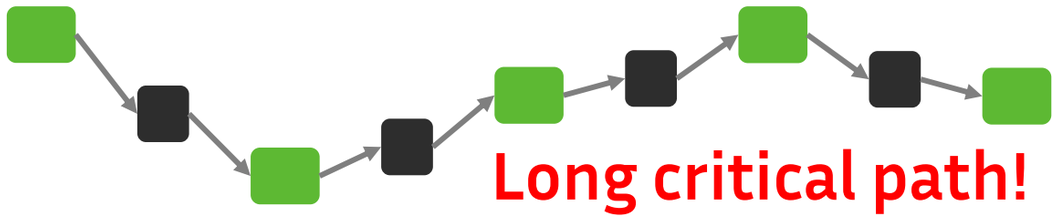

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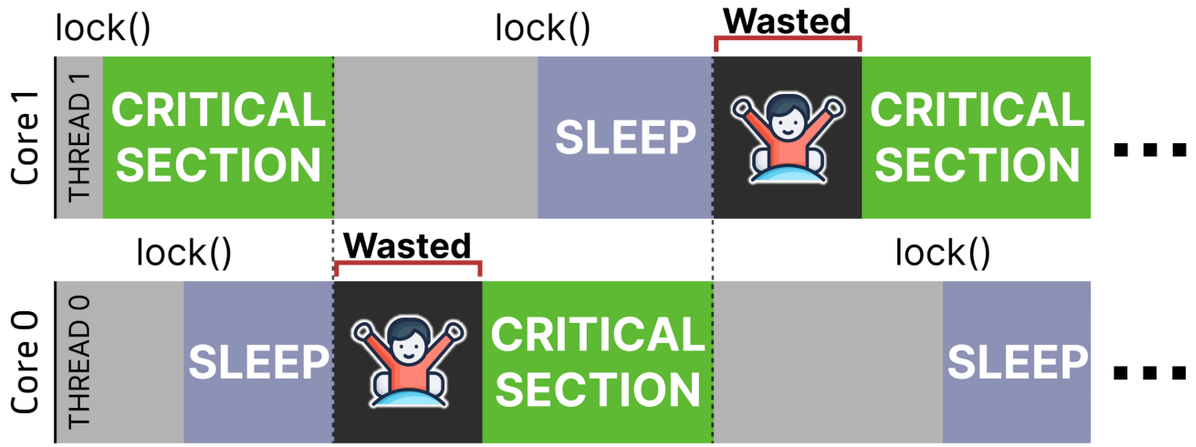

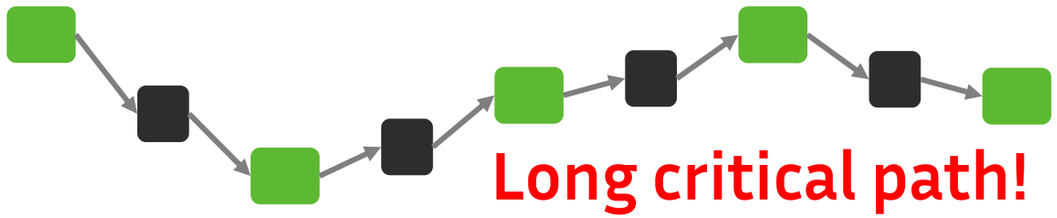

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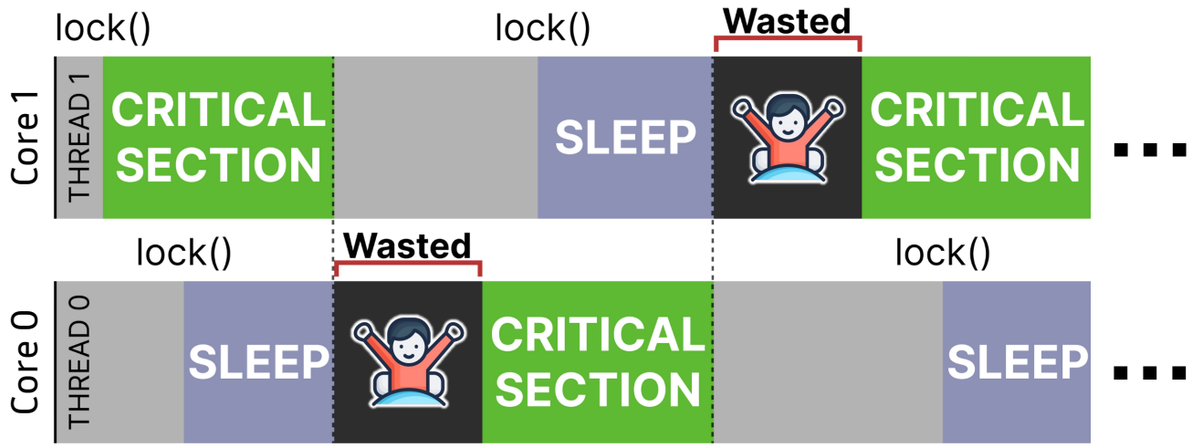

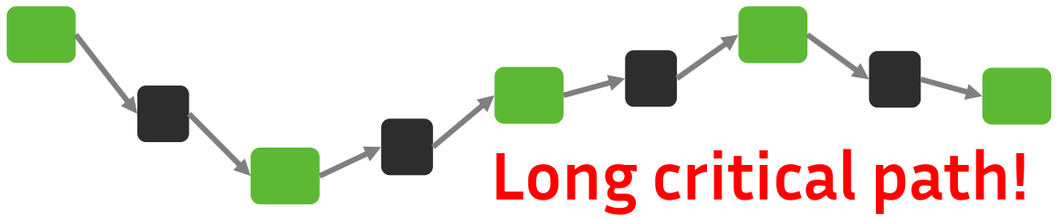

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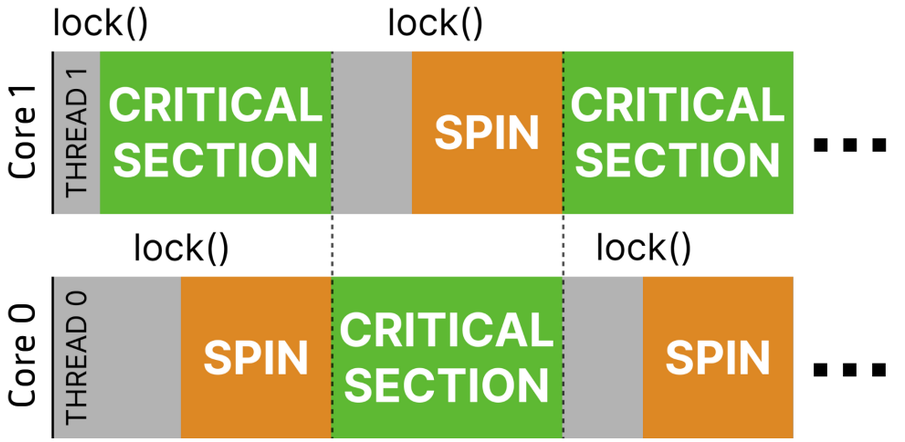

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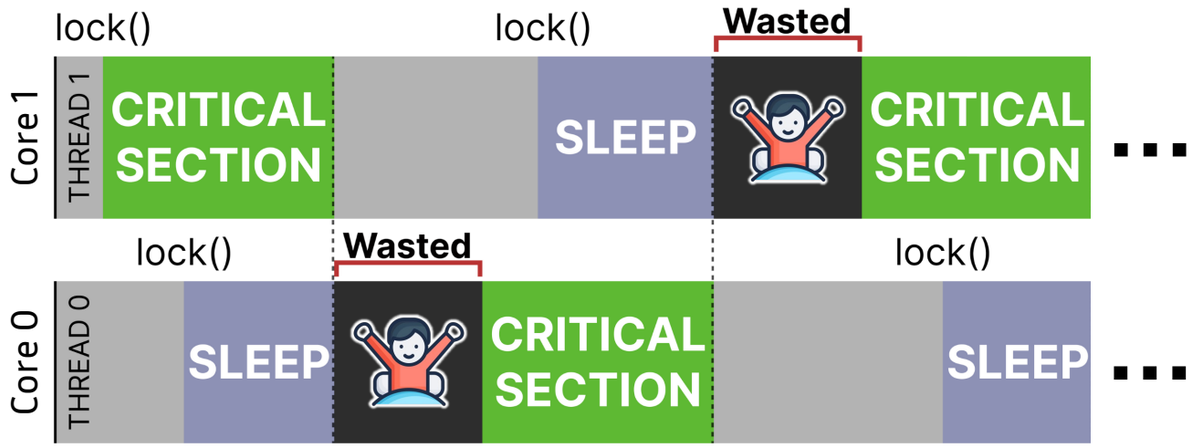

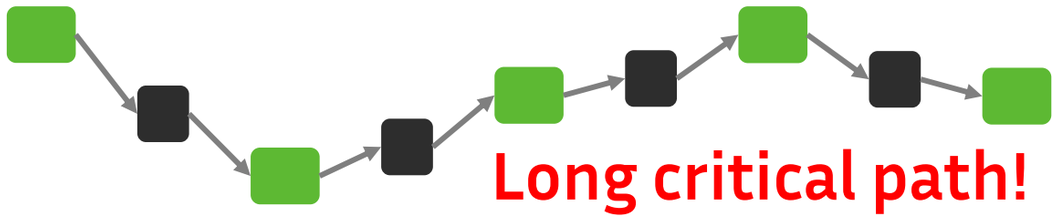

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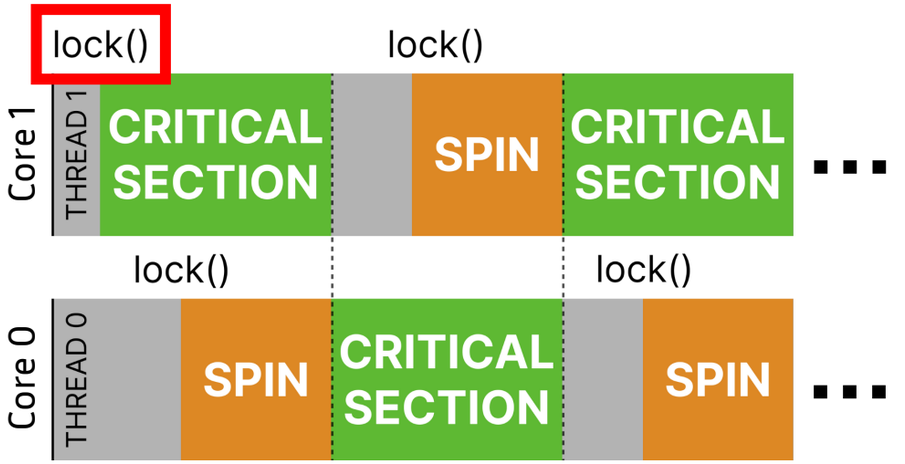

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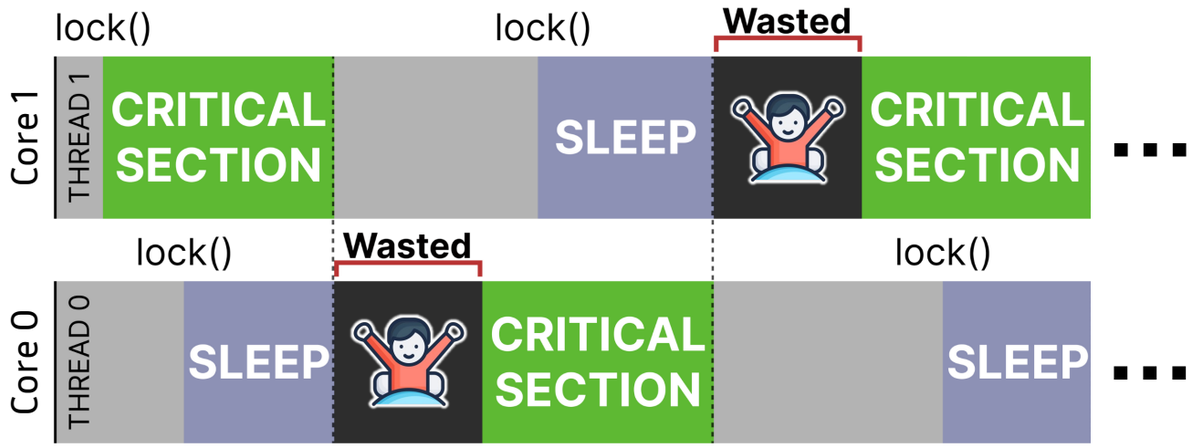

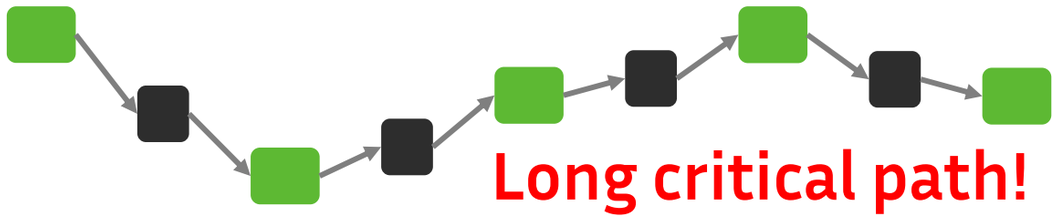

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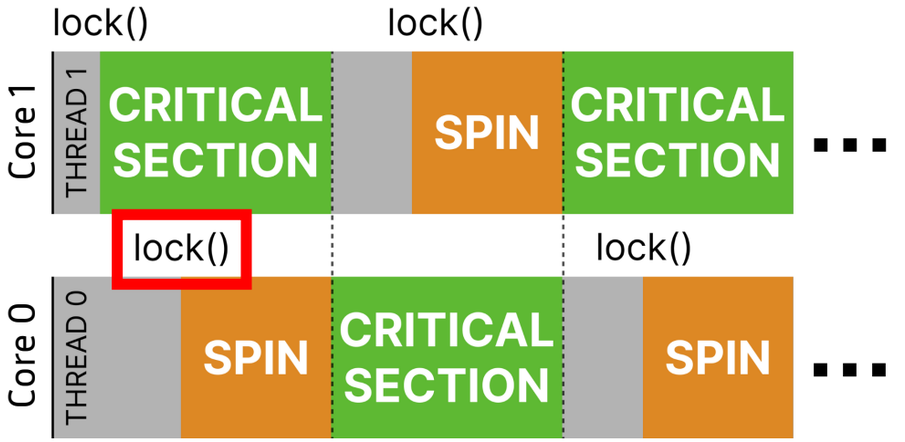

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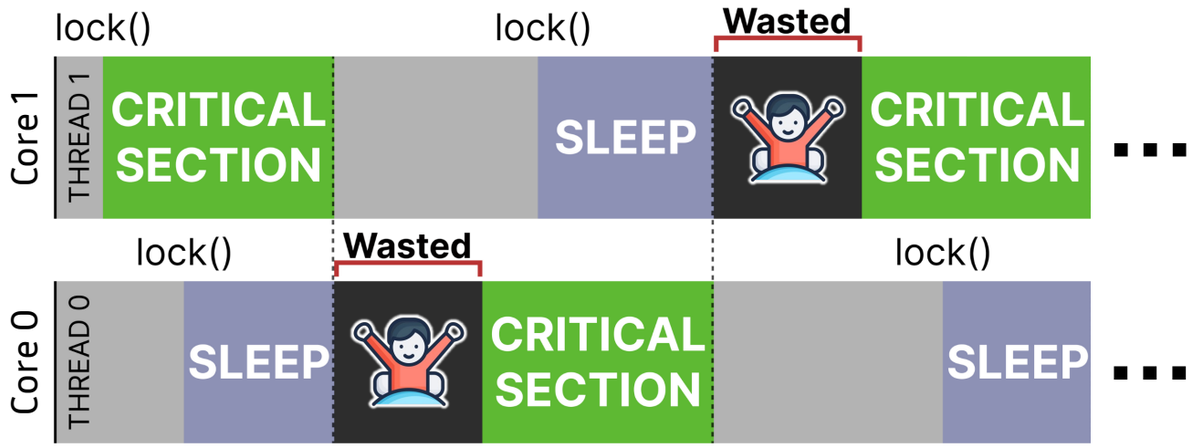

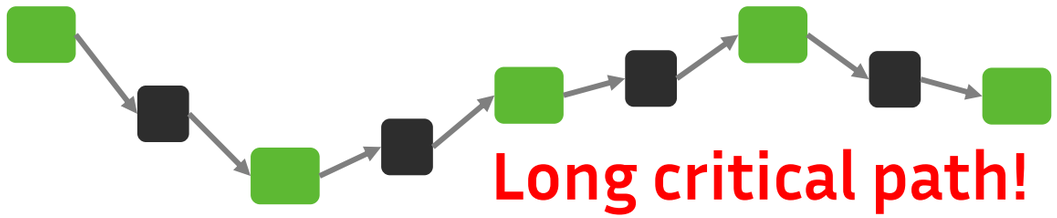

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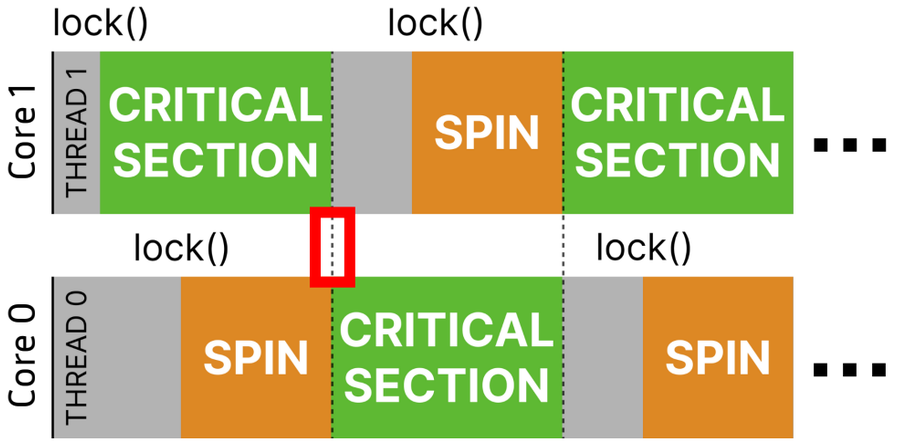

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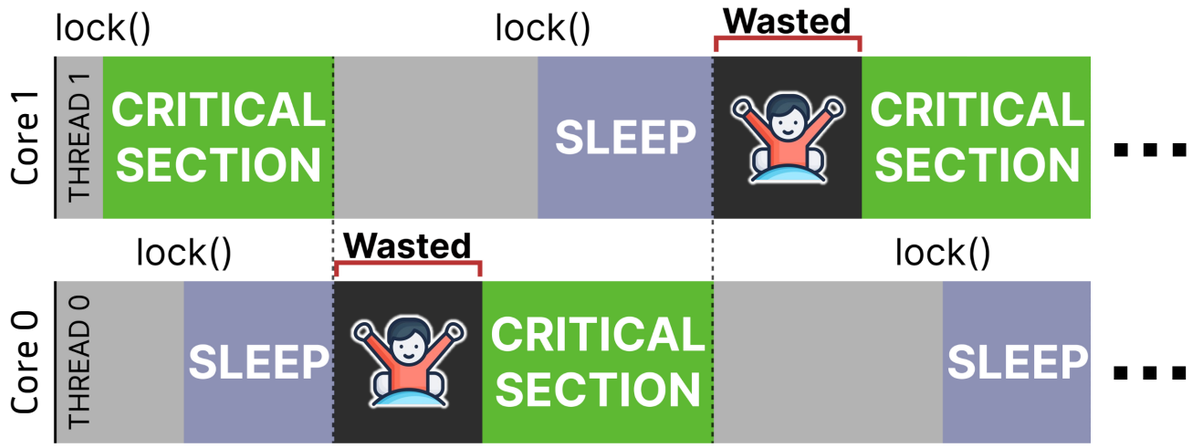

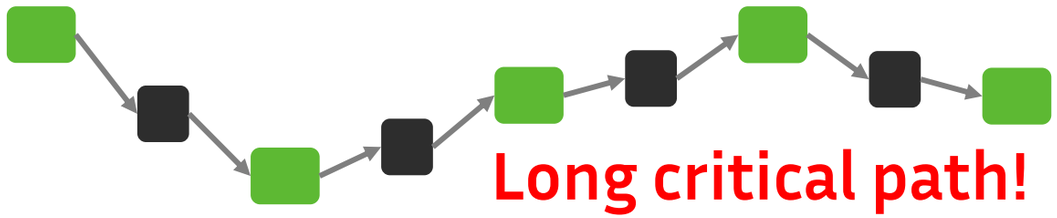

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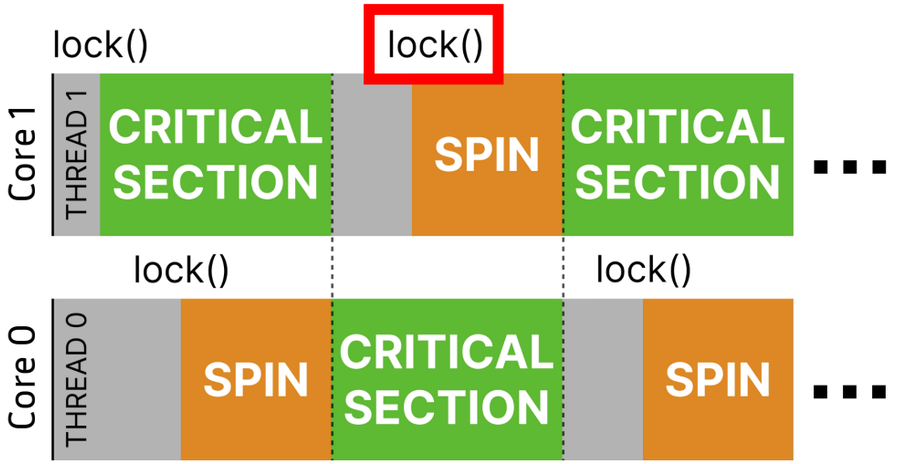

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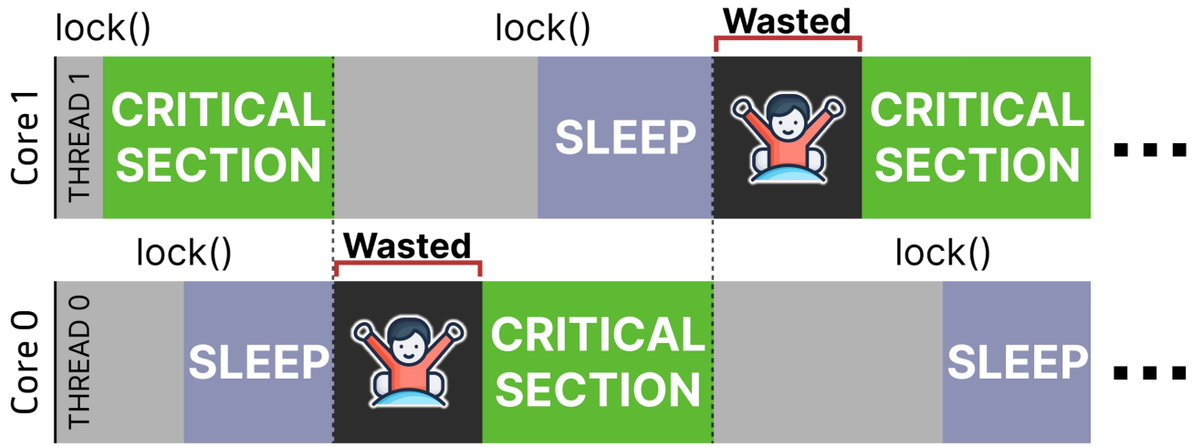

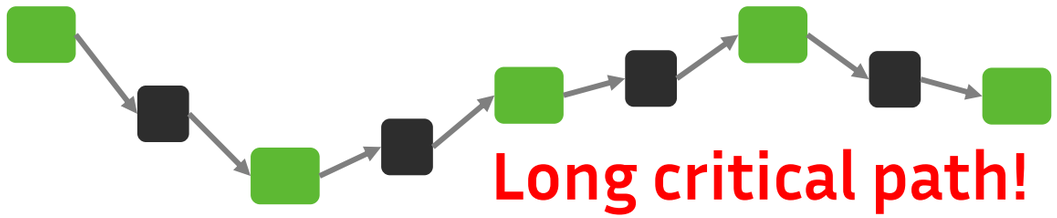

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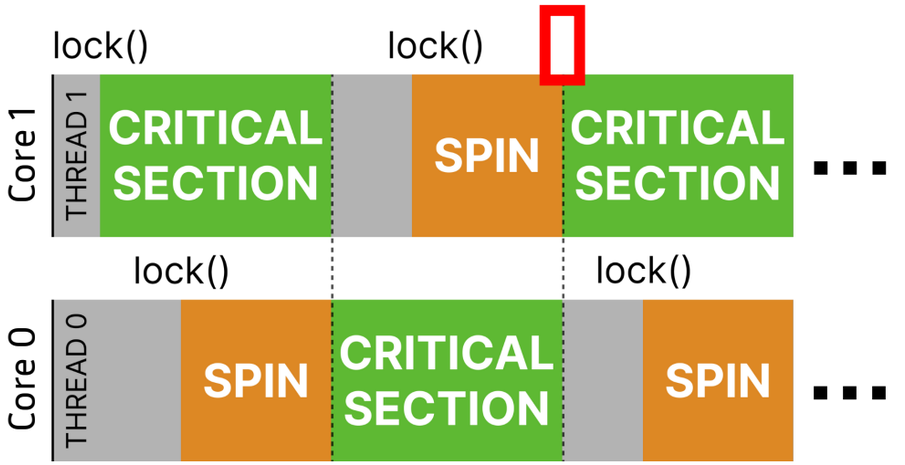

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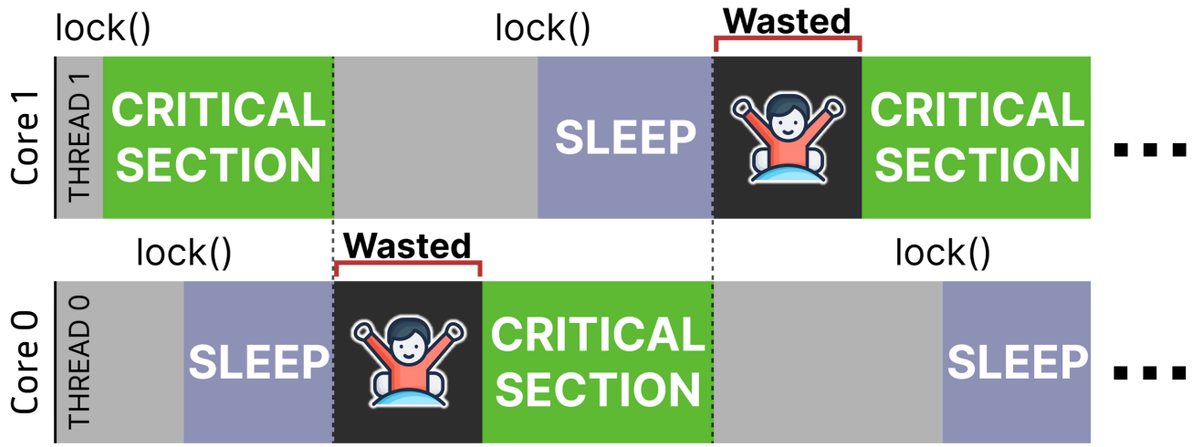

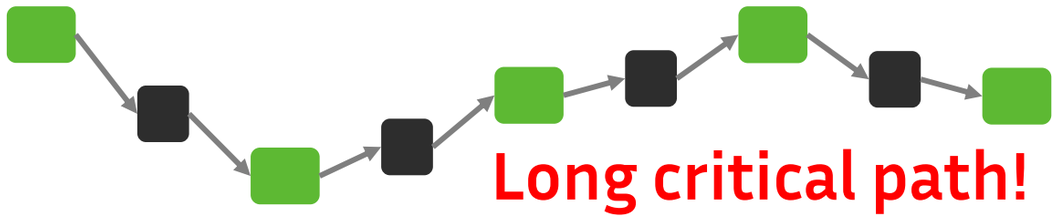

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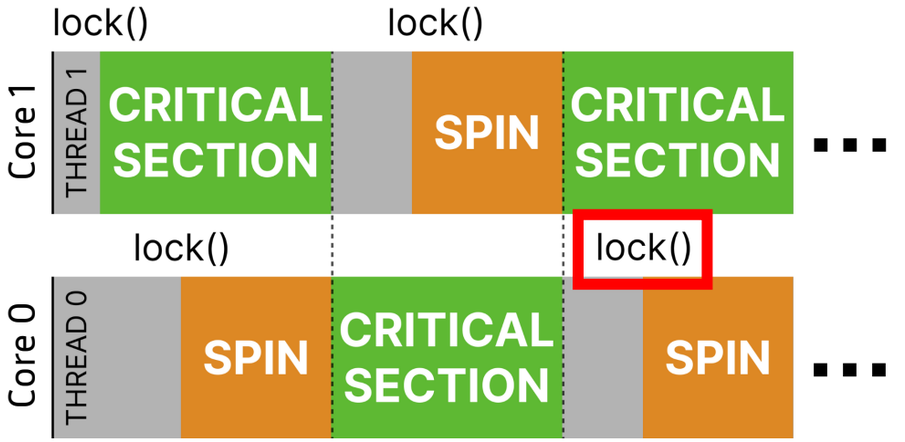

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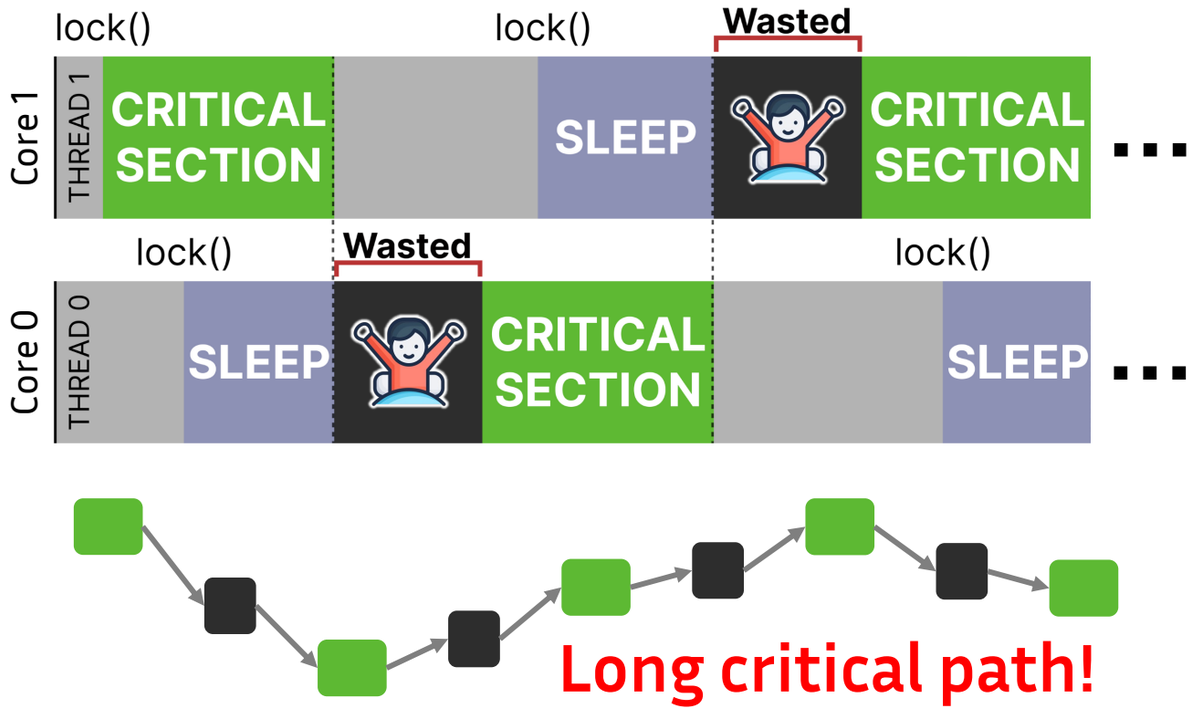

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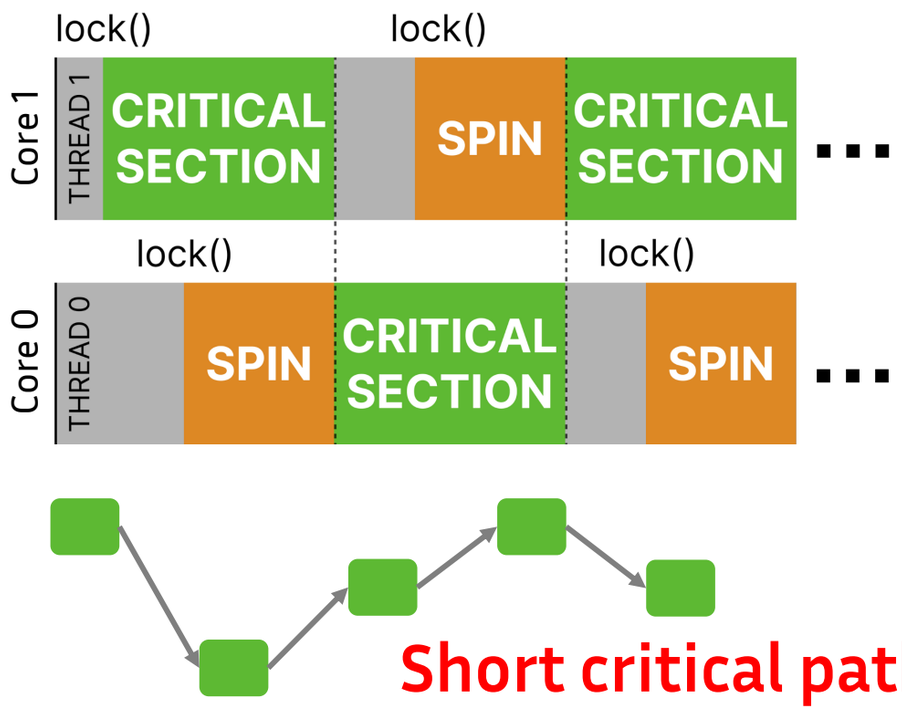

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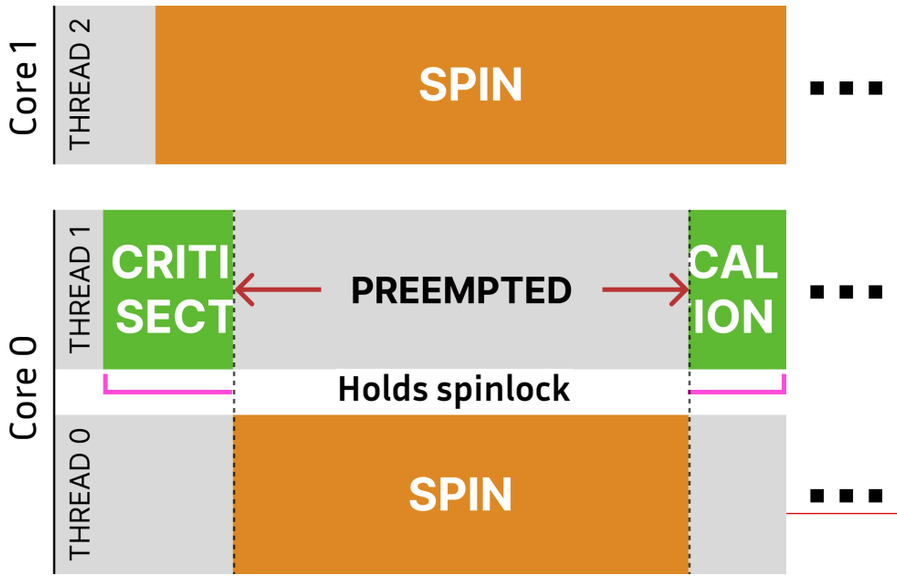

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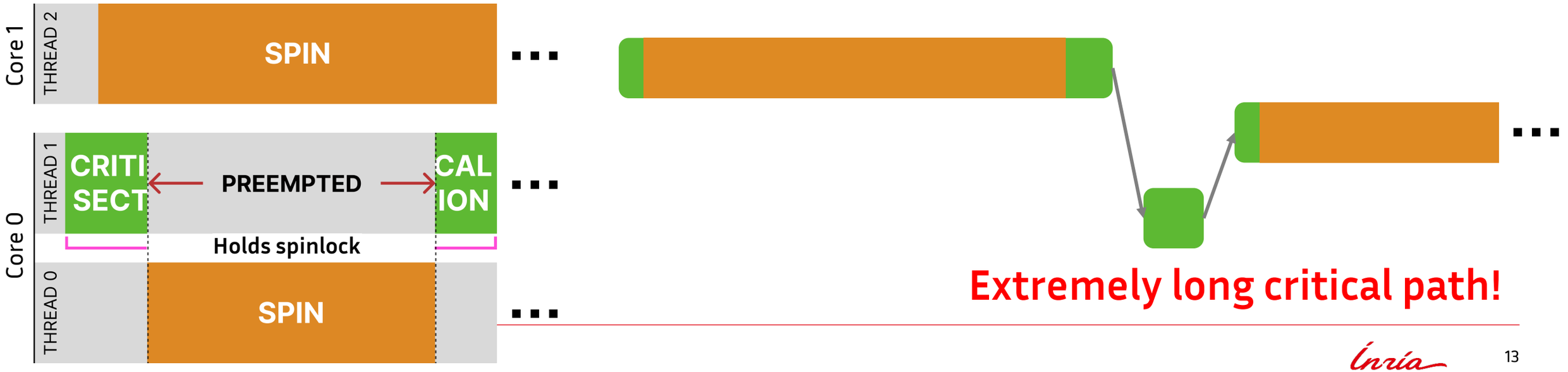

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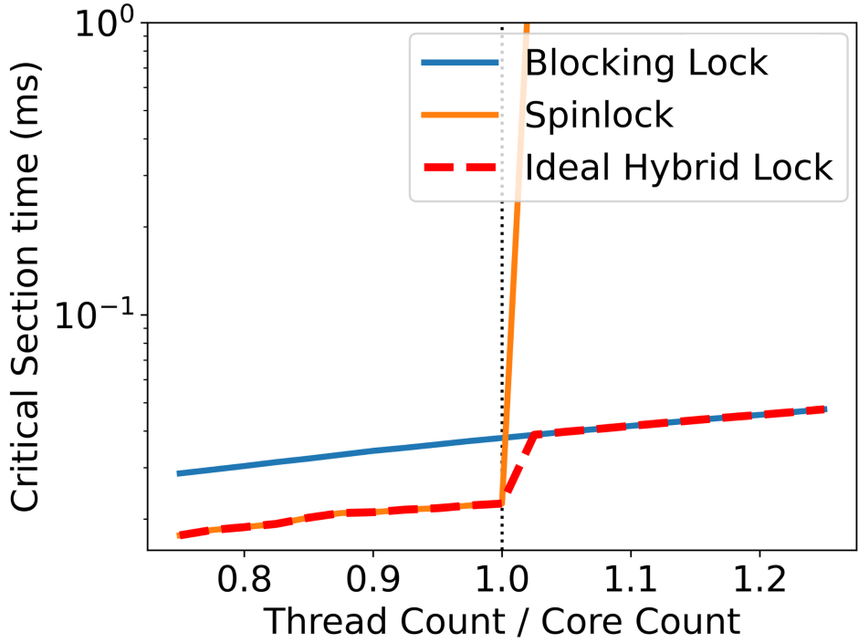

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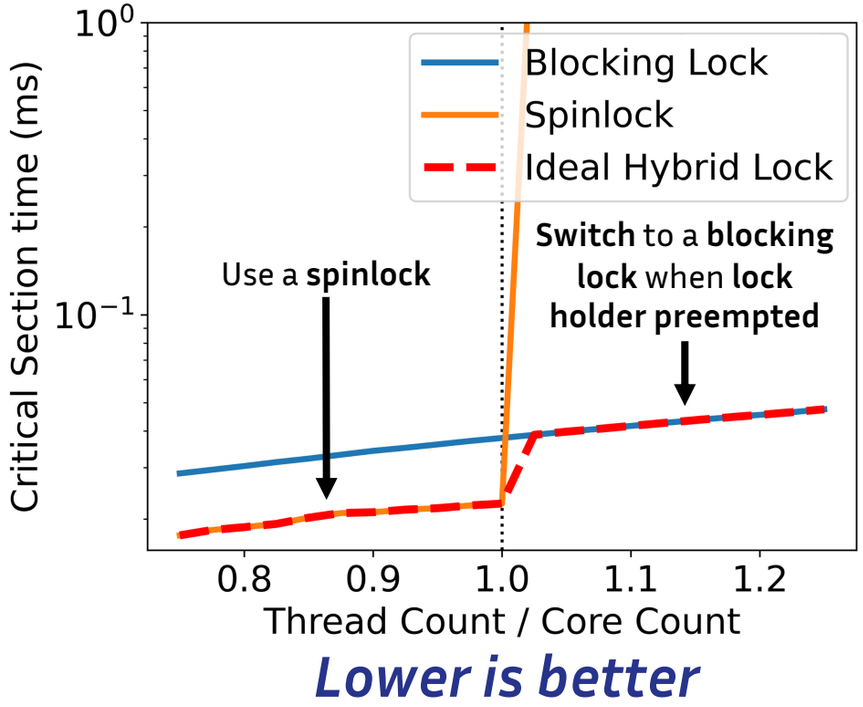

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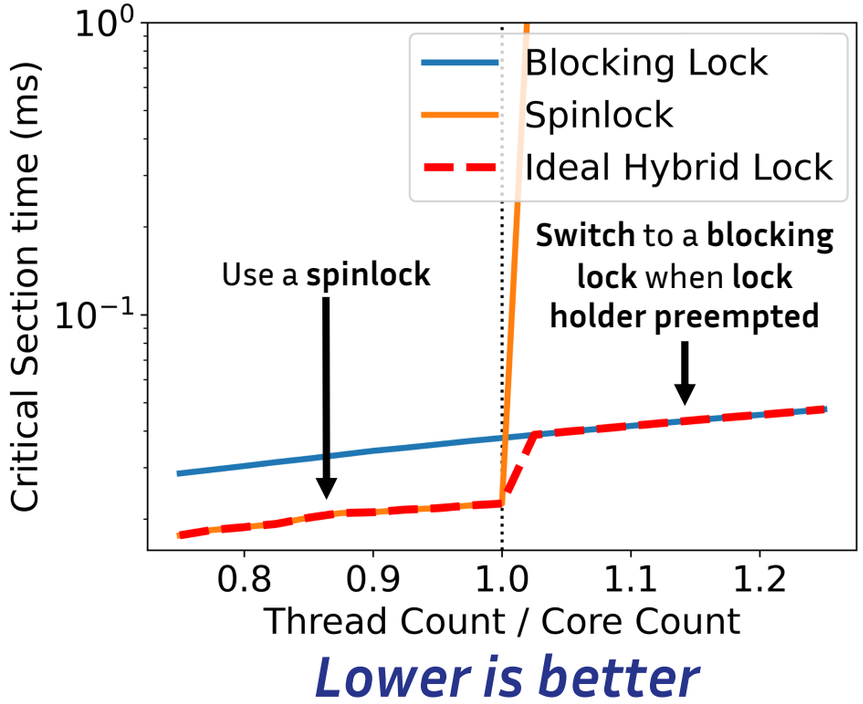

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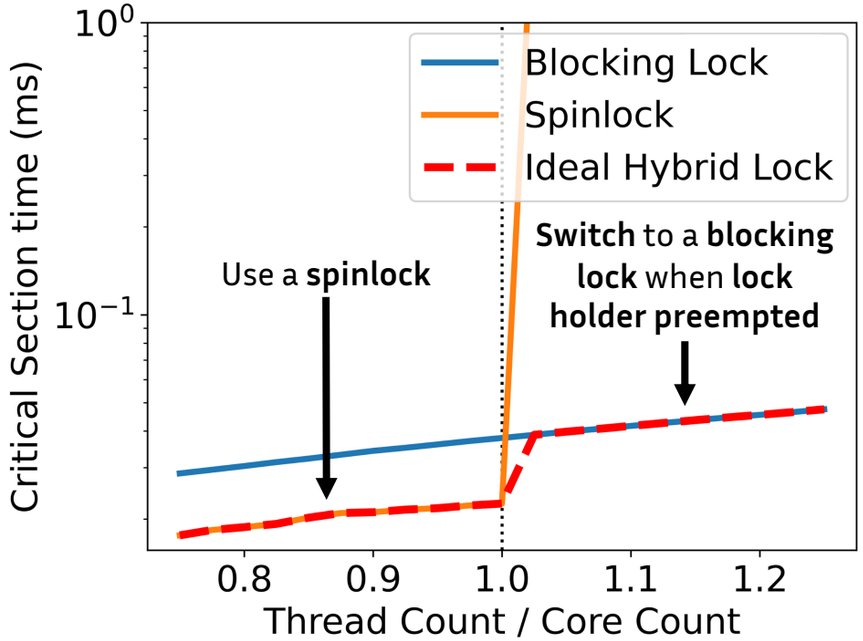

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- **Insight:** nowadays, with eBPF we can!
  - We can instrument context switches to see all preemptions
  - We can view the full state of the thread: preemption address + register contents

⇒ We can 100% tell whether we are in a critical section!

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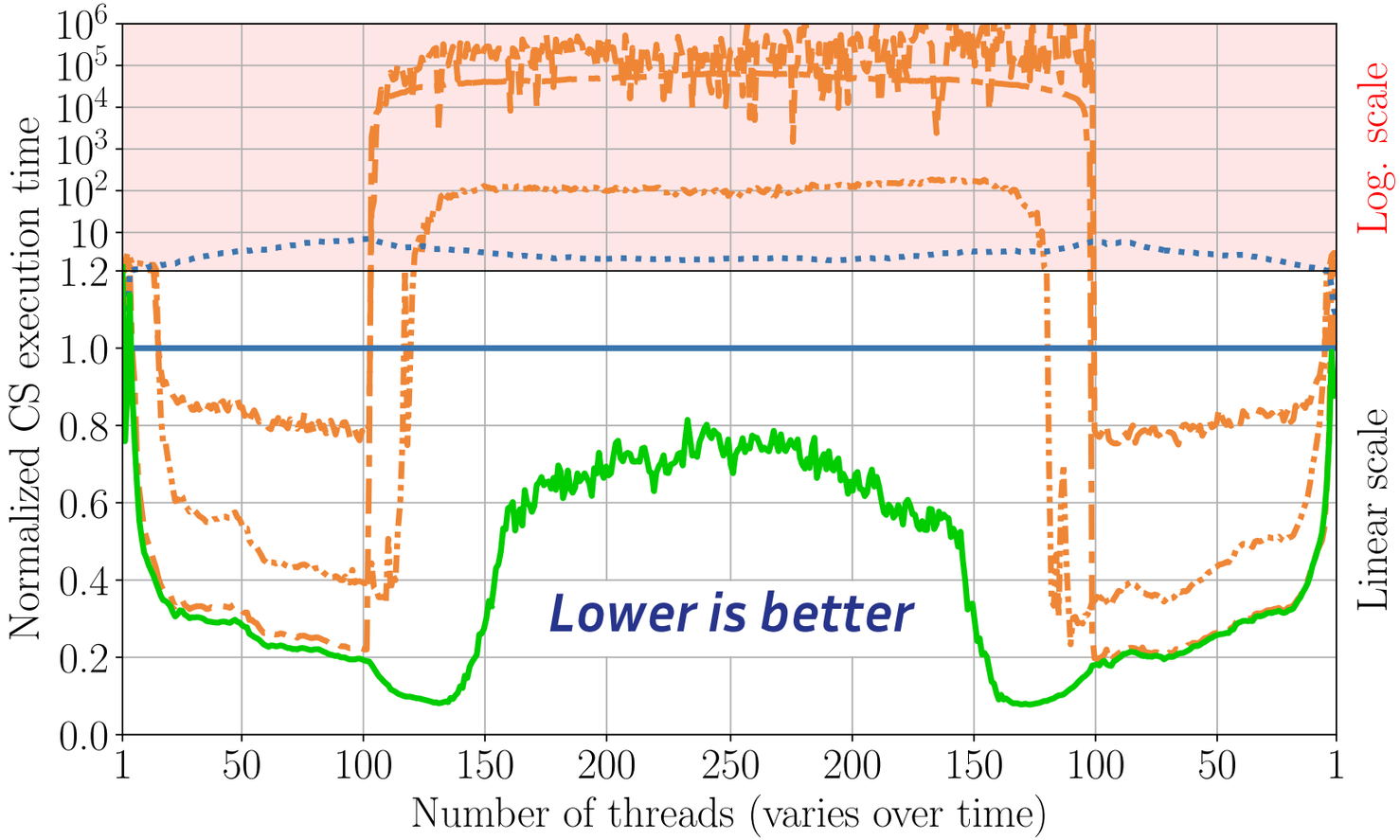
Orange: spinlocks **Blue:** blocking locks **Green:** our solution, **FlexGuard**



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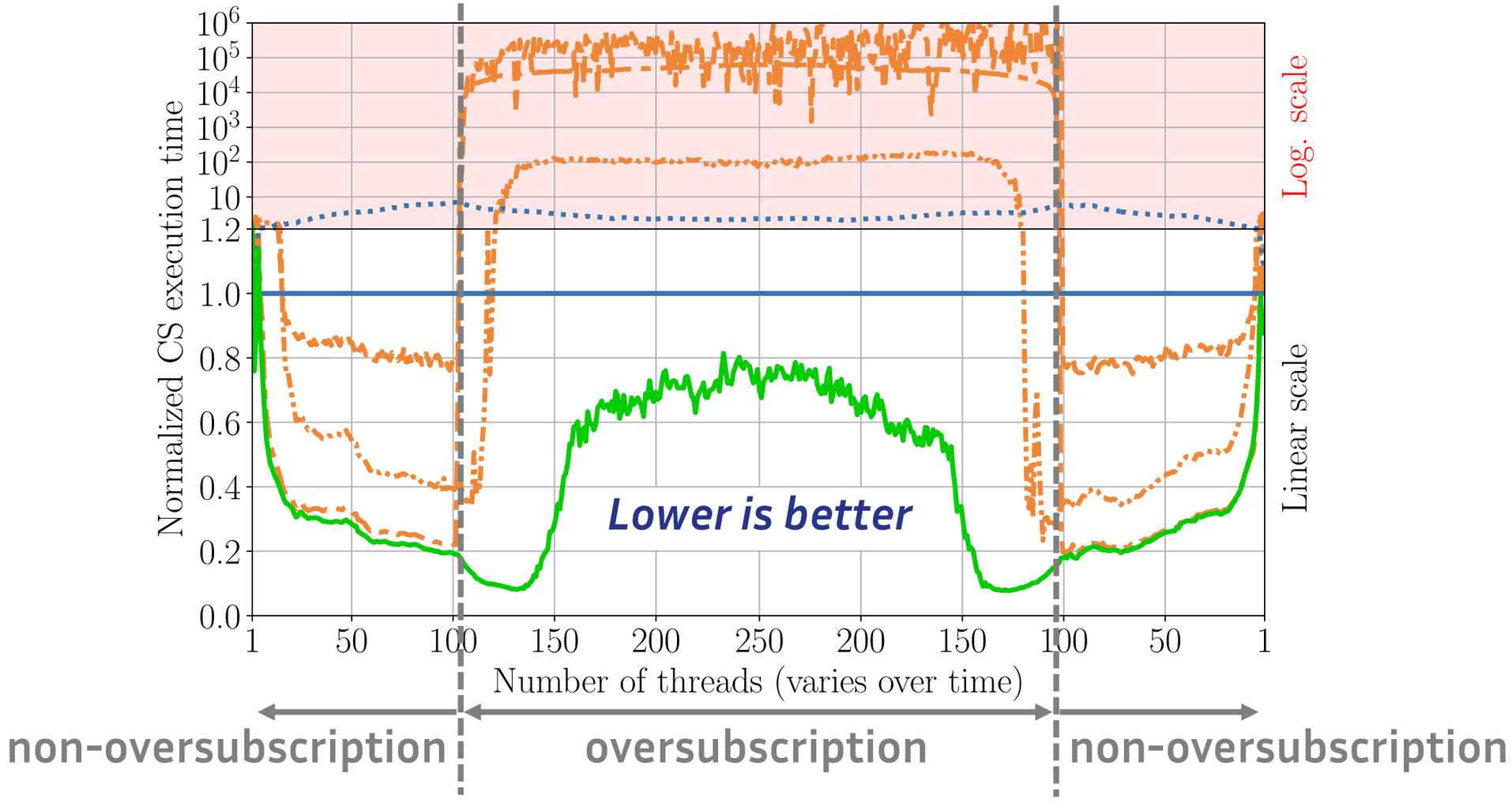

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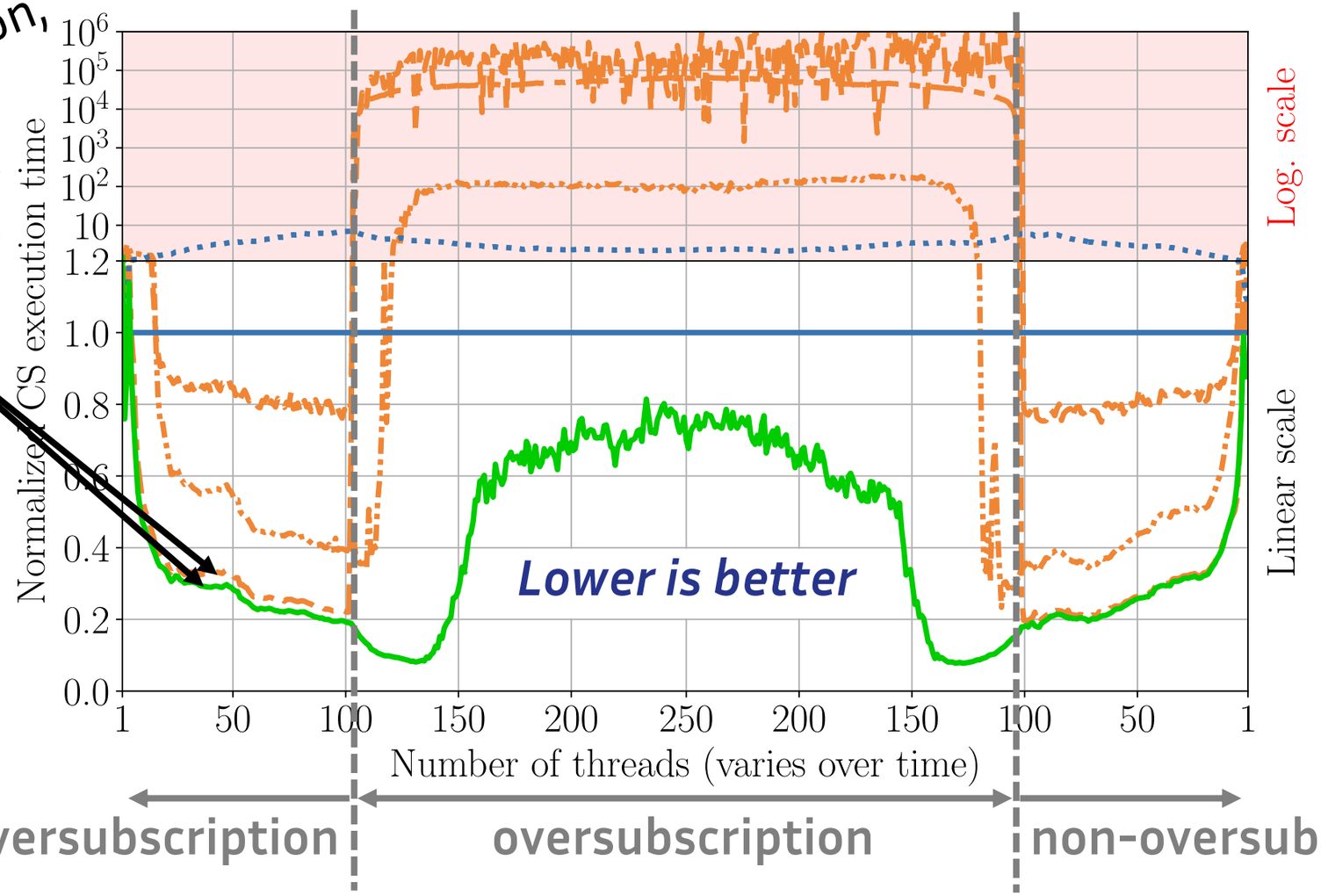
In non-oversubcription, FlexGuard matches the performance of the best spinlocks



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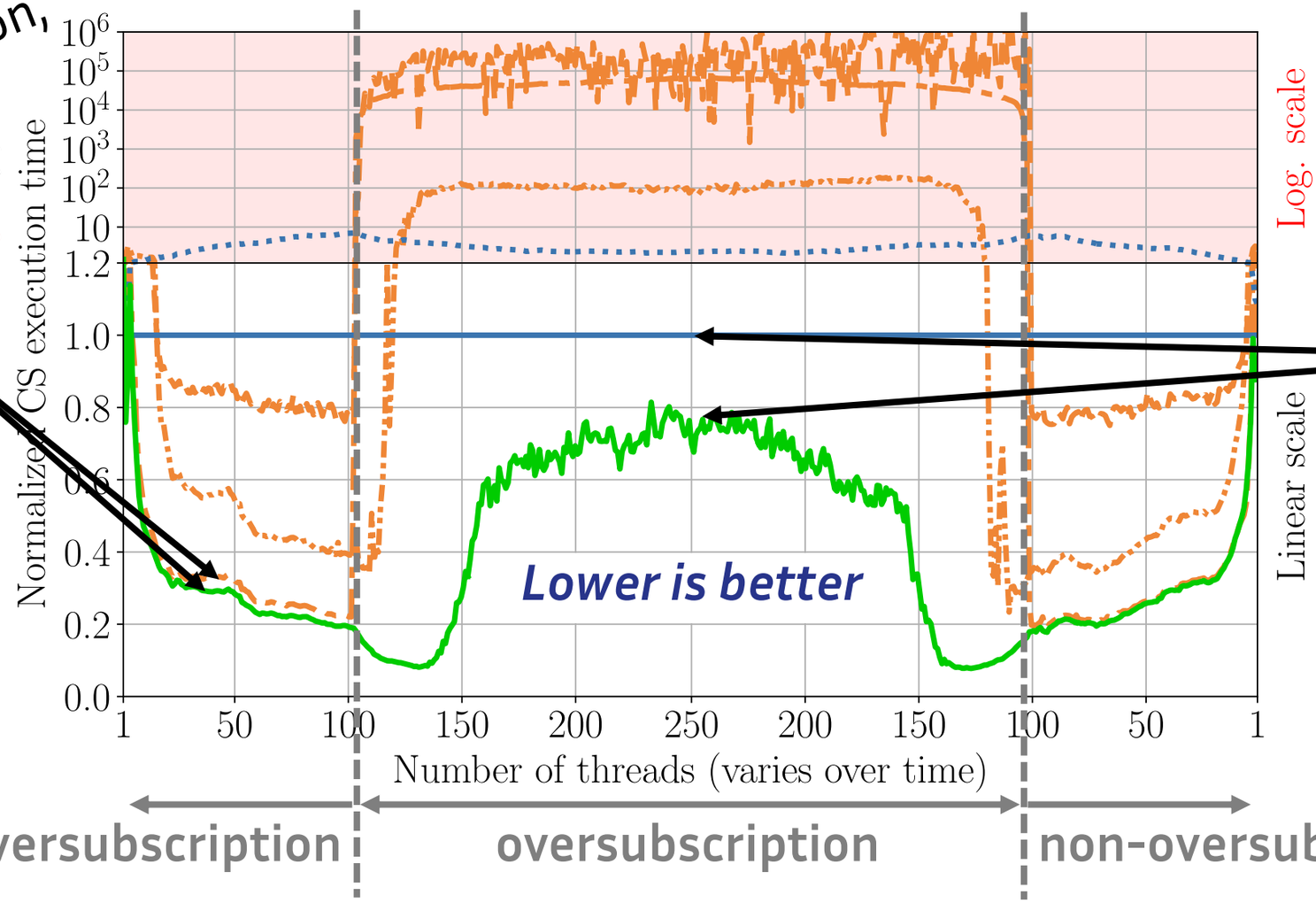

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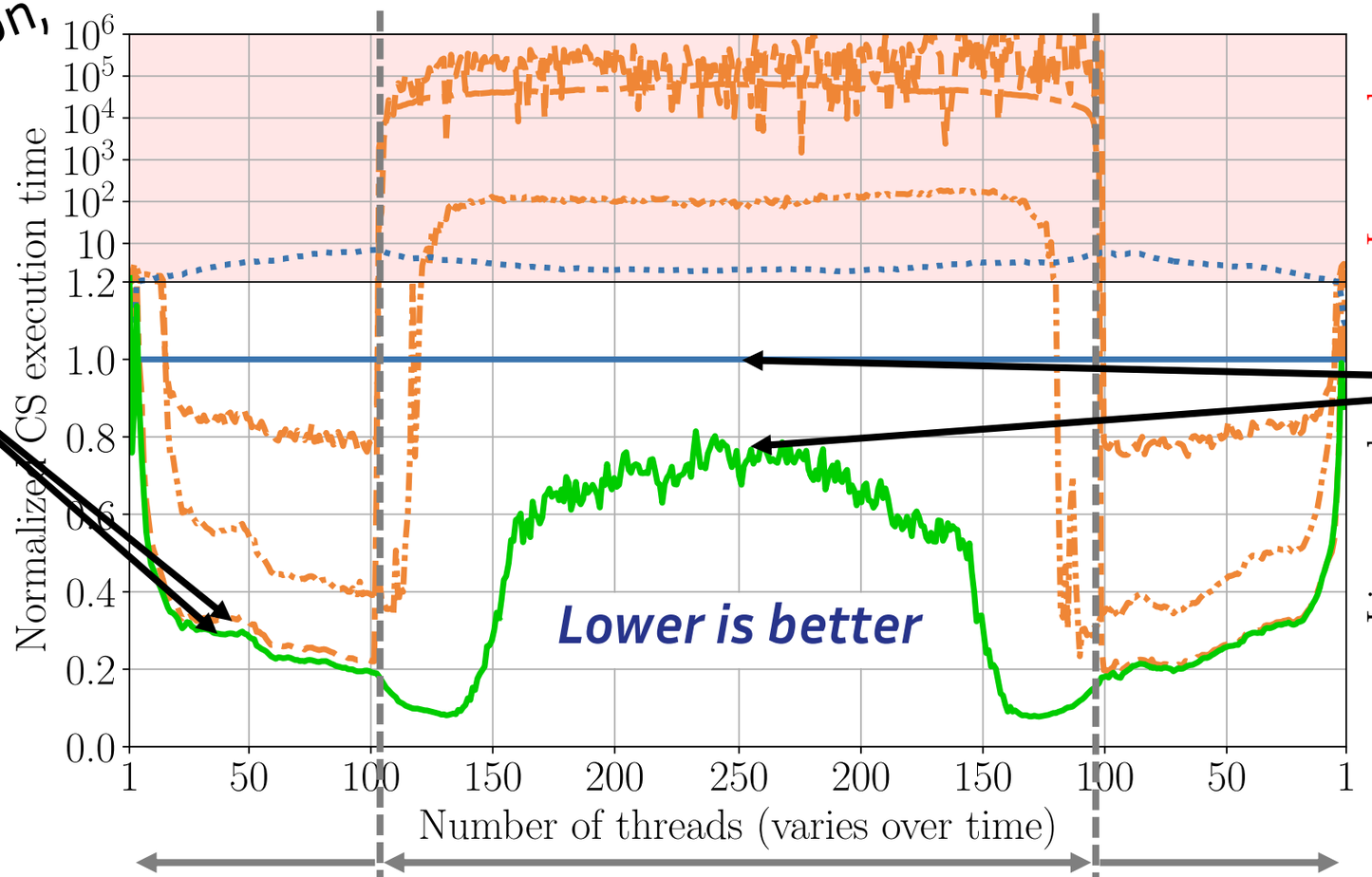

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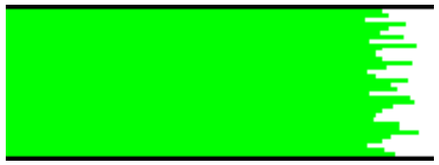

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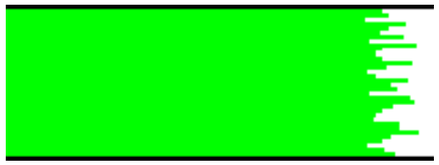

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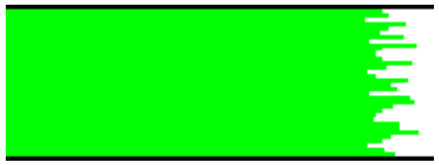

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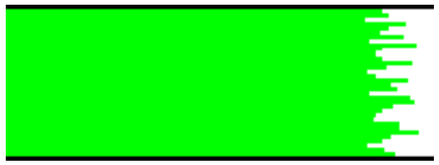

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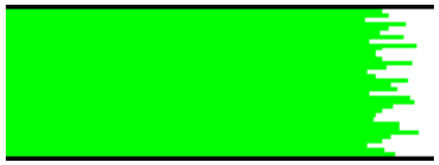

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T_A busy-waits

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while (compare_and_swap(&lock, 0, 1))
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reads

Shared memory

0x…a0	0x00000001
data address	**lock** value

T_B resolves the dependency

0x…38	cmp	%eax, %edx
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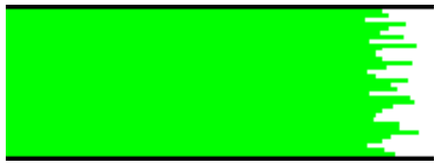

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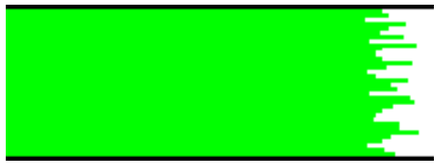

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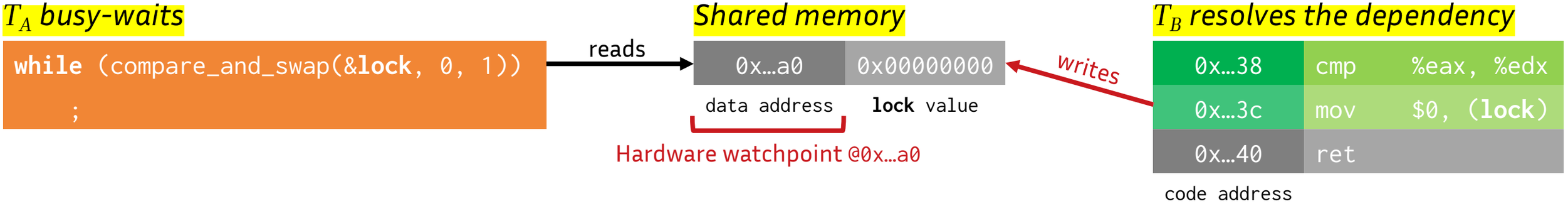

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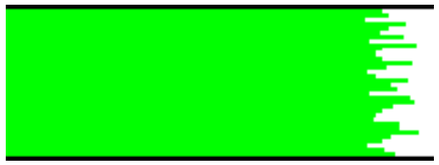

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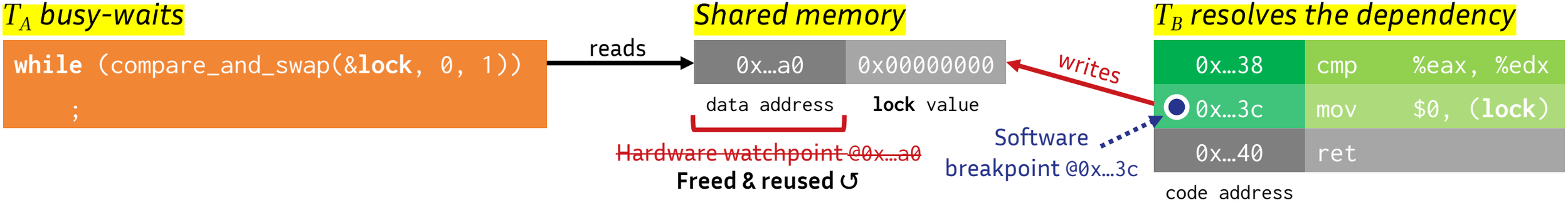

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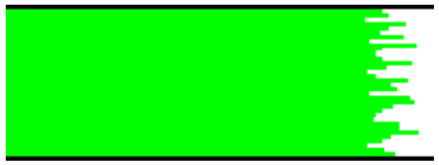

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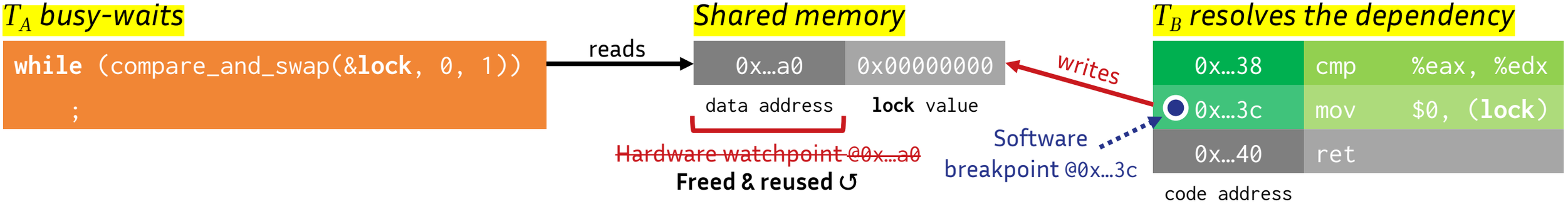

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With a dependency graph, we can run a longest path algorithm to highlight the **critical path!**

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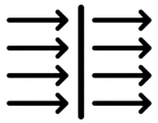

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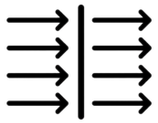

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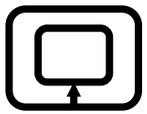

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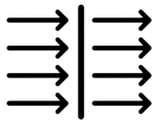

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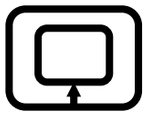

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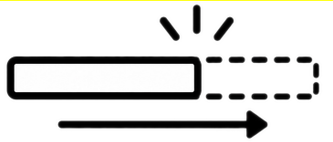

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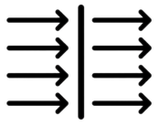

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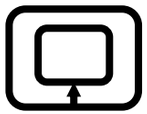

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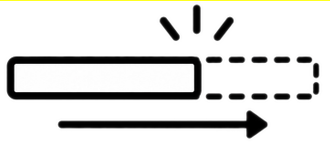

How to best use it?

Towards a new pthread lib?

Fast but also practical, stable algorithms

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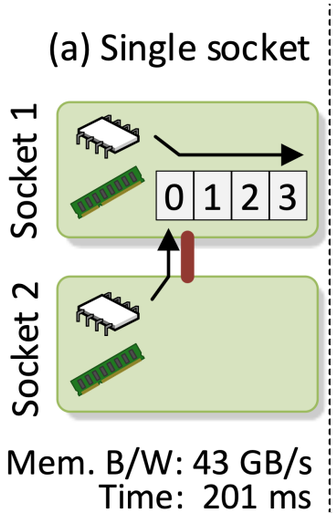

Single-socket

→ **Bottleneck:** socket's memory bandwidth

→ Fast for half the threads

→ *Can perform fine with e.g., good load balancing*

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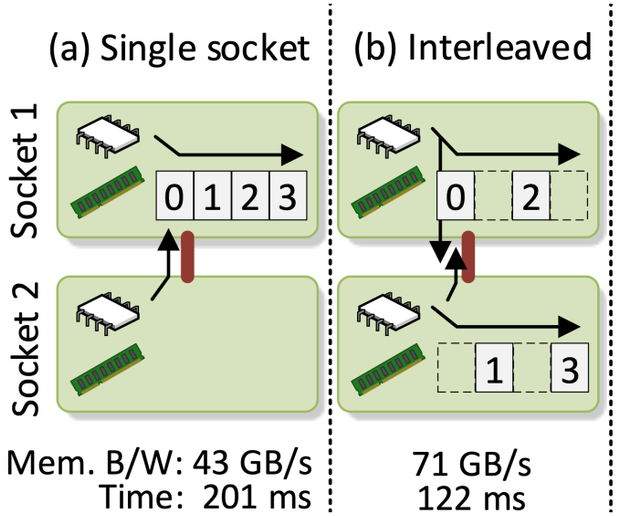

Interleaved

→ More bandwidth (2 sockets)

→ **Bottleneck:** interconnect

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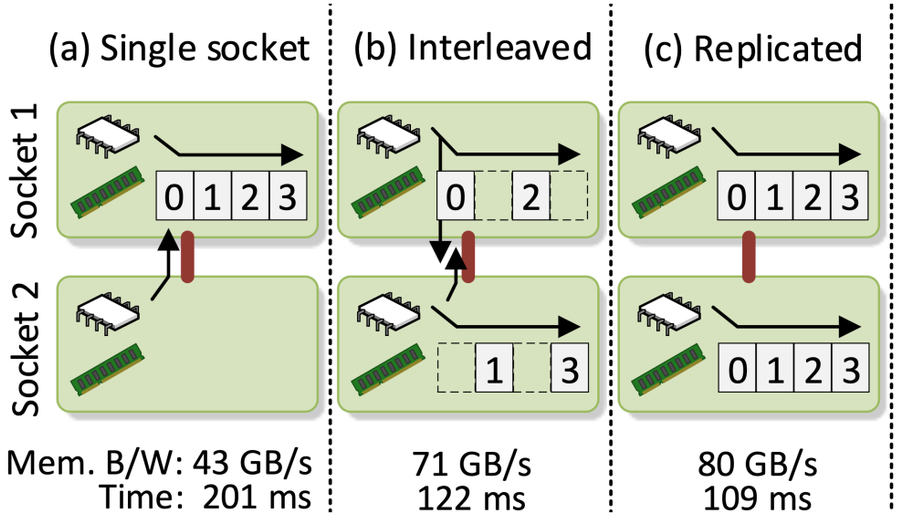

Replicated

→ Only works for read-mostly workloads

→ Removes the interconnect bottleneck

→ Needs enough memory

→ *Replica-building worth it?*
(Multiple/random accesses?)

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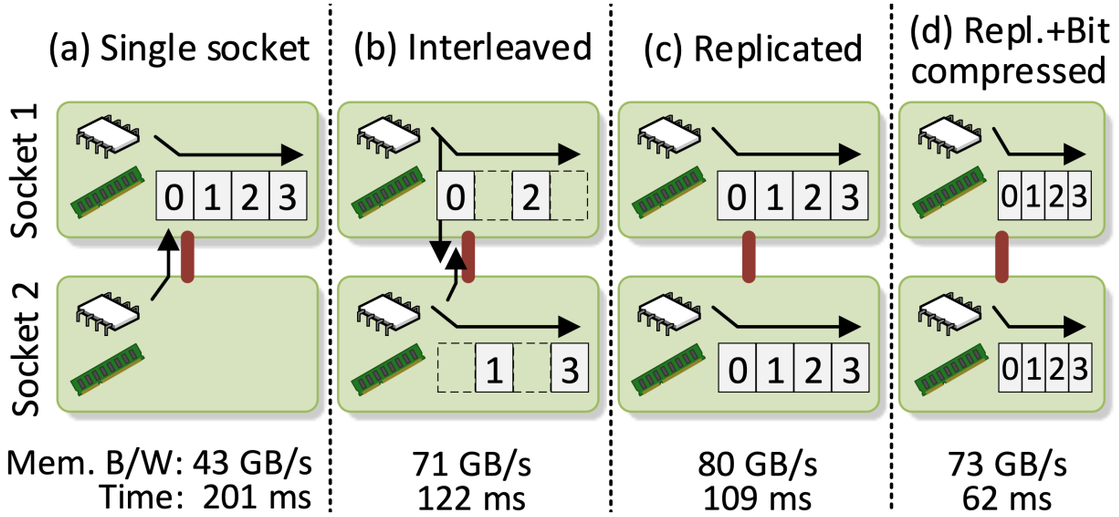

Replicated + Bit compressed

→ Use memory bandwidth more productively

→ Shrinks memory footprint

→ CPU can be a bottleneck

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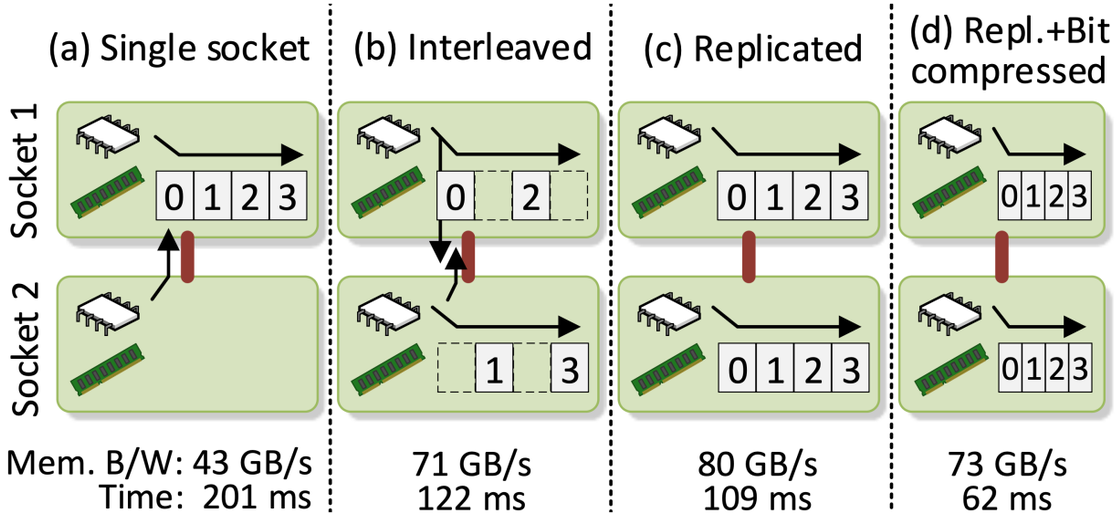

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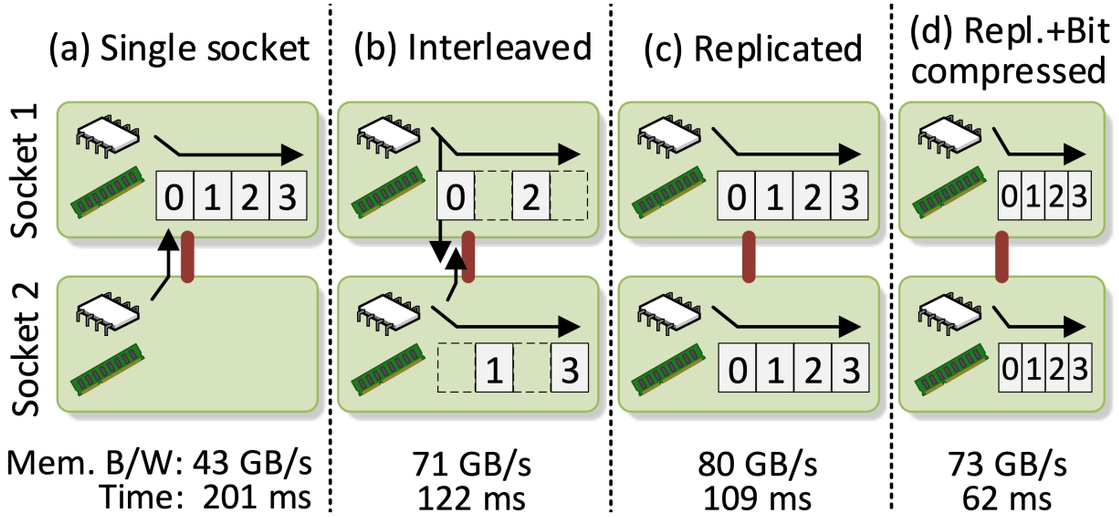

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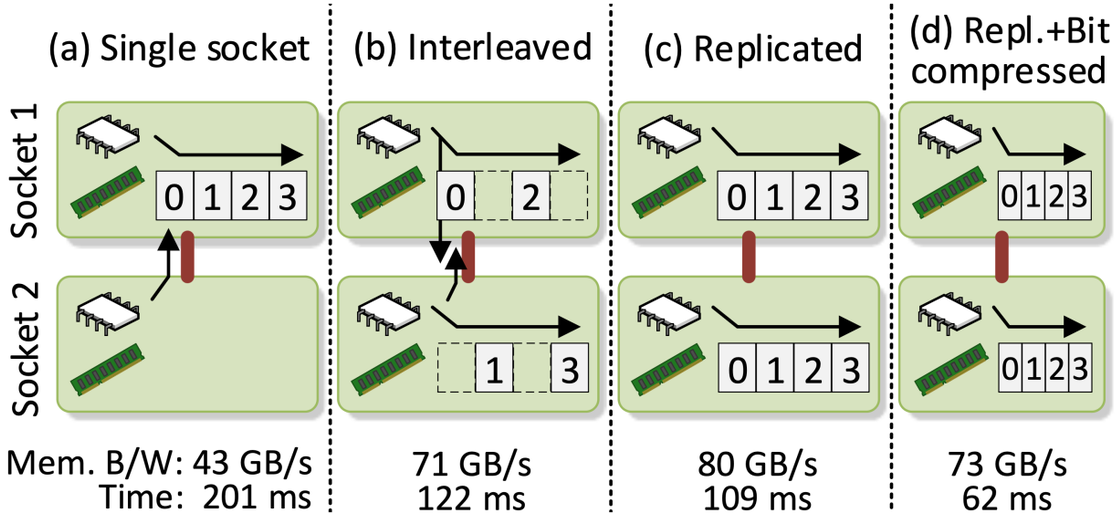

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+Adaptivity!

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- **Goal:** process PGQL queries like,

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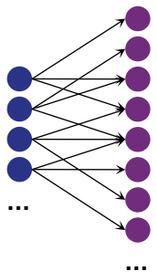
1. Find all matching `a`s
2. Materialize all matching `a->b`s

BFS



3. Graph Analytics: aDFS [USENIX ATC '21]

- **Goal:** process PGQL queries like,

```
SELECT a, c WHERE (a:author) -[:wrote]-> (b:paper) -[:cite]->
                  (c:paper) <-[:wrote]- (d:author)
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  "Pairs of authors who wrote papers that cite each other"

- **BFS vs. DFS tradeoff:** `(a) -> (b) -> (c) <- (d)`

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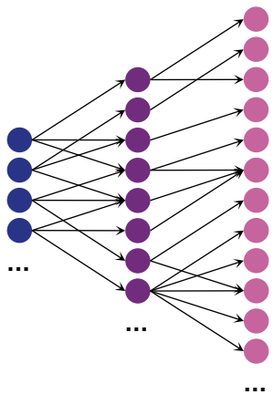

1. Find all matching **a**s
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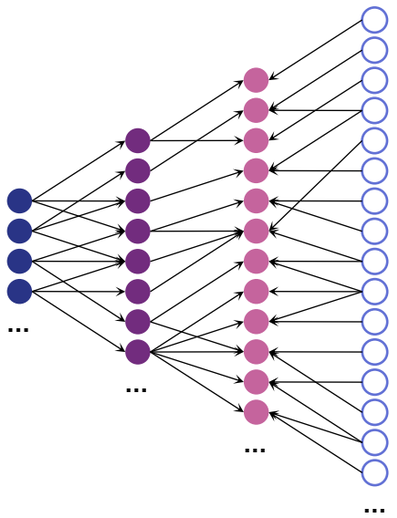

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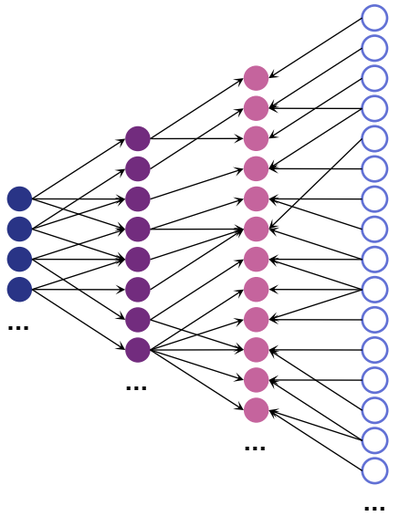

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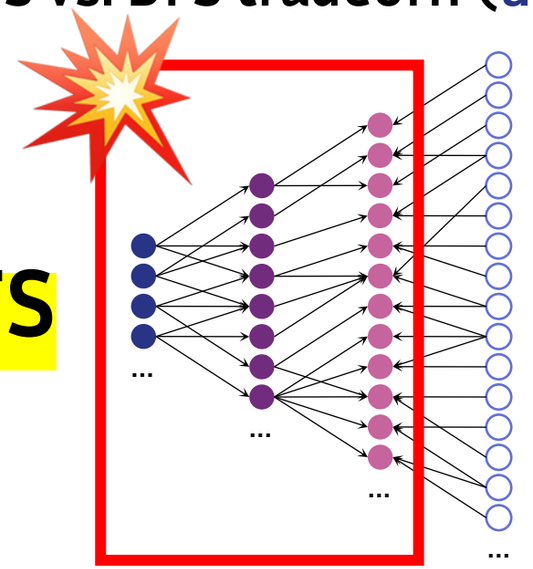

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☹ **Intermediate result explosion!**

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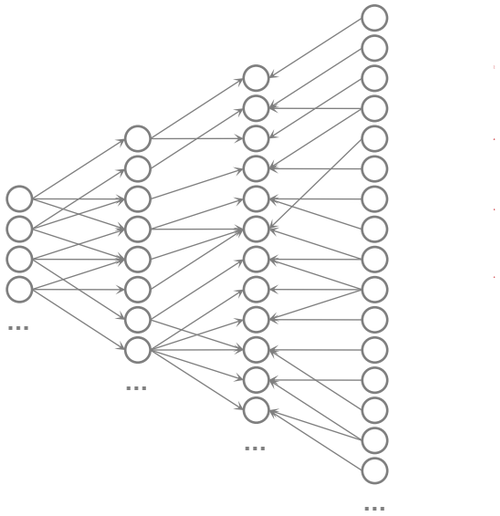

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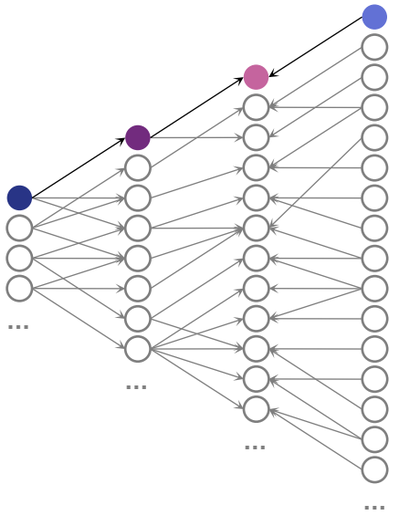

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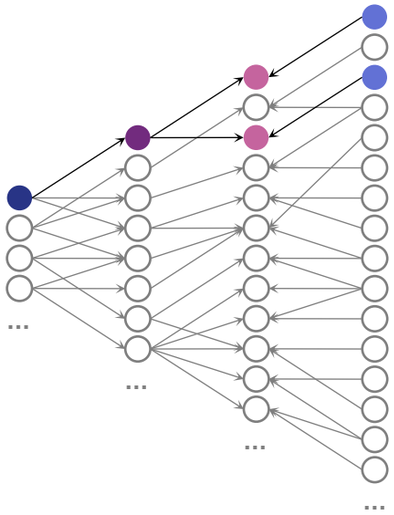

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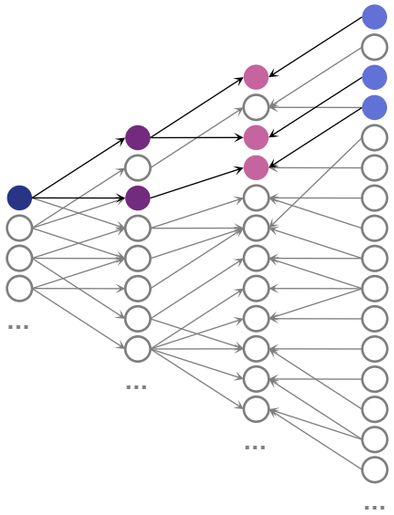

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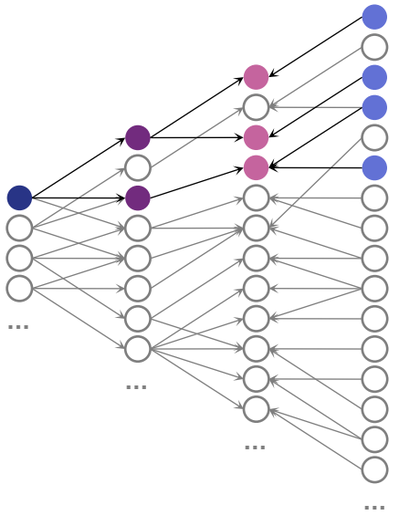

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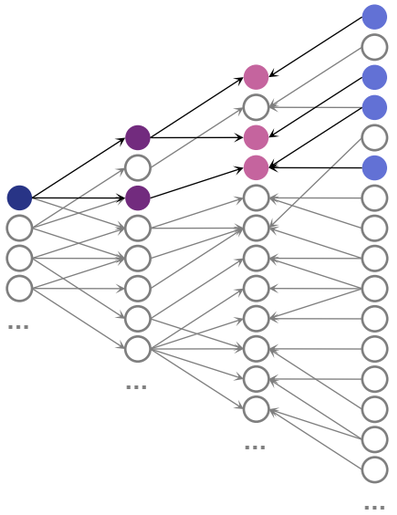

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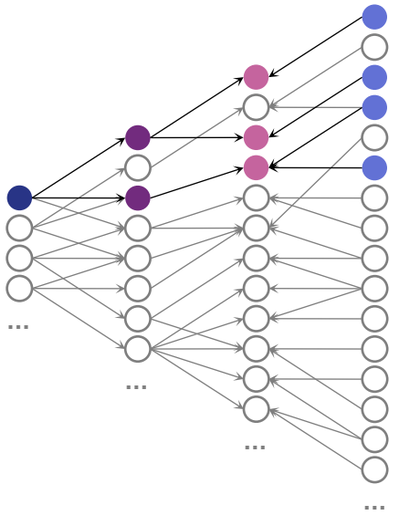

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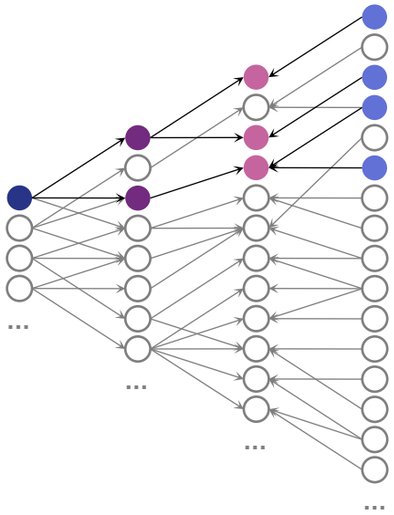

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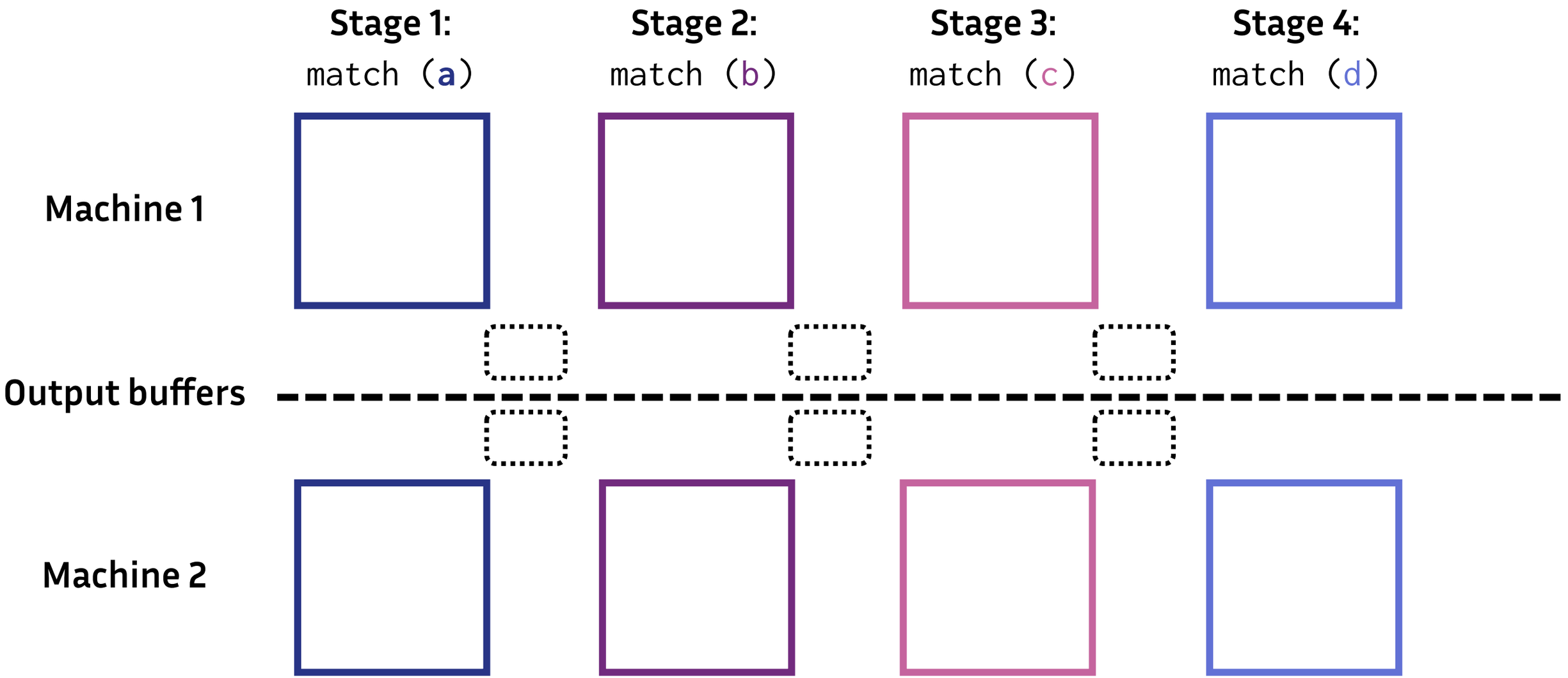
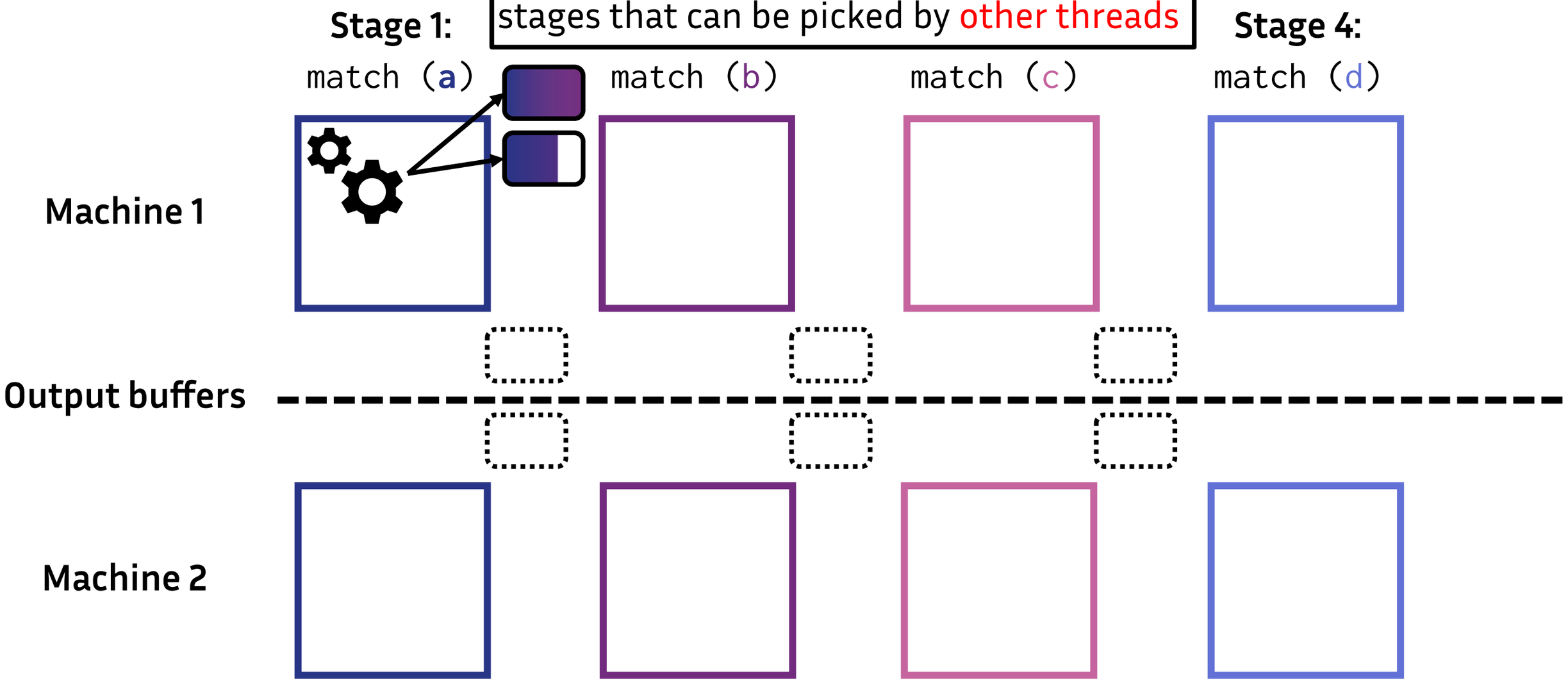
Insight of aDFS: just enough BFS to keep all cores busy!

3. Graph Analytics: aDFS [USENIX ATC '21]



3. Graph Analytics:

Start with BFS
Not enough work to keep threads busy?
Buffer intermediate results for the next stages that can be picked by other threads



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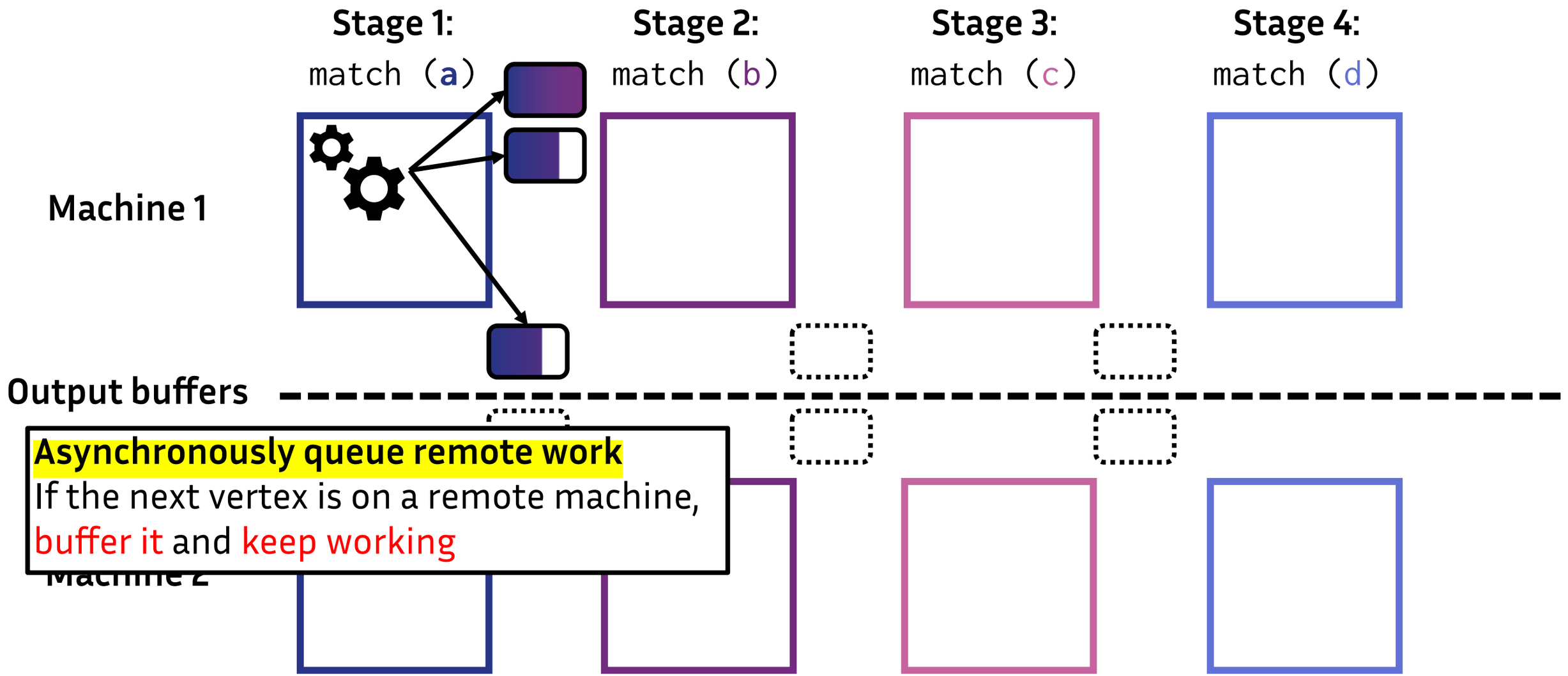
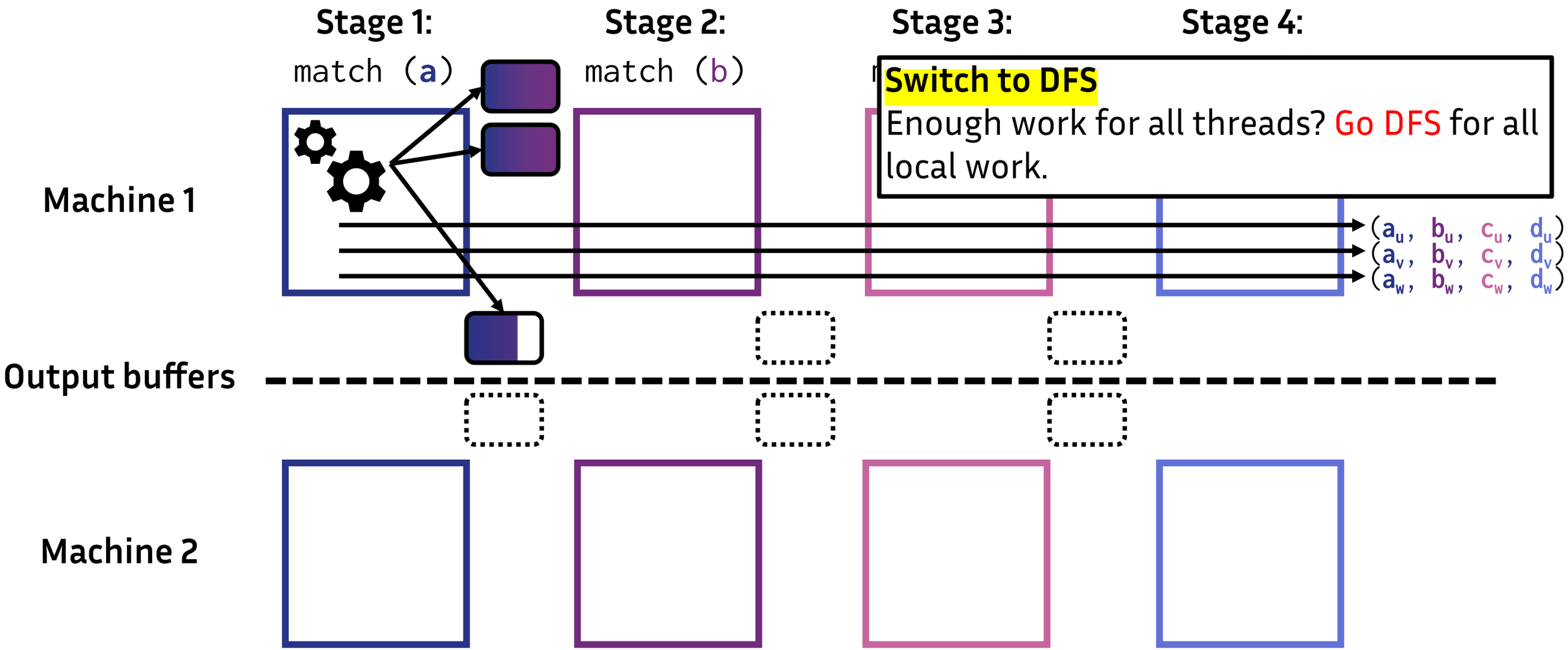


Asynchronously queue remote work

If the next vertex is on a remote machine, buffer it and keep working

3. Graph Analytics: aDFS [USENIX ATC '21]



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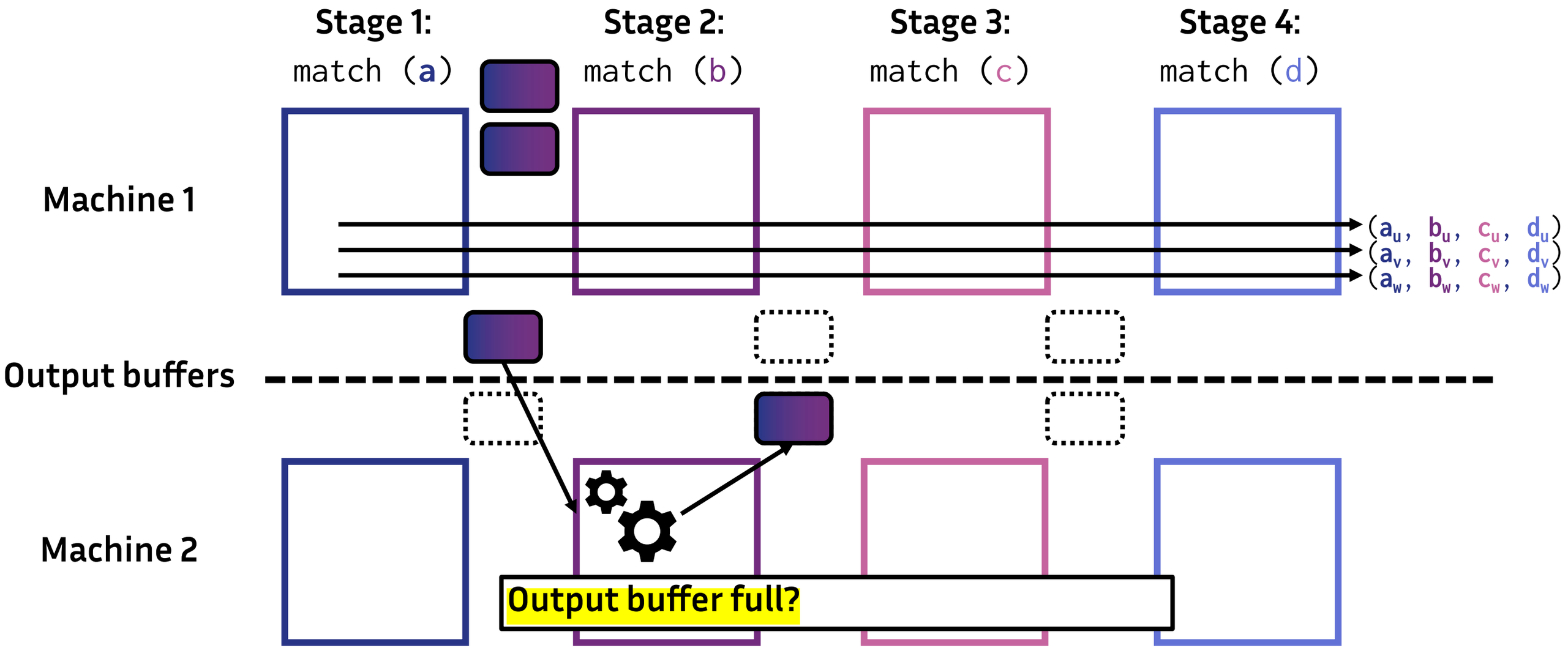

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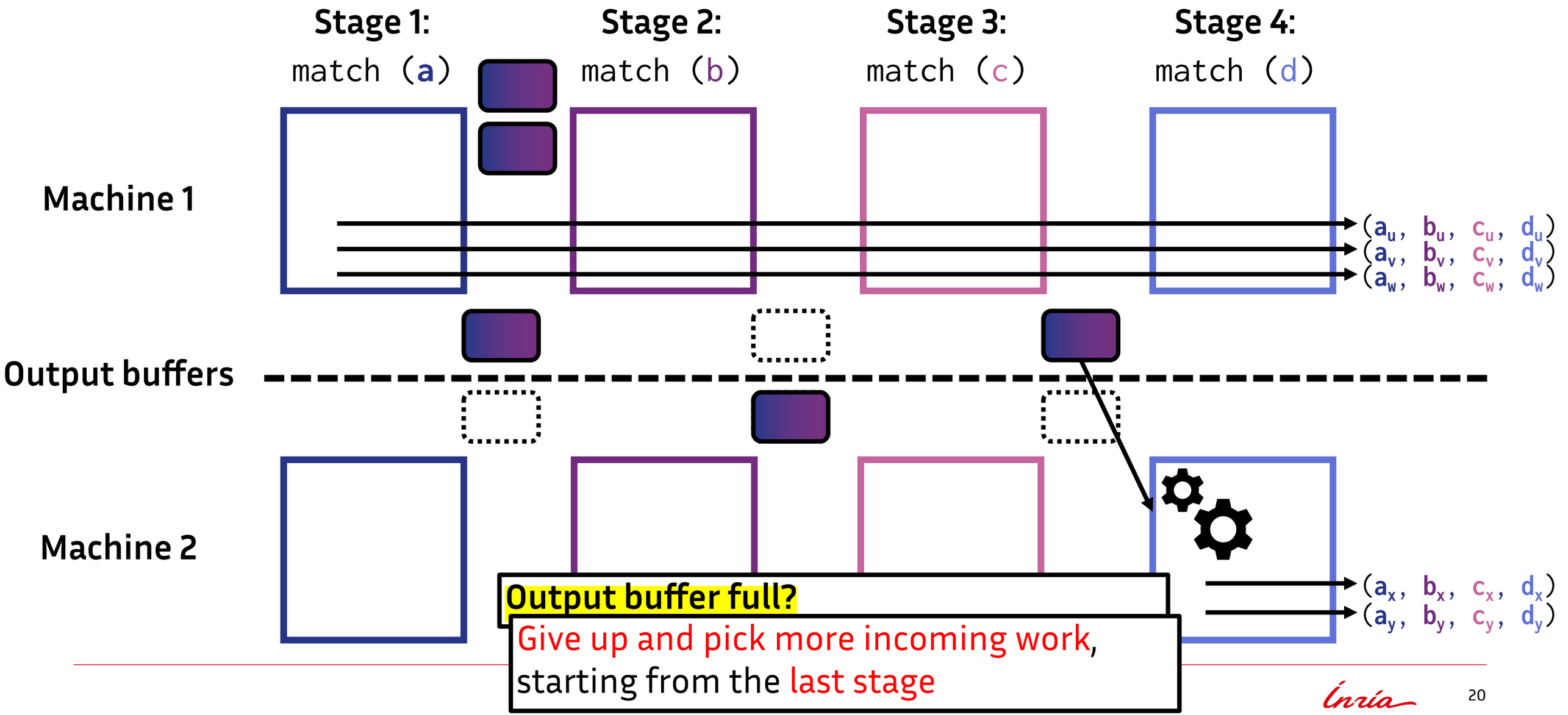

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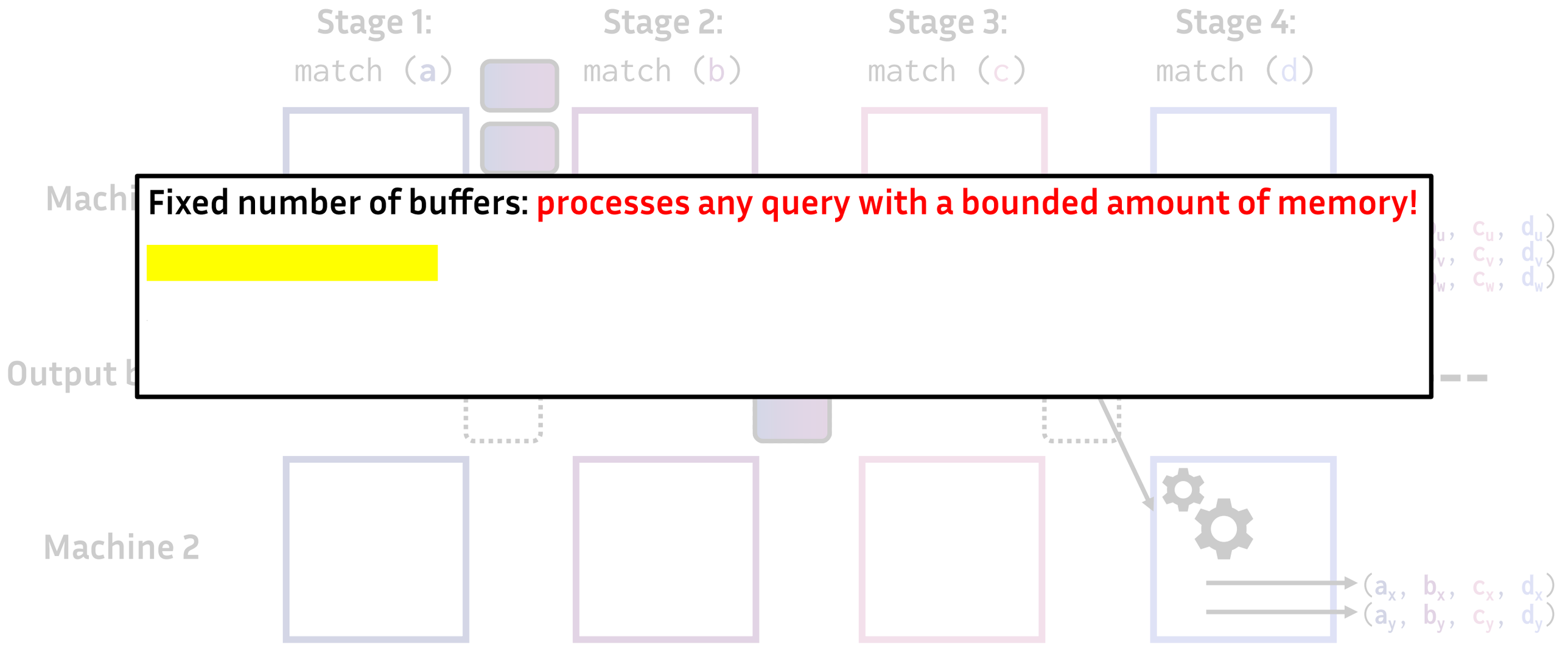

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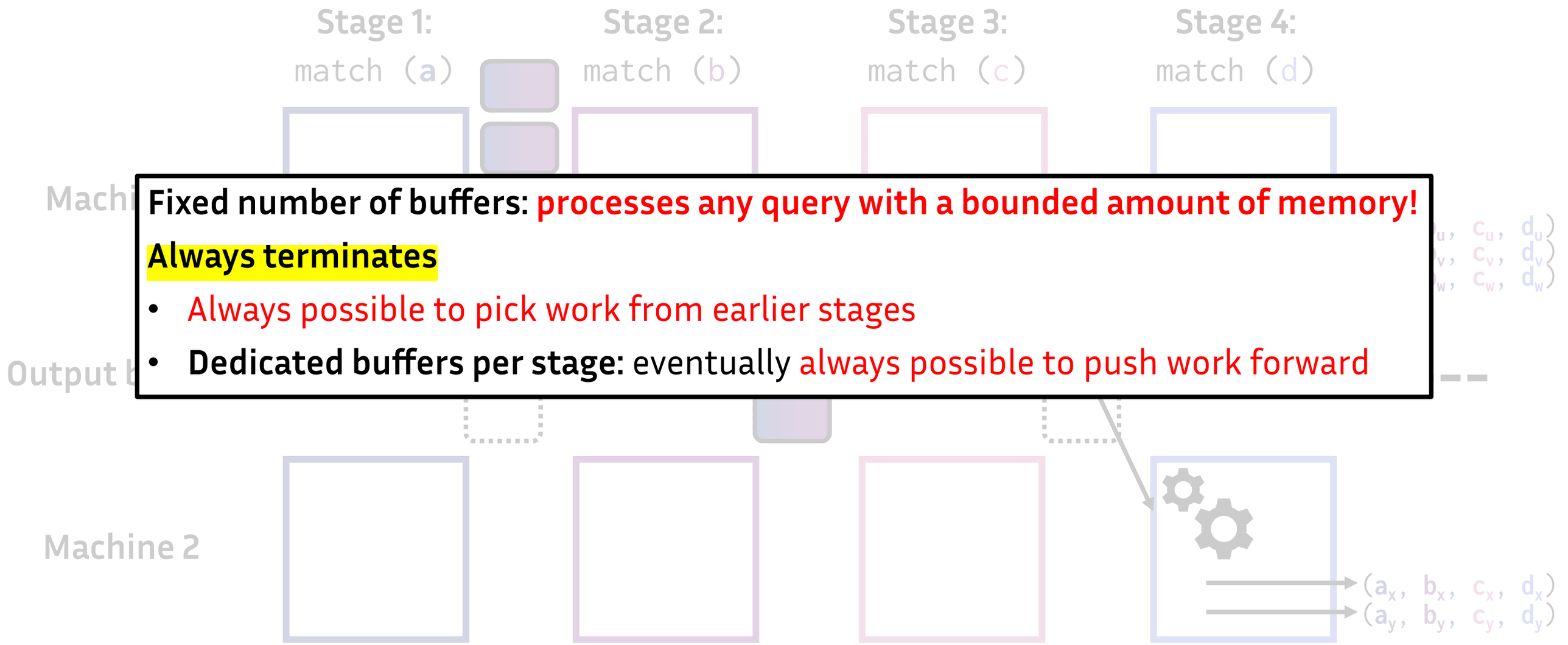


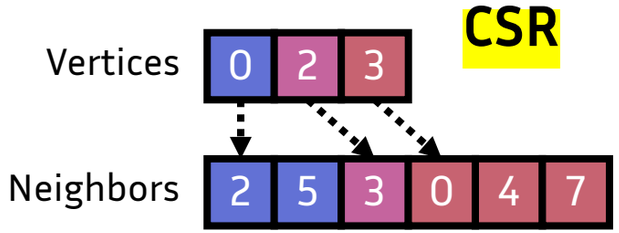
Fixed number of buffers: processes any query with a bounded amount of memory!

Always terminates

- Always possible to pick work from earlier stages
- **Dedicated buffers per stage:** eventually always possible to push work forward

3. Graph Analytics: Other Works

- **CSR++ [OPODIS '20]**



- CSR packs vertices and edges in two arrays for fast reads

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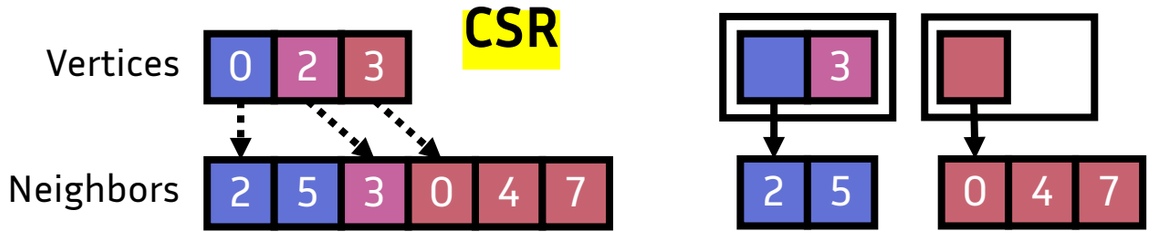

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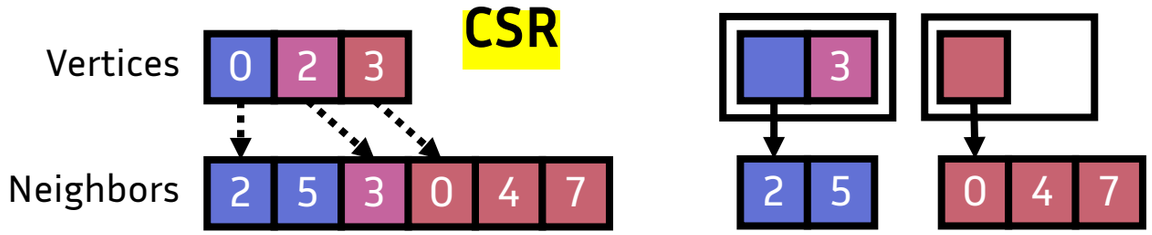

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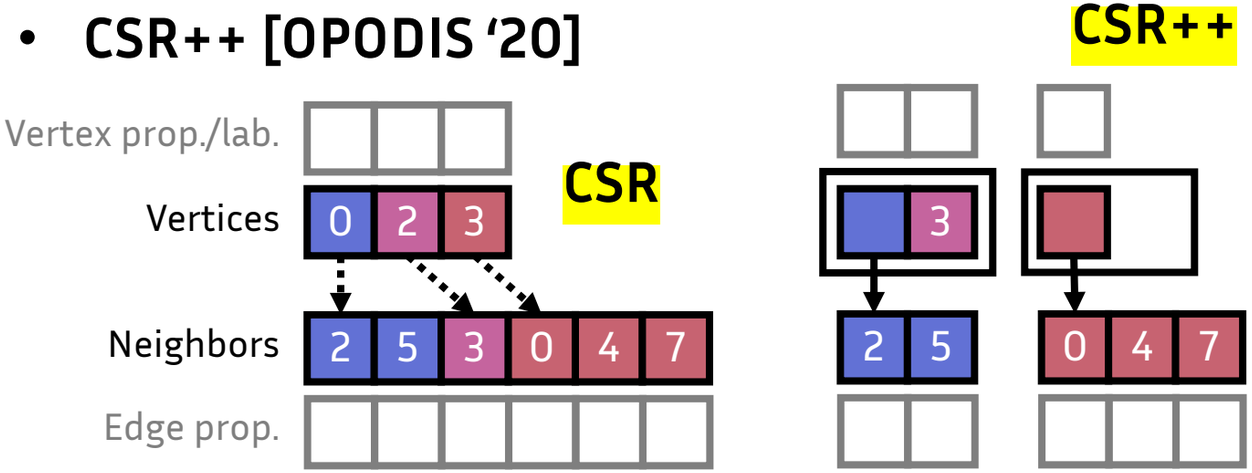

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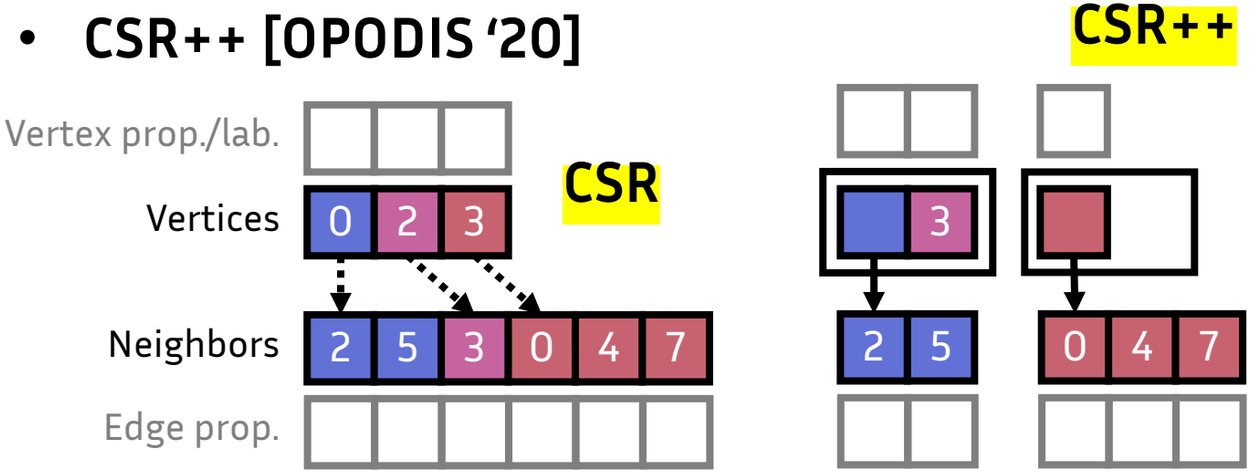

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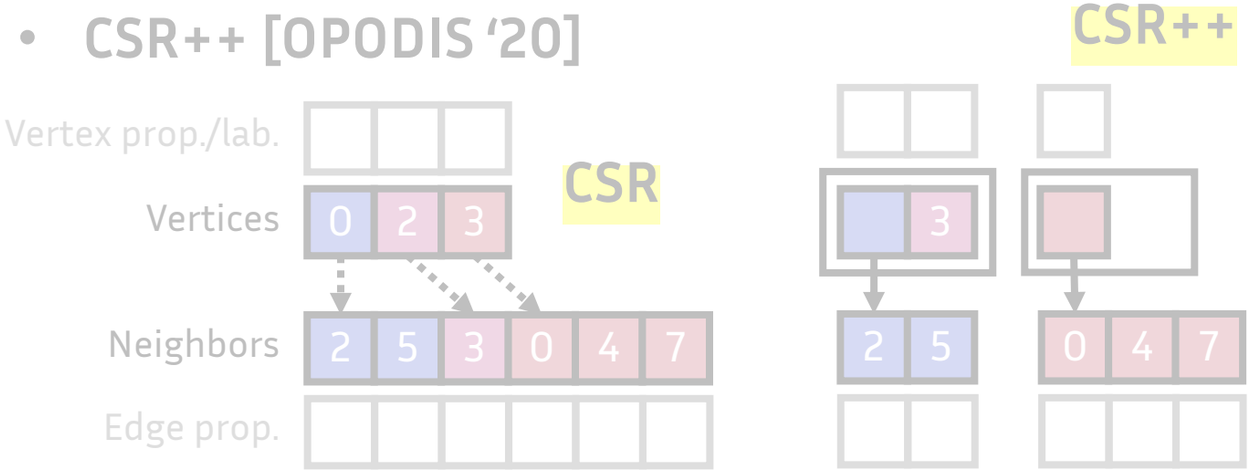

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`Q(A14, A19, (withdrawal·deposit)+)` ✅

- Is t reachable from s by a path whose edge labels match a regular expression `(L)+`?

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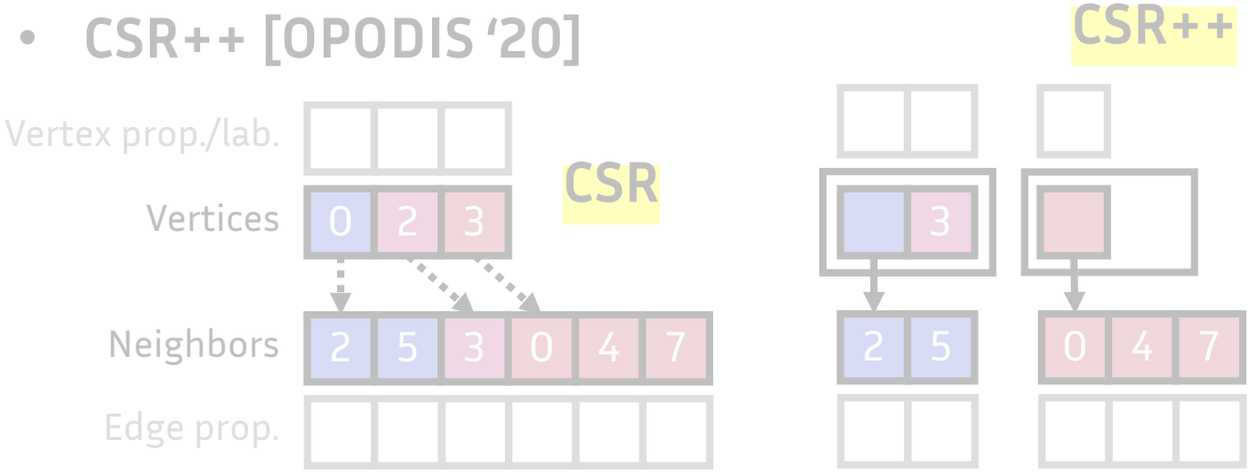

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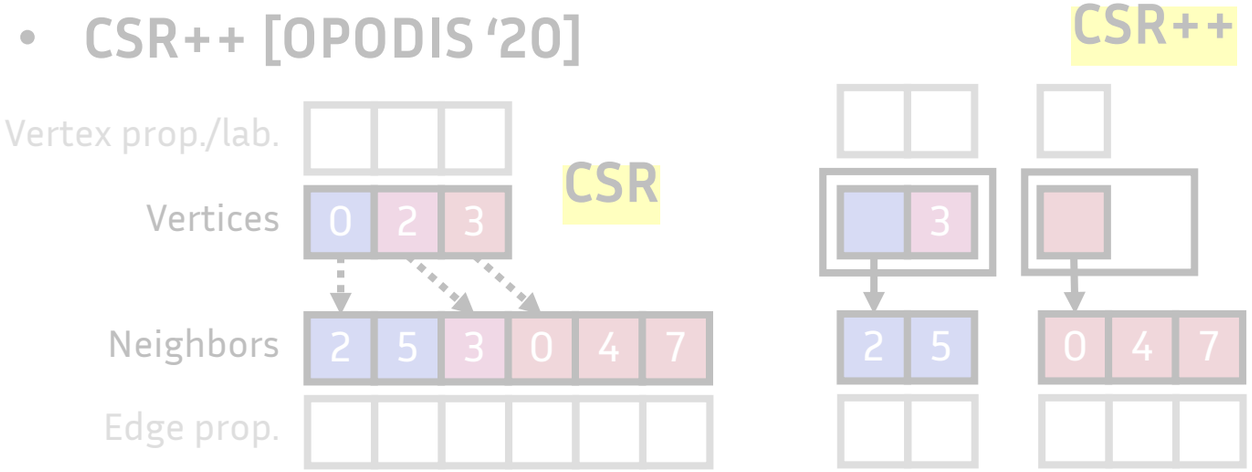

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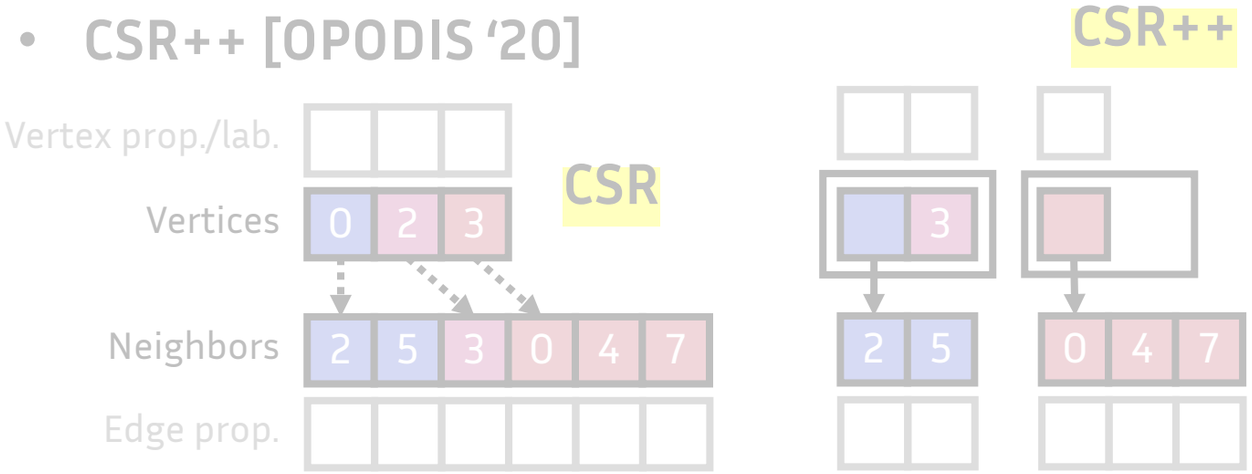

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- Hubs are high-degree nodes; includes pruning rules; tractable due to max L length

Optimization Mechanisms

		Ensuring work conservation	Preferring high-frequency cores	Optimizing inter-thread synchronization	Avoiding critical path preemptions	Leveraging the spinning vs. blocking tradeoff	Optimizing parallelization patterns	Ensuring high memory locality	Sequential performance improvements
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	Ipanema	●							
	NUMA placement							●	
	Frequency inversions		●						
	Nest		●			●		●	
Chapter 2 Task sync.	RCL			●	●		●	●	
	FlexGuard			●	●	●			
	Tapestry			●	●	●		●	
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	RLC Index								●

Optimization Mechanisms

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Chapter 1 Task scheduling	"Wasted cores"	●							
	Ipanema	●							
	NUMA placement							●	
	Frequency inversions		●						
	Nest		●				●		●	
Chapter 2 Task sync.	RCL			●	●		●	●	
	FlexGuard			●	●	●			
	Tapestry			●	●	●		●	
Chapter 3 Graph analytics	Smart arrays							●	●
	CSR++			●			●	●	
	aDFS						●		
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