Lecture 7:

Multiprocessor Scheduling

Linux scheduler illustrations from Jean-Pierre Lozi

(https://www.i3s.unice.fr/~jplozi/wastedcores/files/extended_talk.pdf)

University of Toronto, Department of Computer Science

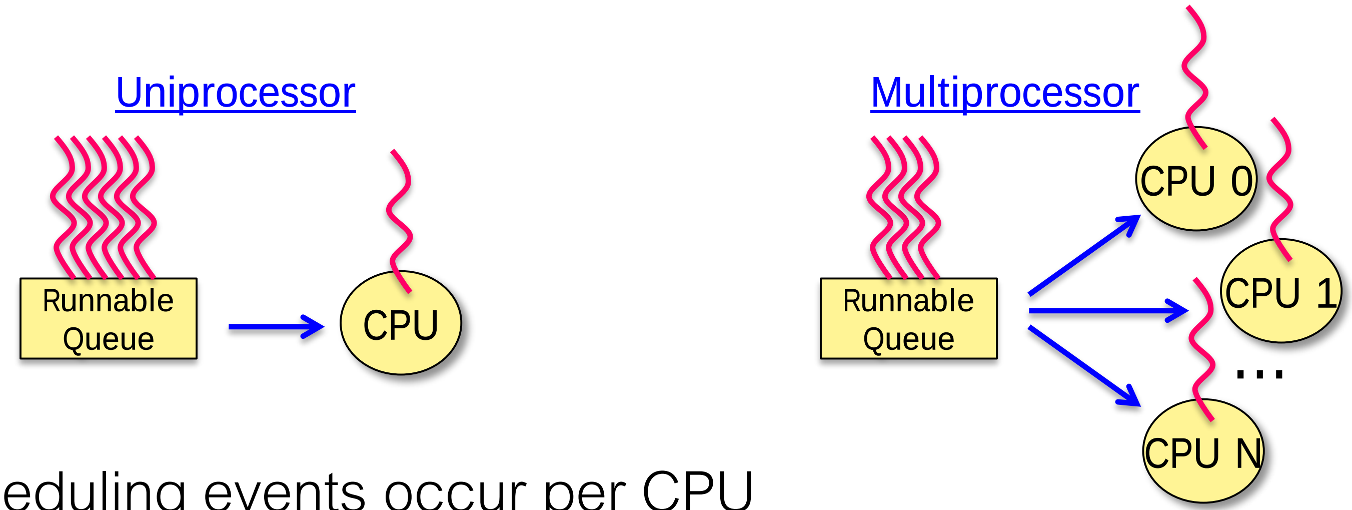
Multiprocessor Scheduling

- Why use a multiprocessor?
  - To support multiprogramming
    - Large numbers of independent processes
    - Simplified administration
    - E.g. CDF wolves, compute servers
  - To support parallel programming
    - "job" consists of multiple cooperating/communicating threads and/or processes
    - *Not* independent!
- First - the easy case: scheduling threads

Basic MP Scheduling

- Given a set of runnable threads, and a set of CPUs, assign threads to CPUs
- Same considerations as uniprocessor scheduling
  - Fairness, efficiency, throughput, response time…
- But also new considerations
  - Ready queue implementation
  - Load balancing
  - Processor affinity

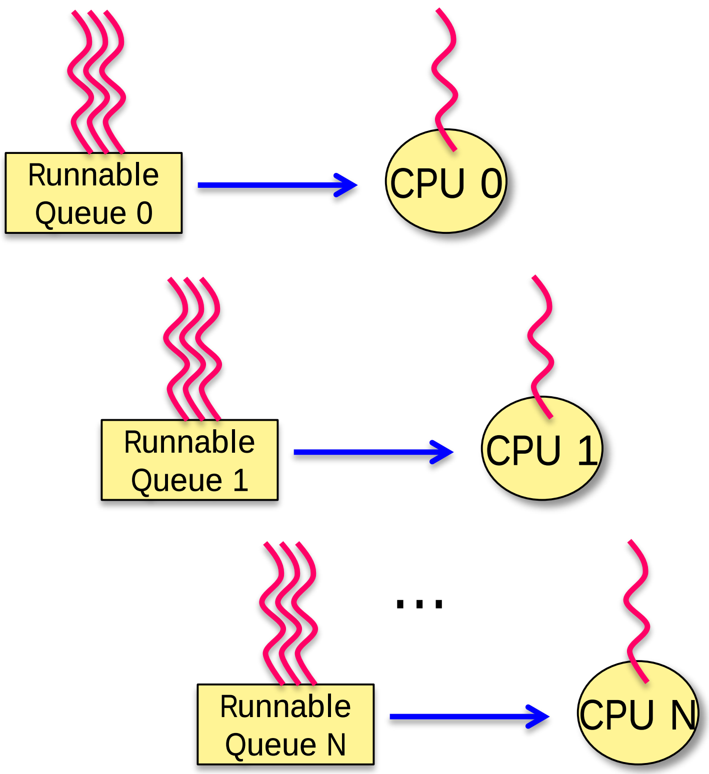
Straightforward Implementation



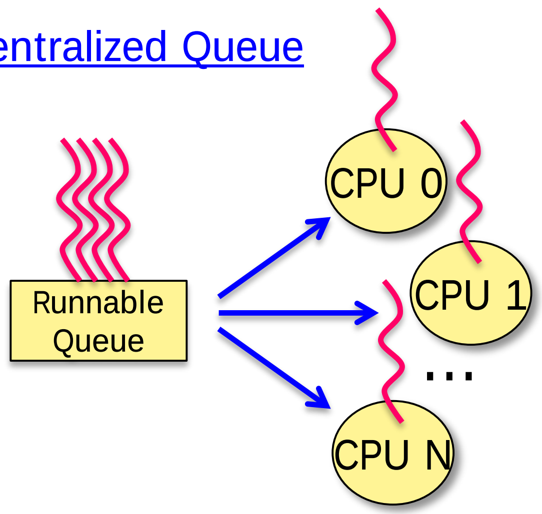
- Scheduling events occur per CPU
  - Local timer interrupt
  - Currently-executing thread blocks or yields
  - Event is handled that unblocks thread
- Scheduler code executing on any CPU simply accesses shared queue
- What might be sub-optimal about this?

Alternative Ready Queue Design

Distributed Queues



Centralized Queue



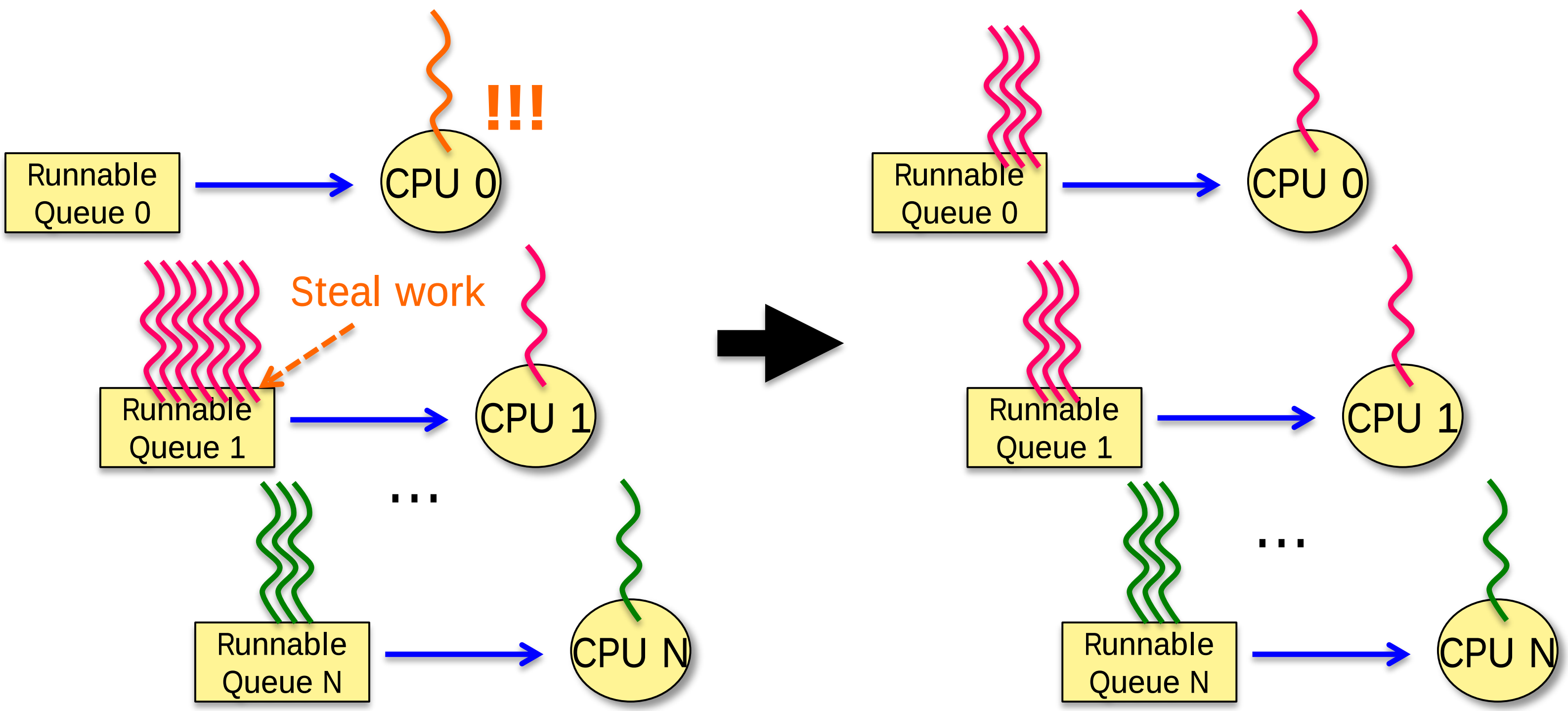
- Advantages of Distributed Queues?

- Disadvantages?

Load Balancing

- Try to keep run queue sizes balanced across system
  - Main goal – CPU should not idle while other CPUs have waiting threads in their queues
  - Secondary – scheduling overhead may scale with size of run queue
    - Keep this overhead roughly the same for all CPUs
- *Push* model – kernel daemon checks queue lengths periodically, moves threads to balance
- *Pull* model – CPU notices its queue is empty (or shorter than a threshold) and steals threads from other queues
- Many systems use both

Work Stealing with Distributed Queues



Notice a problem though?

Processor Affinity

- As threads run, state accumulates in CPU cache
- Repeated scheduling on same CPU can often reuse this state
- Scheduling on different CPU requires reloading new cache
  - And possibly invalidating old cache
- Try to keep thread on same CPU it used last
  - Automatic
  - Advisory hints from user
  - Mandatory user-selected CPU
- Called "affinity scheduling"
- Do they always find a warm cache though? What can happen?

Symbiotic Scheduling

- Threads load data into cache
- Expect multiple threads to thrash each others' state as they run
- Can try to detect cache needs and schedule threads that can share nicely on same CPU
  - Examples? What kind of threads should be scheduled together?

Linux Scheduler: Case Study

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.

- Linus Torvalds, 2001

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(https://www.i3s.unice.fr/~jplozi/wastedcores/files/extended_talk.pdf)

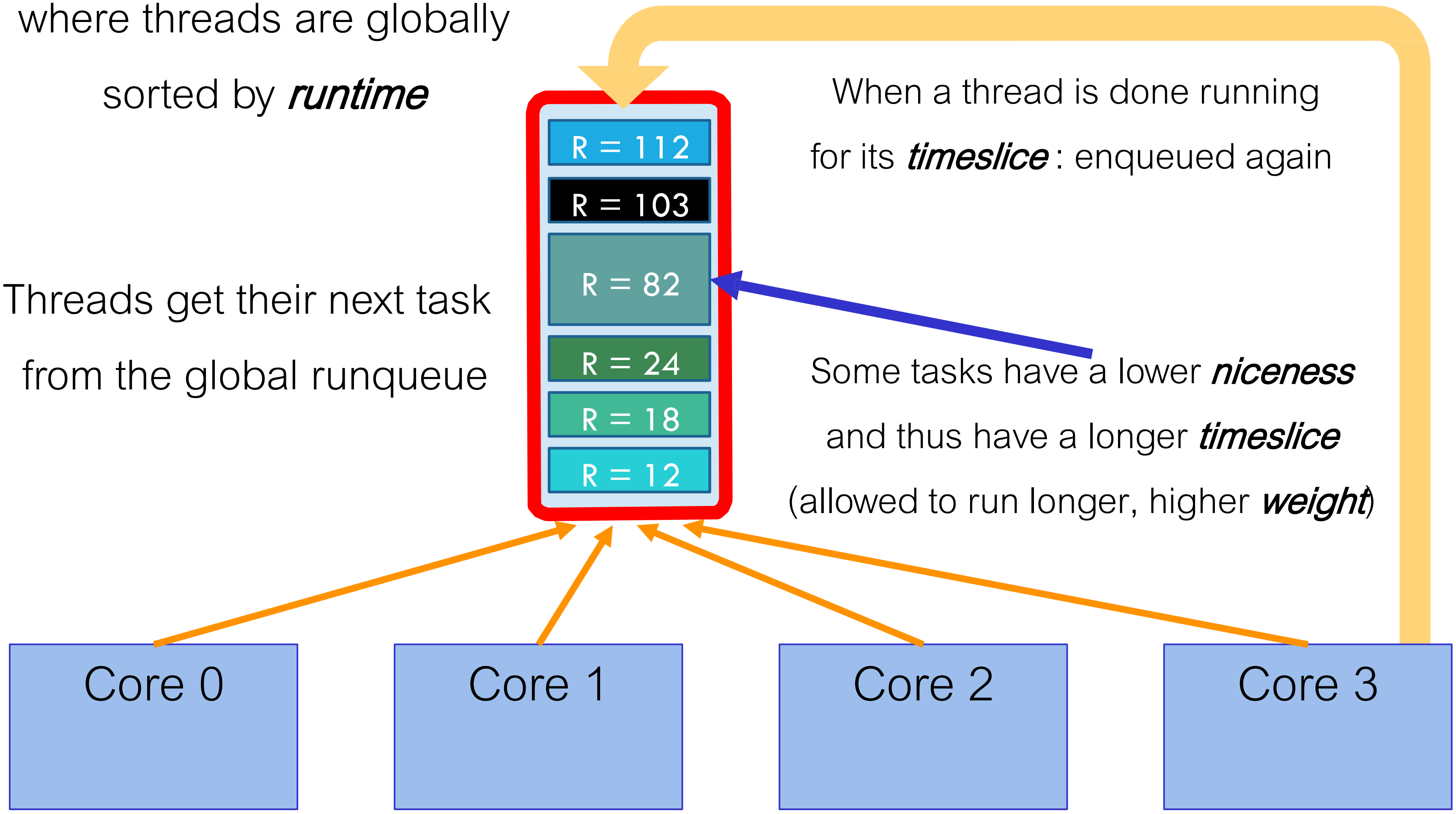
The Completely Fair Scheduler (CFS)

Conceptually, one runqueue where threads are globally sorted by ***runtime***

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

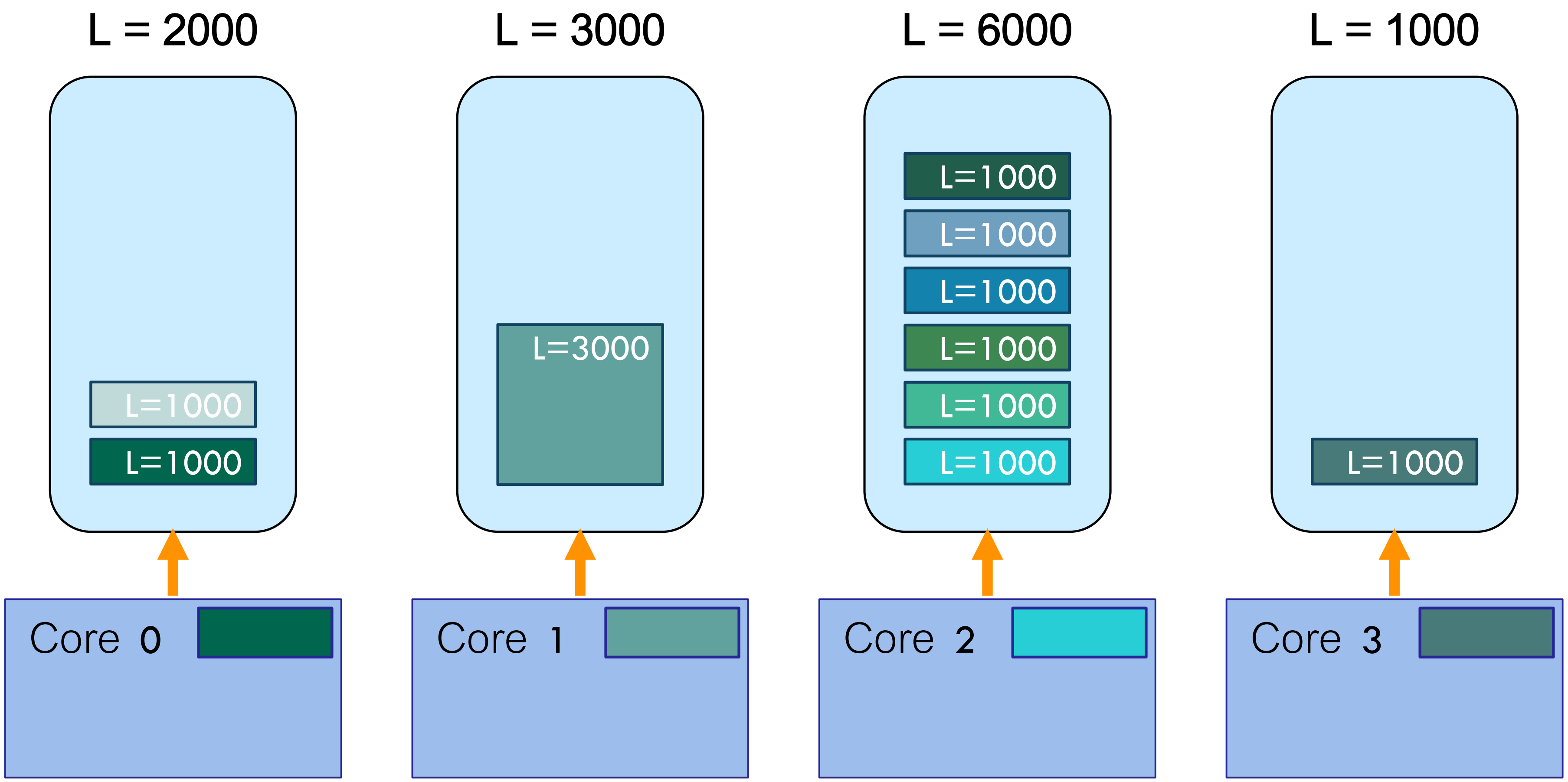
Threads get their next task from the global runqueue

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



CFS on Multiprocessor

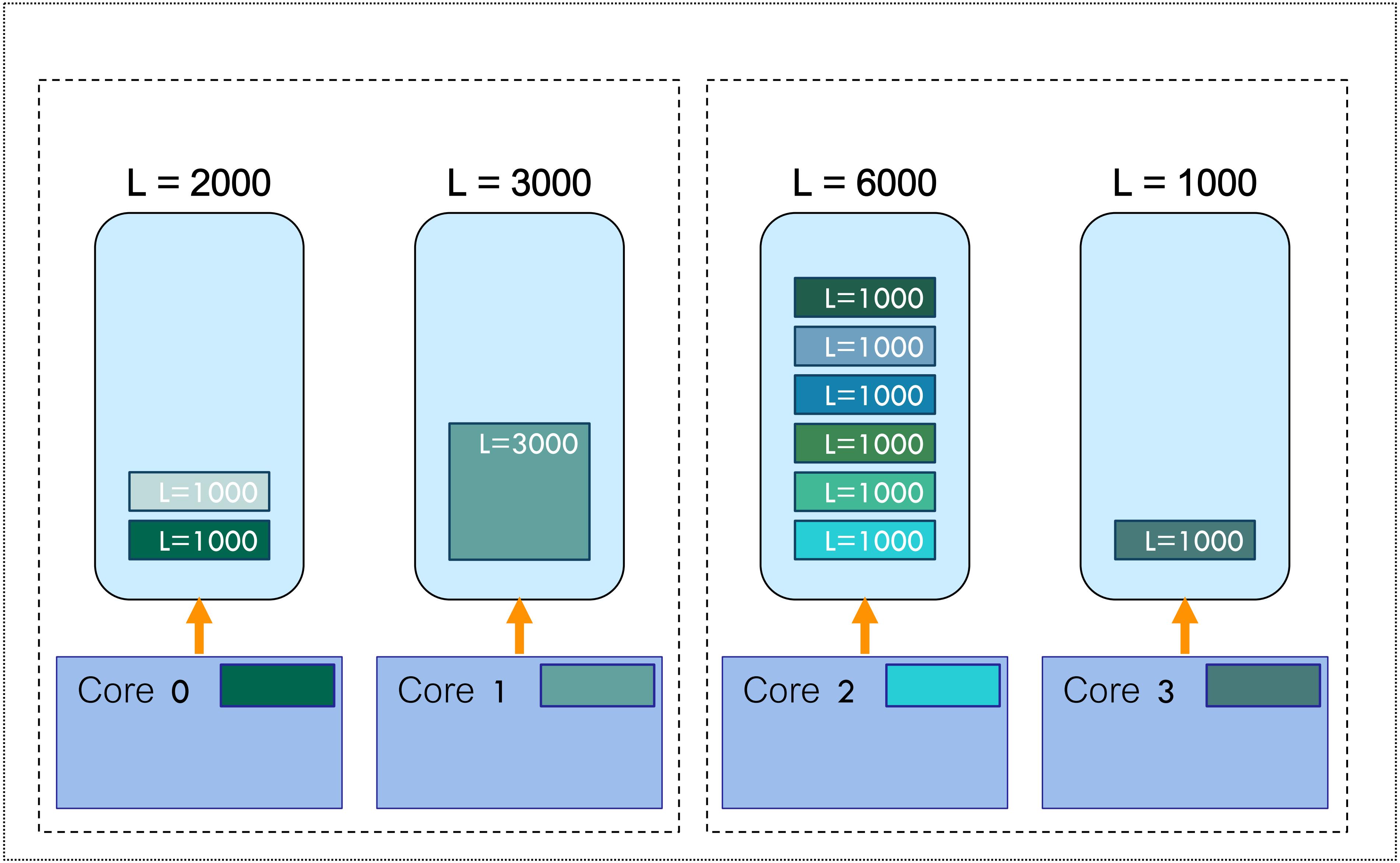
- Accumulated runtime is not a useful metric for load balancing
- Define CPU load of a thread: Load = Weight x %CPU



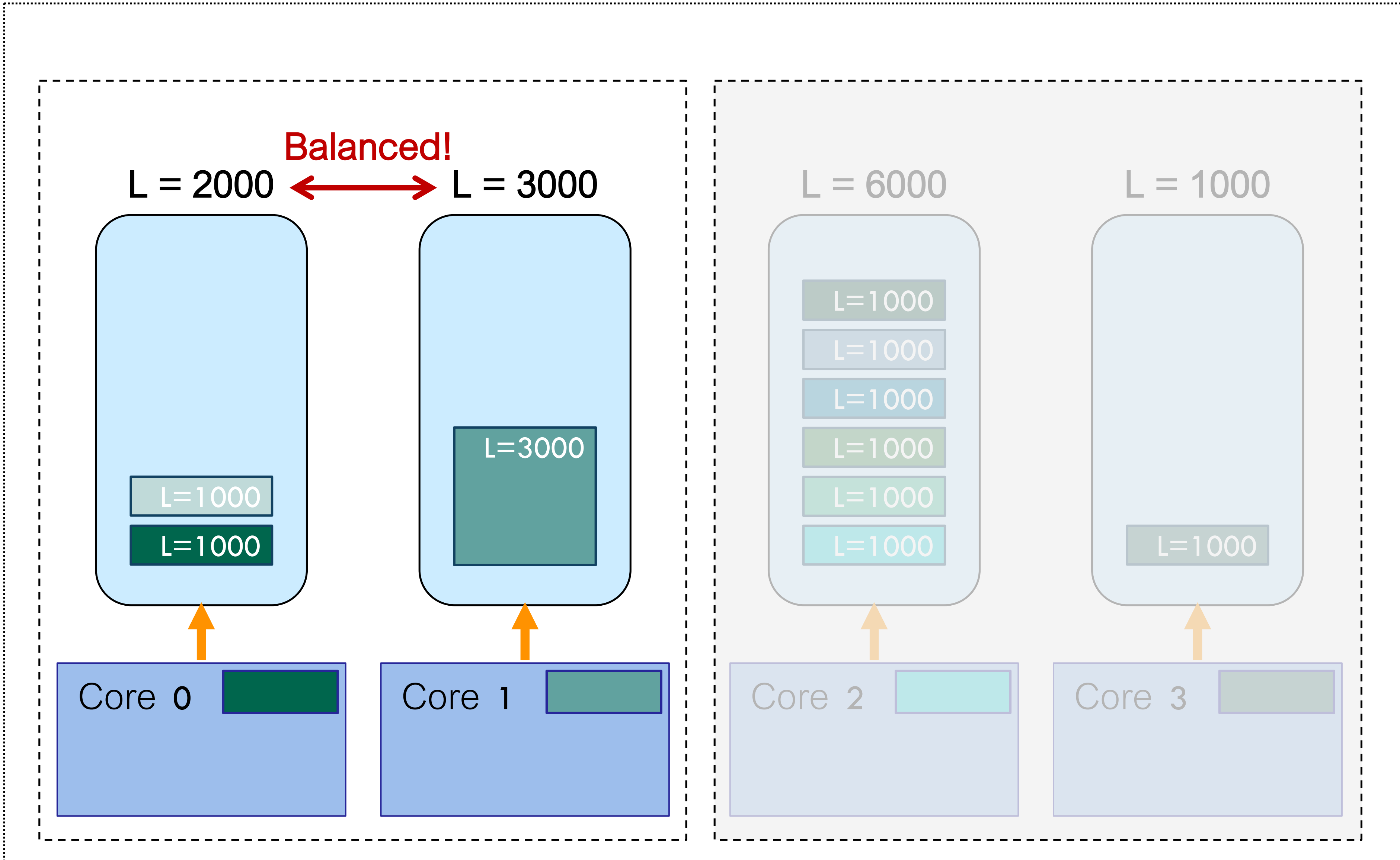
Linux Scheduler Basics

- per-CPU runqueues
  - Actually a red-black tree with the CFS scheduler
- CPUs are organized into *scheduling domains*
  - A set of CPUs whose load is kept balanced by kernel
  - Each domain contains a set of groups
- Load balancing is hierarchical
  - On each tick, recomputes local load statistics
  - Checks if time to invoke load_balance() for each domain from base to top-level

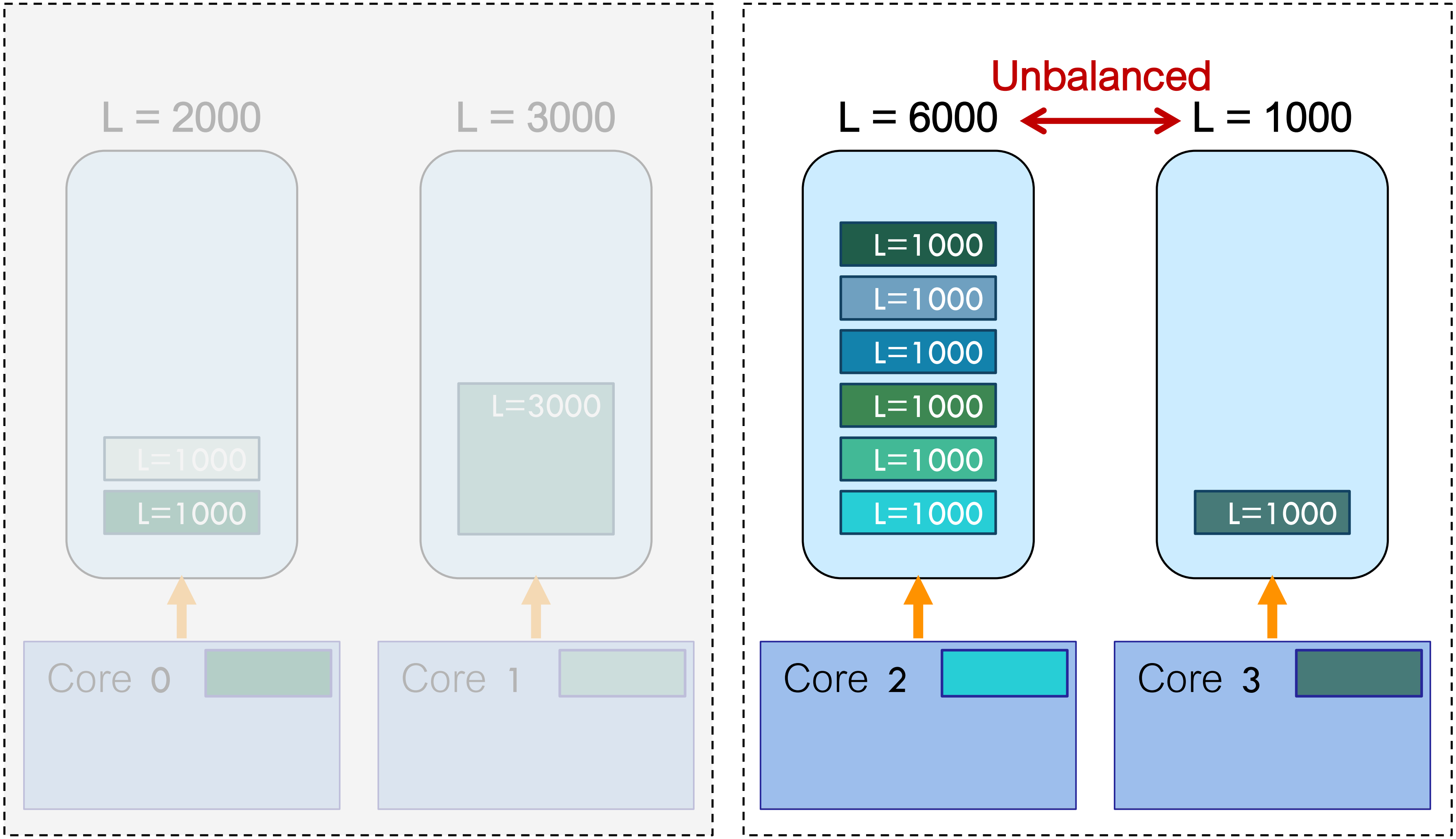
Hierarchical Load Balancing



Hierarchical Load Balancing



Hierarchical Load Balancing



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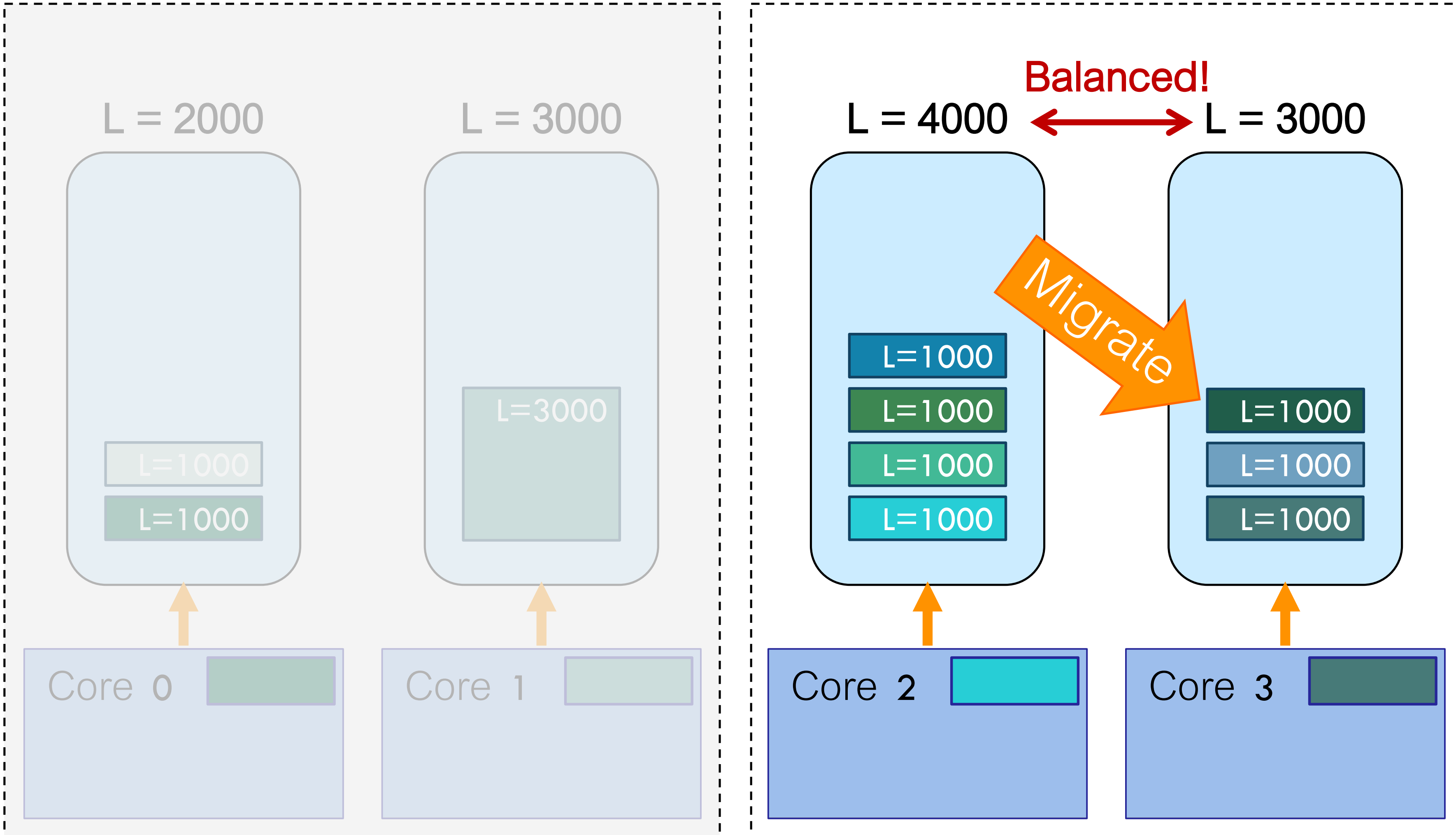

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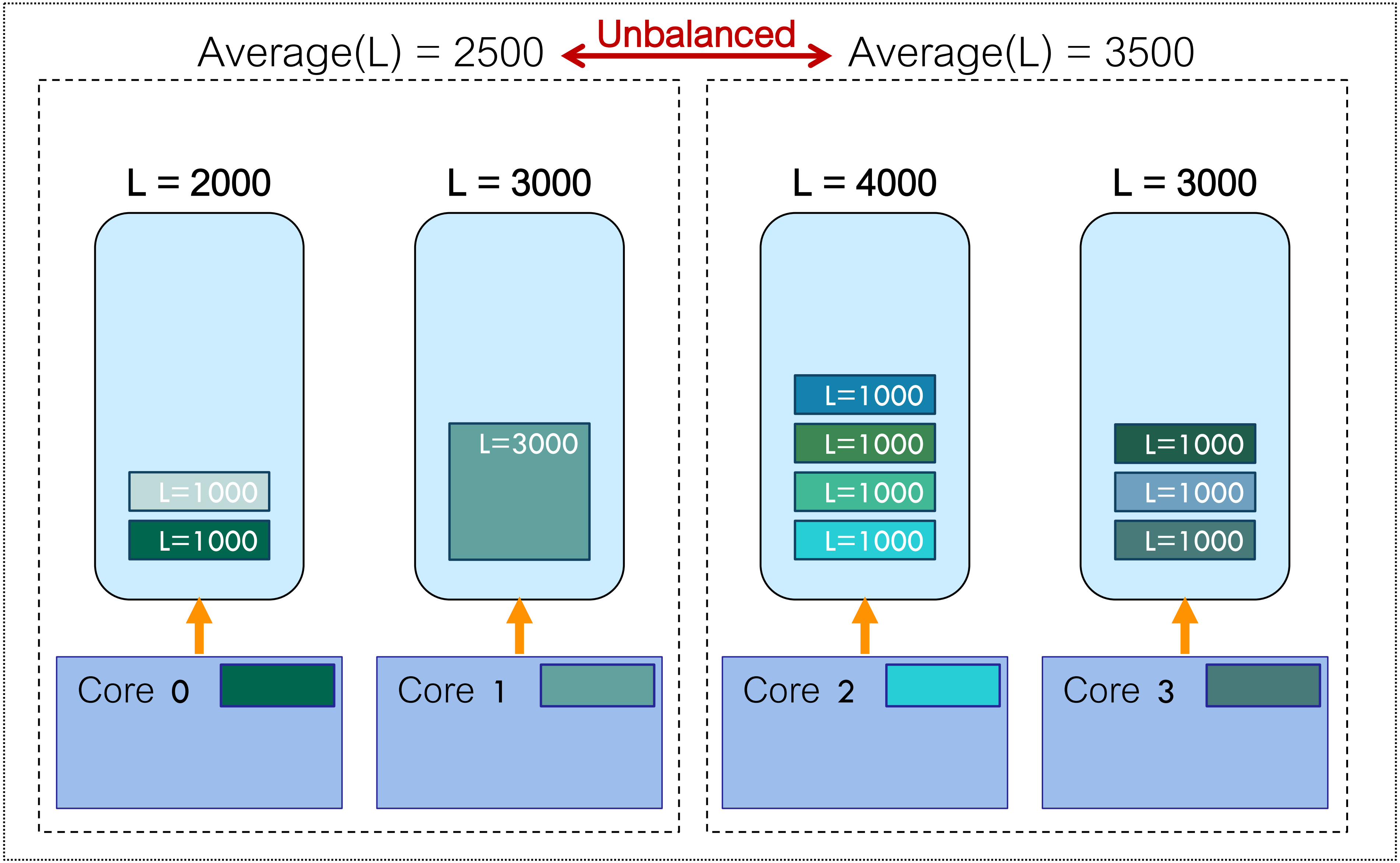

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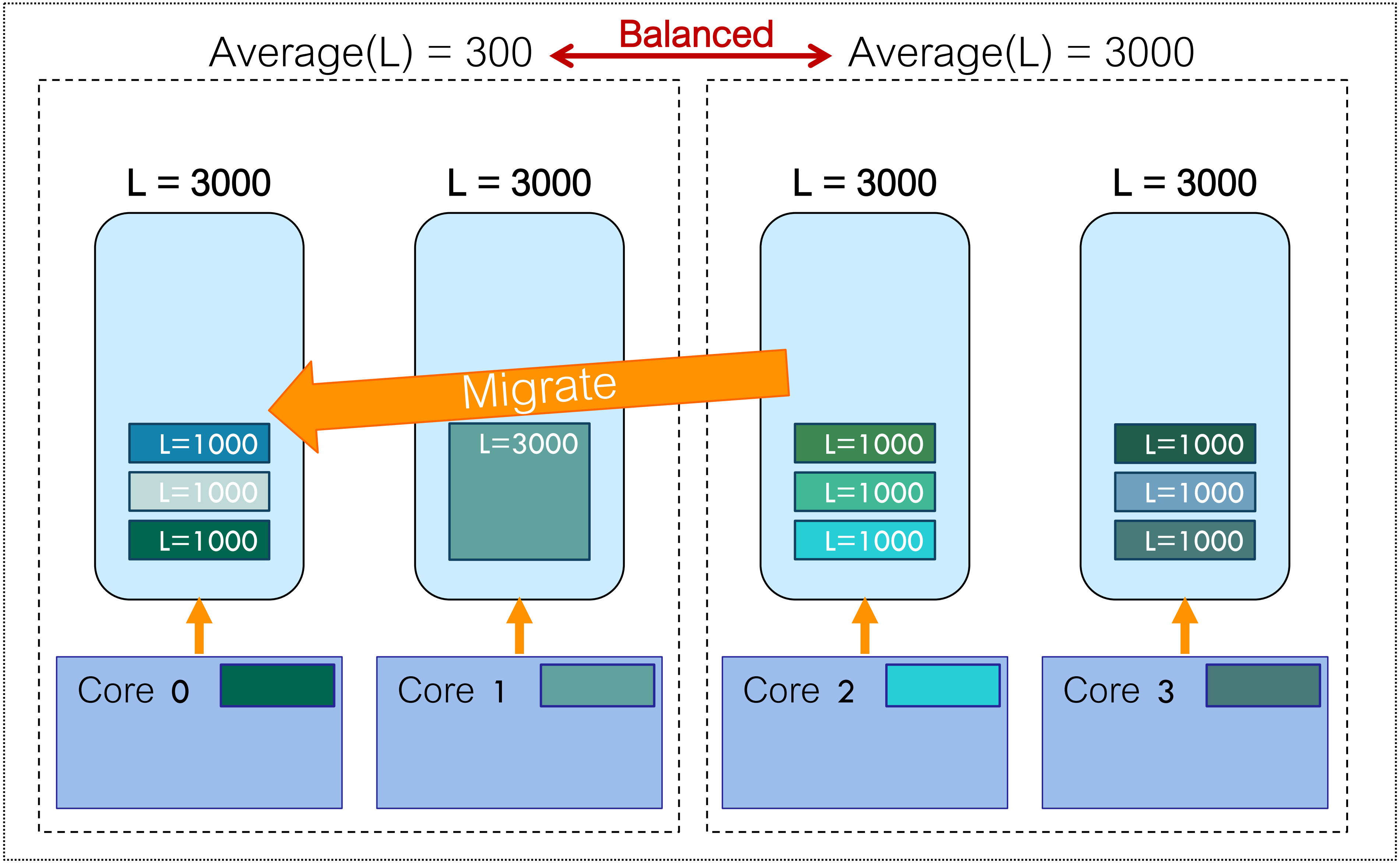


Linux Load Balancing

- Finds busiest group in current domain
- Finds busiest queue (CPU) in that group
- Invokes move_tasks to actually move threads
  - move_tasks attempts to preserve affinity when finding task to move
    - Can't be currently executing
    - Target CPU must be allowable for task
    - Target CPU is idle OR process is not "cache hot" OR kernel has failed repeatedly to move processes
- Actual load calculations in Linux are quite complex
  - Can fail to achieve balance and fairness in some scenarios
- Further reading (optional):
  - The Linux Scheduler – a decade of wasted cores (Eurosys 2016)
  - https://www.ece.ubc.ca/~sasha/papers/eurosys16-final29.pdf

Parallel Job Scheduling

- "Job" is a collection of processes/threads that cooperate to solve some problem (or provide some service)
  - *Not* independent!
- How the components of the job are scheduled has a major effect on performance
  - Want scheduler to be aware of dependences
- We will look at two major strategies
  - Space sharing – each job has dedicated processors
  - Time sharing – multiple jobs share same processors

Why Job Scheduling Matters?

- Recall threads in a job are not independent
  - Synchronize over shared data
    - De-schedule lock holder, other threads in job may not get far
  - Cause/effect relationships (e.g. producer-consumer problem)
    - Consumer is waiting for data on queue, but producer is not running
  - Synchronizing phases of execution (barriers)
    - Entire job proceeds at pace of slowest thread

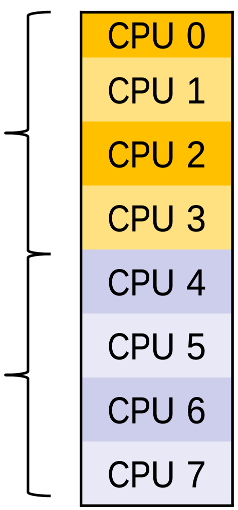
Forms of scheduler-awareness

- 1. Know threads are related, schedule all at same time
  - Space sharing: all threads are from same job
  - Time sharing: group threads that should be scheduled together
- 2. Know when threads hold spinlocks
  - Don't deschedule lock holder
  - Extends timeslice, but not indefinitely
- 3. Know about general dependences
  - E.g. infer producer/consumer relationships

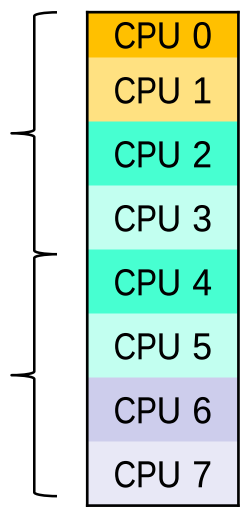
Space Sharing Scheduling

- Divide processors into groups
  - Fixed, variable, or adaptive
- Assign job to dedicated set of processors
  - Ideally one CPU per thread in job
- Job waits until required number of CPUs are available (batch scheduling)

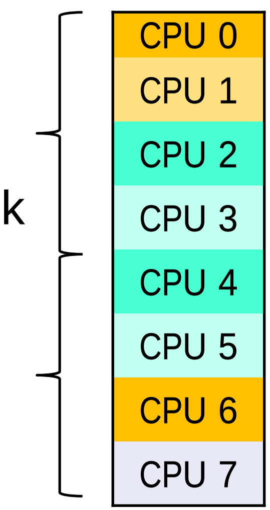
Fixed:
Always 2 groups of 4 CPUs.



Variable:
Currently 3 groups of 2, 4, and 2 CPUs; changes as jobs come and go.



Adaptive:
Job can ask for more CPUs as it runs.



Space Sharing

- Typically used on supercomputers
- Pros:
  - All runnable threads execute at the same time
  - Reduce context switch overhead (no involuntary preemption)
  - Strong affinity
- Cons?
  - Inflexible
    - CPUs in one partition may be idle while another partition has multiple jobs waiting to run
    - Difficult to deal with dynamically-changing job sizes
      - Adaptive scheme is complicated and uncommon

Choosing Jobs to Run

- At job creation, specify number of threads
- Scheduler finds set of CPUs
  - May negotiate with application

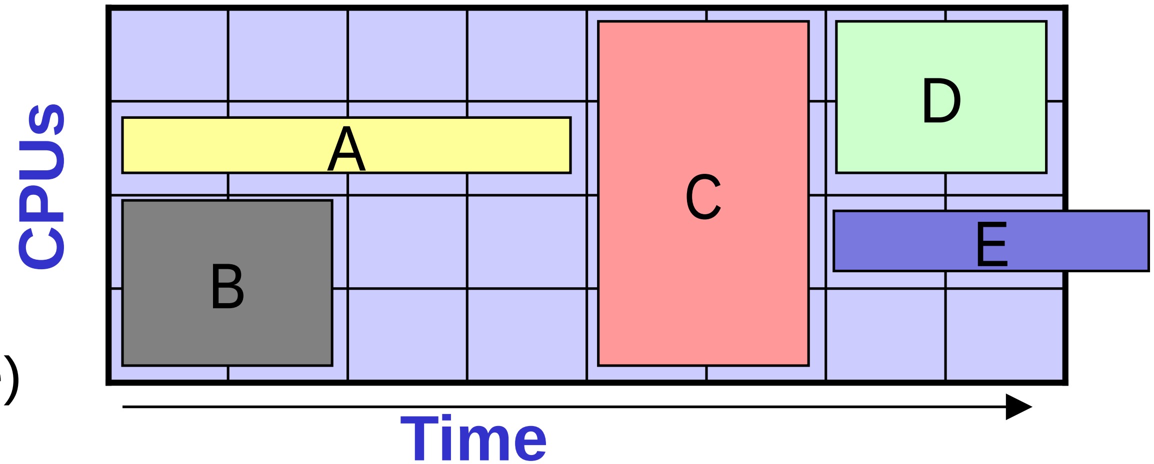
- How should scheduler choose jobs to assign to CPUs? What is optimal (in terms of average wait time)?
  - Uniprocessor scheduling → Shortest Job First (SJF) (shortest expected next CPU burst)
  - MP version → smallest expected number of CPU cycles (cycles == num_cpus * runtime)

Estimating Runtime

- Estimates typically come from users who submit the jobs
  - Low estimates make it “easier” to do scheduling
  - But cause trouble if not accurate!
  - Soln: kill jobs that exceed estimate
    - What user behaviour does that incentivize?
- How accurate are user estimates?
- Can automatic estimates based on history do better?
- How much does it matter?

Space Sharing - FCFS

- Scheduling convoy effect
  - Long average wait times due to large job
  - Exists with FCFS uniprocessor batch systems
  - Much worse in parallel systems
    - Fragmentation of CPU space



Scheduler queue (CPUs, time)

E	D	C	B	A
1,3	2,2	4,2	2,2	1,4

Solution: Backfilling

- Fill CPU "holes" from queue in FCFS order
- Not FCFS anymore. What can happen?
- Want to prevent "fill" from delaying threads that were in queue earlier
  - EASY (Extensible Argonne Scheduling sYstem)
    - Make reservation for next job in queue

Scheduler queue (CPUs, time)

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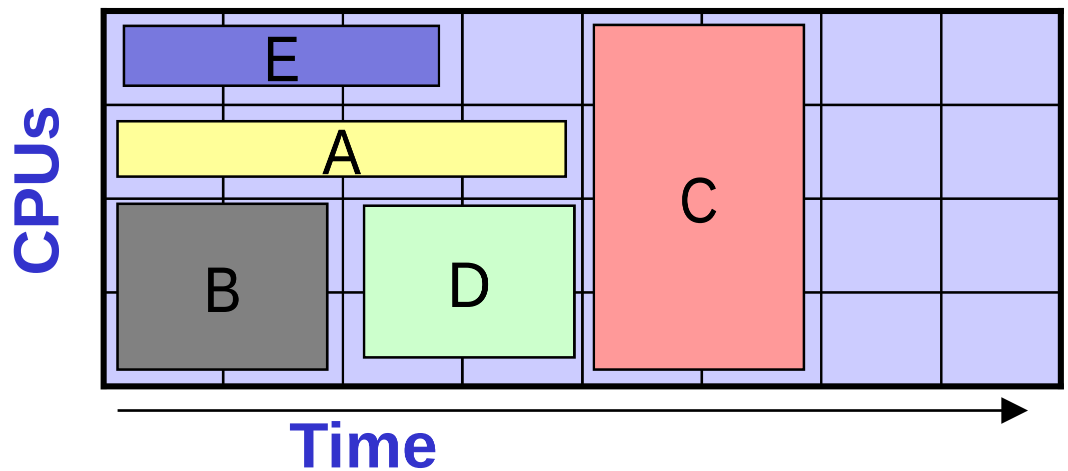


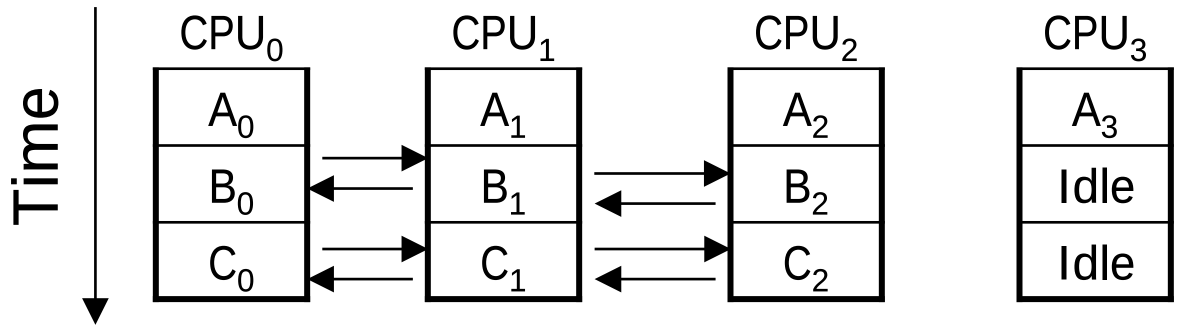
Variations on Backfilling

- EASY
  - 1. Used FCFS to order jobs in queue
  - 2. Made reservation for first blocked job in queue
  - 3. Backfilled jobs by looking at queue one at a time
- 1. Ordering alternative: include priority in queue
  - Administrative to distinguish between users
  - User to distinguish between own jobs
  - Scheduler to prevent starvation
- 2. Reservation alternatives
  - All queued jobs get a reservation (too much can go wrong)
  - Queued job gets a reservation if it has been waiting more than a threshold
- 3. Queue lookahead
  - Use dynamic programming to determine optimal packing

Parallel Time Sharing

- Each CPU may run threads from multiple jobs
  - But with awareness of jobs
- Co-scheduling (Ousterhout, 1982)
  - Identify "working set" of processes (analogous to working set of memory pages) that need to run together
- Gang scheduling
  - All-or-nothing → co-scheduled working set is all threads in the job
  - Get scheduling benefits of dedicated machine
  - Allows all jobs to get service

Gang Scheduling Example



- Multiprogramming level is typically controlled by either:
  - Monitoring memory demand, or
  - Fixed number of slots (rows)
    - e.g. IBM LoadLeveler Gang Scheduling allows up to 8 sets of jobs to be multiprogrammed on a set of CPUs

Gang Scheduling Issues

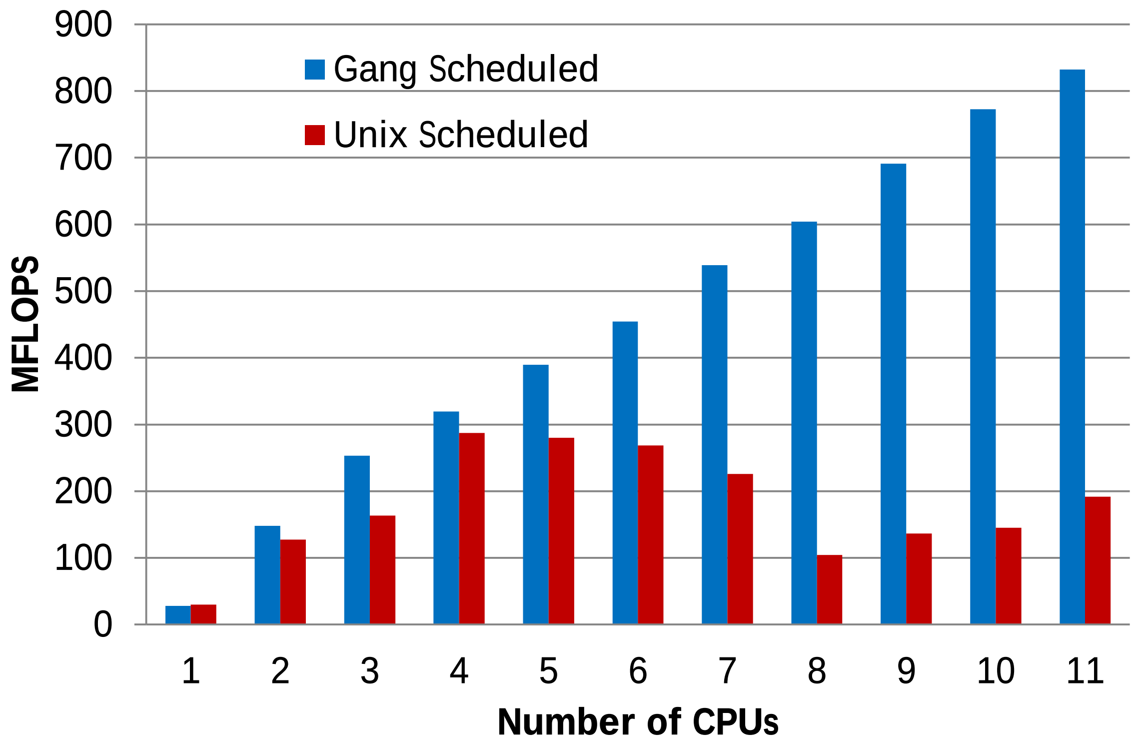
- All CPUs must context switch together
  - To avoid fragmentation, construct groups of jobs that fill a slot on each CPU
    - E.g., 8-CPU system, group one 4-thread job with two 2-thread jobs
  - Inflexible
    - If 4-thread job blocks, should we block entire group, or schedule group and leave 4 CPUs idle?

- Alternative 1: Paired gang scheduling
  - Identify groupings with complementary characteristics and pair them. When one blocks, the other runs

- Alternative 2: Only use gang scheduling for thread groups that benefit
  - Fill holes in schedule with any single runnable thread from those remaining

Example: Effect of Gang Scheduling

- LLNL gang scheduler on 12-CPU Digital Alpha 8400
  - Parallel gaussian elimination program
  - Run concurrently with 12 single-threaded interfering processes
  - Benefits due to synchronization effects and better cache use



Source:
“Expanding symmetric multiprocessor capability through gang scheduling”, Morris A. Jette, in Job Scheduling Strategies for Parallel Processing, LNCS 1998, Volume 1459/1998

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  - Don't deschedule lock holder
  - Extends timeslice, but not indefinitely
- 3. Know about general dependences
  - E.g. infer producer/consumer relationships

Knowing about Spinlocks

- Thread acquiring spinlock sets kernel-visible flag
- Clears flag on release
- Scheduler will not immediately deschedule a thread with the flag set
  - Gives thread a chance to complete critical section and release lock
  - Spinlock-protected critical sections are (supposed to be) short
  - Does not defer scheduling indefinitely

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Knowing General Dependences

- Implicit Co-scheduling (Arpaci-Dusseau et al.)
- Designed for workstation cluster environment
  - Explicit messages for all communication/synchronization
  - MUCH more expensive if remote process is not running when local process needs to synchronize
- Communicating processes decide when it is beneficial to run
  - Infer remote state by observing local events
    - Message round-trip time
    - Message arrival
- Local scheduler uses communication info in calculating priority

OS Noise

- Or: how to schedule OS activities
- Massively parallel systems are typically split into I/O nodes, management nodes, and compute nodes
  - Compute nodes are where the real work gets done
  - Run customized, lightweight kernel on compute nodes
  - Run full-blown OS on I/O nodes and mgmt nodes
  - Why?
- Asynchronous OS activities perturb nice scheduling properties of running jobs together
  - Up to a factor of 2 performance loss in real large-scale jobs
  - Need to either eliminate OS interference, or find ways to coordinate it as well

Illustration of OS Noise Issue

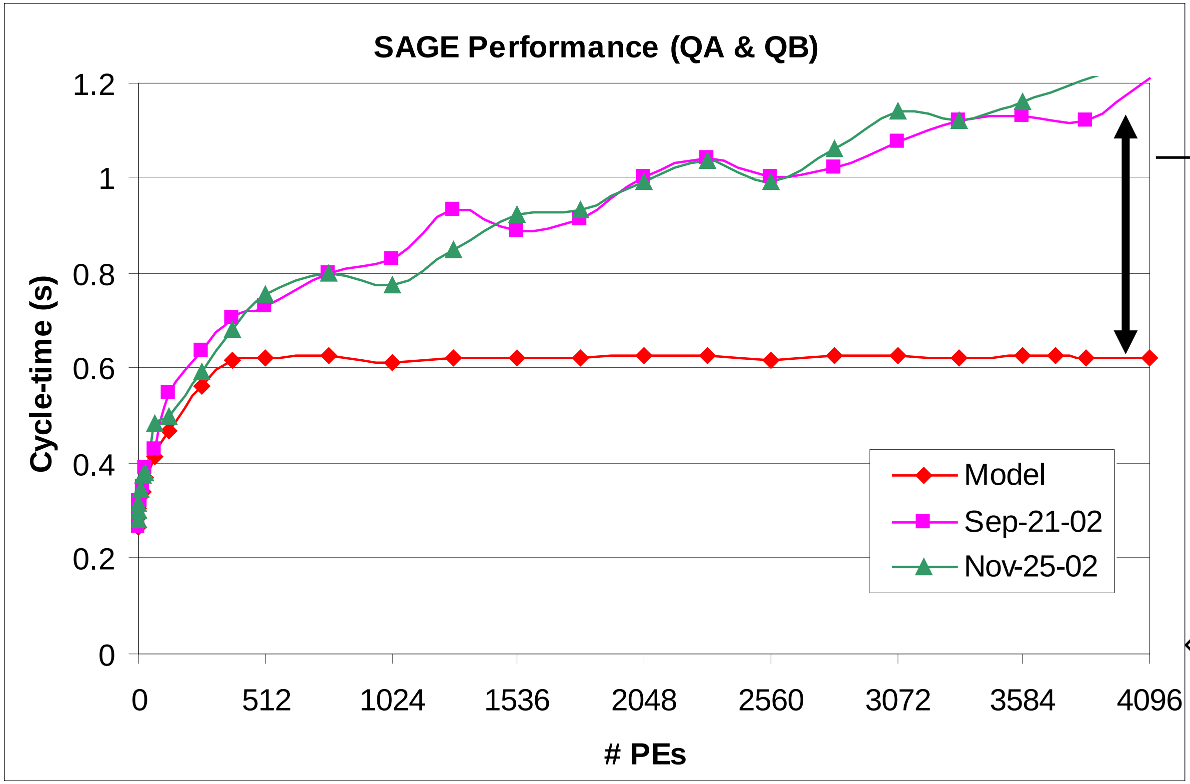
- The following 4 slides are extracted from a tutorial given at EuroPar 2004 (www.di.unipi.it/europar04/Tutorial2/tutorial_europar04.ppt)
  - They illustrate the issue with OS Noise on the ASCI Q supercomputer, published in Supercomputing 2003 ("The case of the missing supercomputer performance")

"Achieving Usability and Efficiency in Large-Scale Parallel Computing"

  - Kei Davis and Fabrizio Petrini {kei,fabrizio}@lanl.gov
  - Performance and Architectures Lab (PAL), CCS-3
    - (Computer and Computational Sciences Division, Los Alamos National Labs)

Performance of SAGE on 1024 nodes

- Performance consistent across QA and QB (the two segments of ASCI Q, with 1024 nodes/4096 processors each) ← *4 processors / node*
  - Measured time 2x greater than model (4096 Processor Elements)



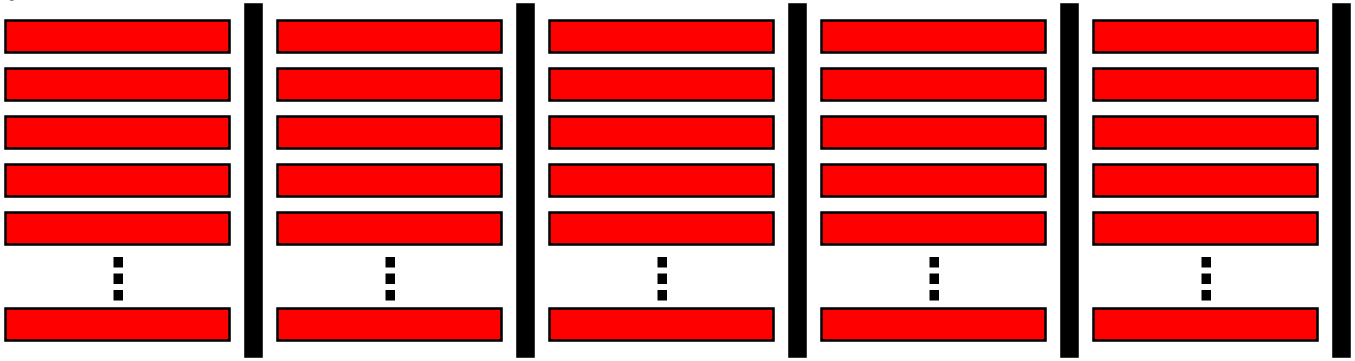
There is a difference why ?

OS activity is the culprit!

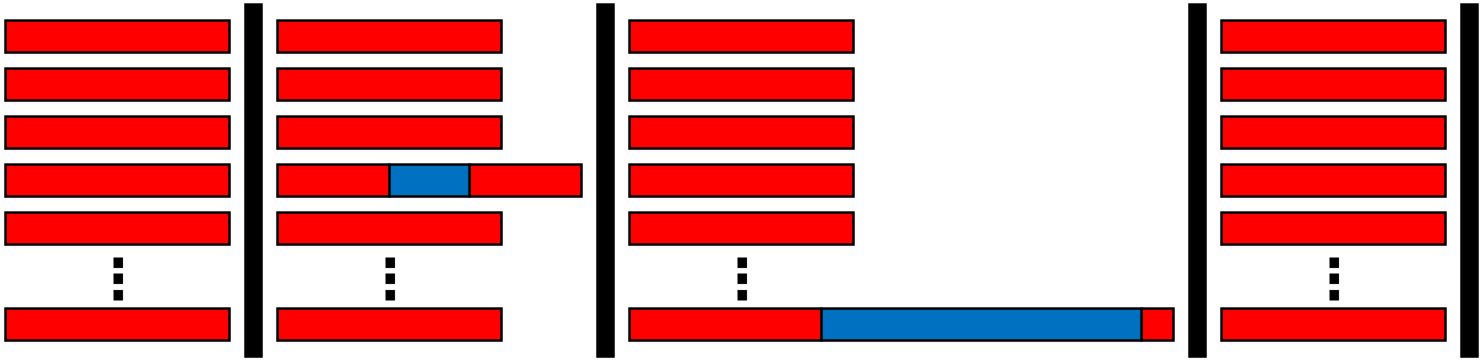
Lower is better!

The effect of the noise

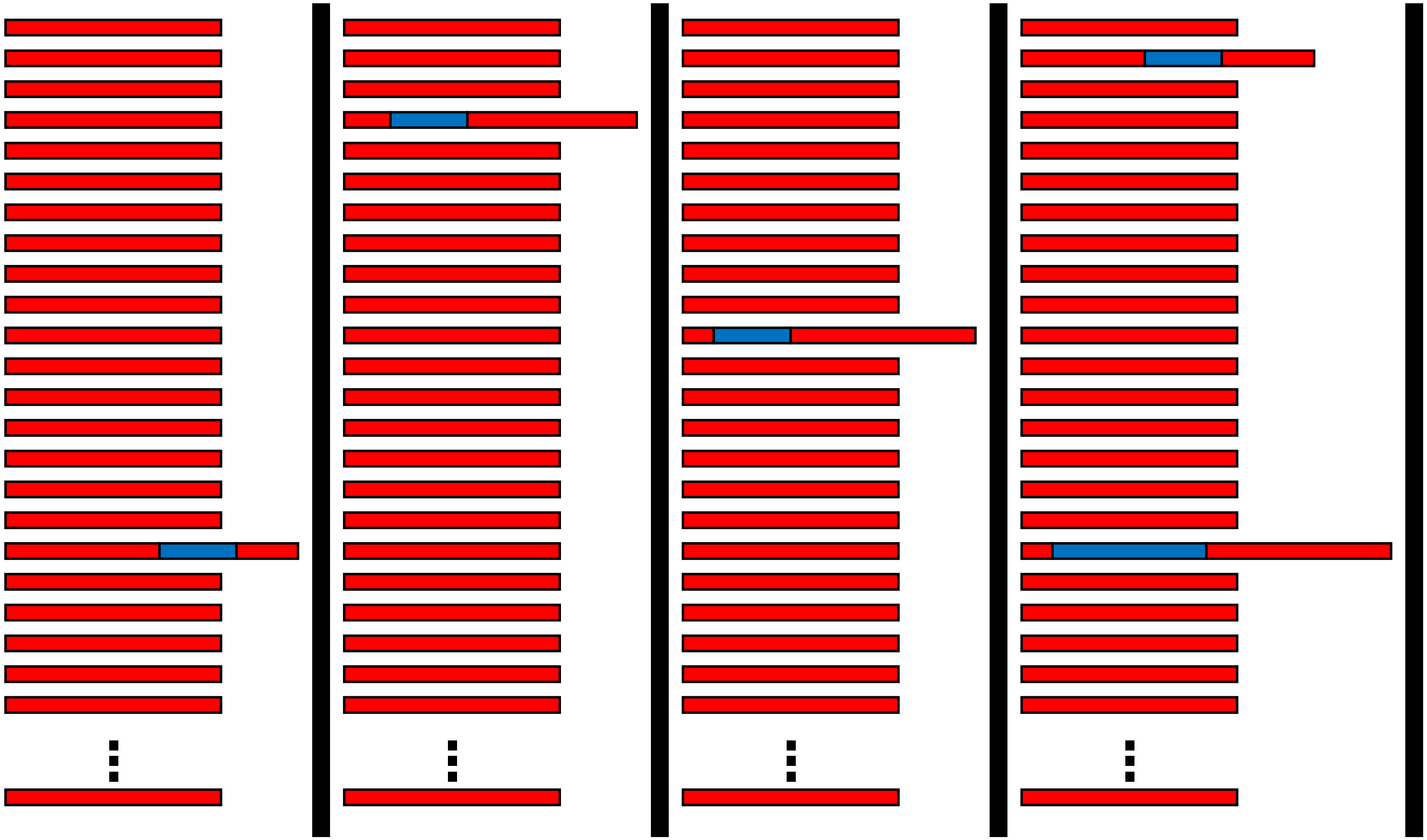
- An application is usually a sequence of a computation followed by a synchronization (collective):



- But if an event happens on a single node, it can affect all the other nodes

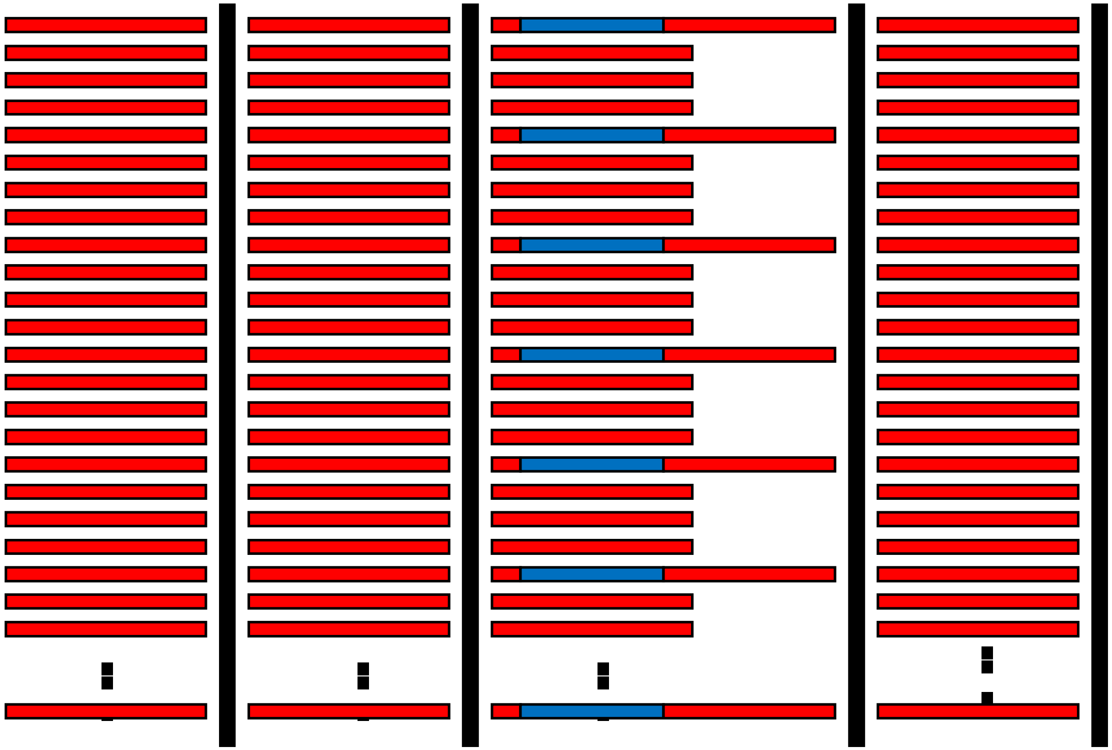


Effect of System Size



- The probability of a random event occurring increases with the node count

Tolerating Noise: Buffered Coscheduling



- We can tolerate the noise by coscheduling the activities of the system software on each node

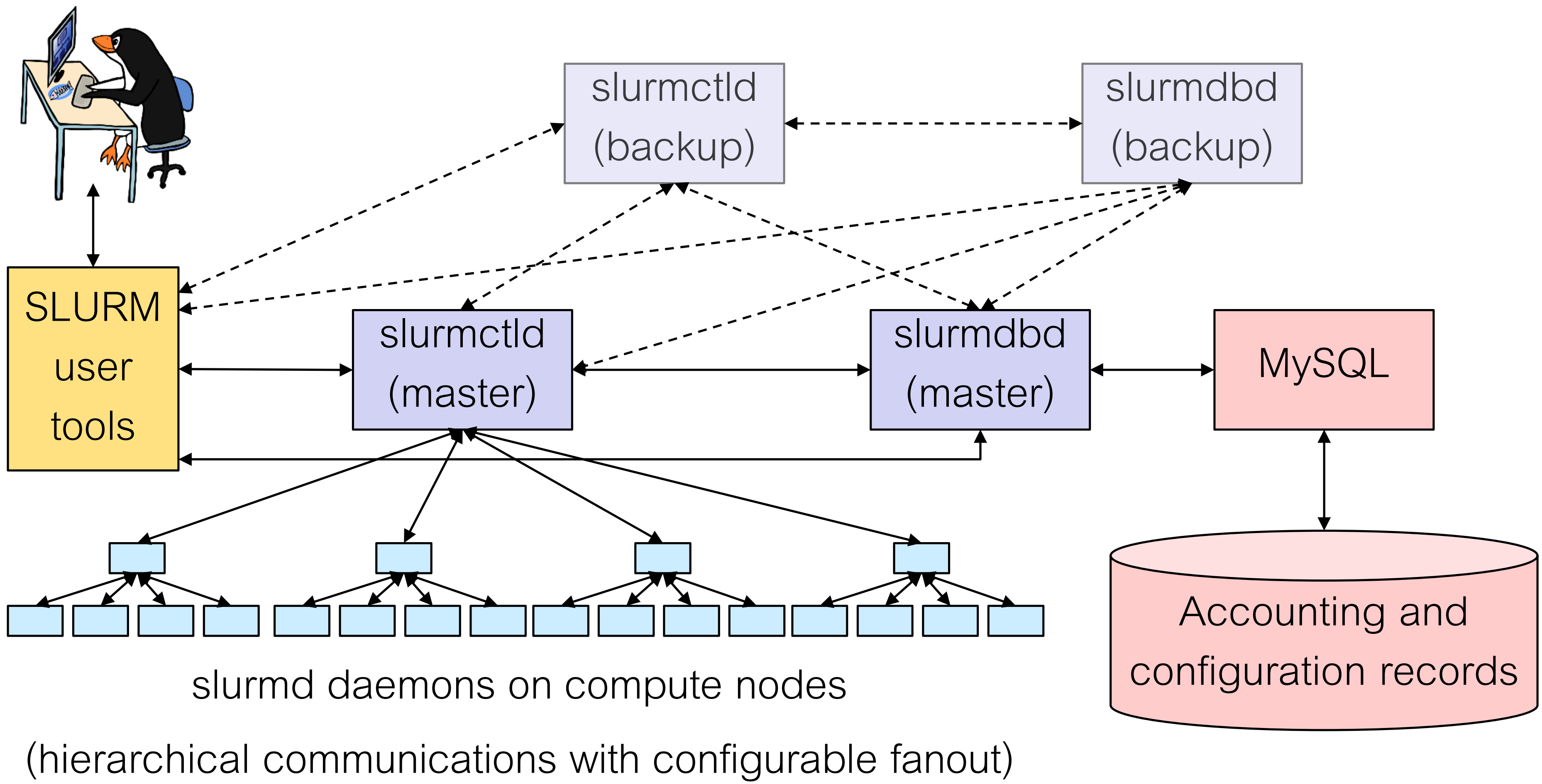
Example Cluster Scheduler: SLURM

- Simple Linux Utility for Resource Management
  - Performs resource management within single cluster => 3 roles:
    - Allocates access to computer nodes and their interconnect
    - Launches parallel jobs and manages them (I/O, signals, time limits, etc.)
    - Manages contention in the queue
- Developed by Lawrence Livermore National Lab (LLNL)
  - With help from HP, Bull (European high performance computing company), Linux NetworX, and others
  - Open Source
  - Extensible, provides flexible plugin mechanism
  - Active development still on-going
- Widely used on high performance compute clusters

SLURM Features

- Plugins support multiple scheduling policies
  - FIFO
  - Backfilling
  - Gang Scheduling
    - Requires multi-core awareness at slurmctld
  - Priority-based preemption
  - Topology-aware scheduling
    - Reduce contention on interconnect
- Includes many management & accounting features

SLURM Architecture



Further readings

- Scheduling problem encountered in many contexts (e.g., datacenters)
- Omega (Eurosys 2013)
  - https://research.google.com/pubs/pub41684.html
  - https://people.csail.mit.edu/malte/pub/talks/2013-04-17_eurosys-omega.pdf
- Hawk (USENIX 2015)
  - https://www.usenix.org/conference/atc15/technical-session/presentation/delgado
- Mesos (NSDI 2011)
  - https://people.eecs.berkeley.edu/~alig/papers/mesos.pdf
- Sparrow (SOSP 2013)
  - https://dl.acm.org/citation.cfm?id=2522716
- Thoth (VLDB 2013)
  - https://dl.acm.org/citation.cfm?id=2733062
- And many more ...

Announcements

- Midterm
  - Friday!
  - Bring T-card!
  - Covers up end of last week (OS Scalability, not Scheduling)
- Location and logistics:
  - Starts at **9AM**, as discussed in the first week of classes
  - Please be on time, we start at **9:10 sharp** => 110 minutes
  - Check website and Piazza announcements!