Real-Time Systems

Marcus Völp

Hard Real-Time

Multiprocessor Scheduling

TECHNISCHE UNIVERSITÄT DRESDEN

Outline

- Introduction
- Terminology, Notation and Assumptions
- Anomalies + Impossibility Results
- Partitioned Scheduling (no migration)
- Global Scheduling (task- / job-level migration)
  - G-FP
  - G-EDF
- Optimal MP Scheduling
- MP – Resource Access Protocols
- Open Research Issues

Lessons Learned From UP

- **Liu-Layland Criterion for fixed task priority algorithms:**
  - can schedule any workload up to a utilization of $U_{RMS}(n) = n\sqrt[n]{2} - 1 \leq 0.693$
  - scheduling of workloads with higher utilization not guaranteed
- **fixed job priority algorithms are optimal: (e.g., EDF)**
- **there are optimal greedy algorithms**
  - with a single measure characterizing the "importance" of a job (e.g., time to deadline, laxity, …)
- **all pre-emptive FTP, FJP algorithms are predictable**
  - response times cannot increase when decreasing execution times
- **all pre-emptive FTP algorithms and EDF are sustainable**
  - no period / deadline anomalies
- **simultaneous release is critical instance**
- **response times depend on <u>set</u> but not on order of high-prio. tasks**

Taxonomy of Multiprocessor Scheduling

- Two problems to solve:
  - Priority Problem: When to run a given job of the workload?
    - fixed task priority (e.g., RMS, ...)
    - fixed job priority (e.g., EDF, ...)
    - dynamic job priority (e.g., least laxity, PFAIR, DP-FAIR, ...)

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    - fixed job priority (e.g., EDF, ...)
    - dynamic job priority (e.g., least laxity, PFAIR, DP-FAIR, …)
  - Allocation Problem: Where to run this job?
    - no migration — partitioned
    - task-level migration (no migration of running jobs)
    - job-level migration (migrate also running jobs)

    global

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Pre-emption Costs – UP / MP

  - Allocation Problem: Where to run this job?
    - no migration partitioned
    - task-lev
    - job-leve global

Migration Costs - MP

Pre-emption Costs

- direct costs:
  - timer / device interrupt
  - save register state
  - manipulate ready list
    - UP: no synchronization required
  - load register state of next thread
- indirect costs
  - cache evictions between two consecutive runs
  - TLB refills after evictions / shootdown

Pre-emption Costs

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- indirect costs
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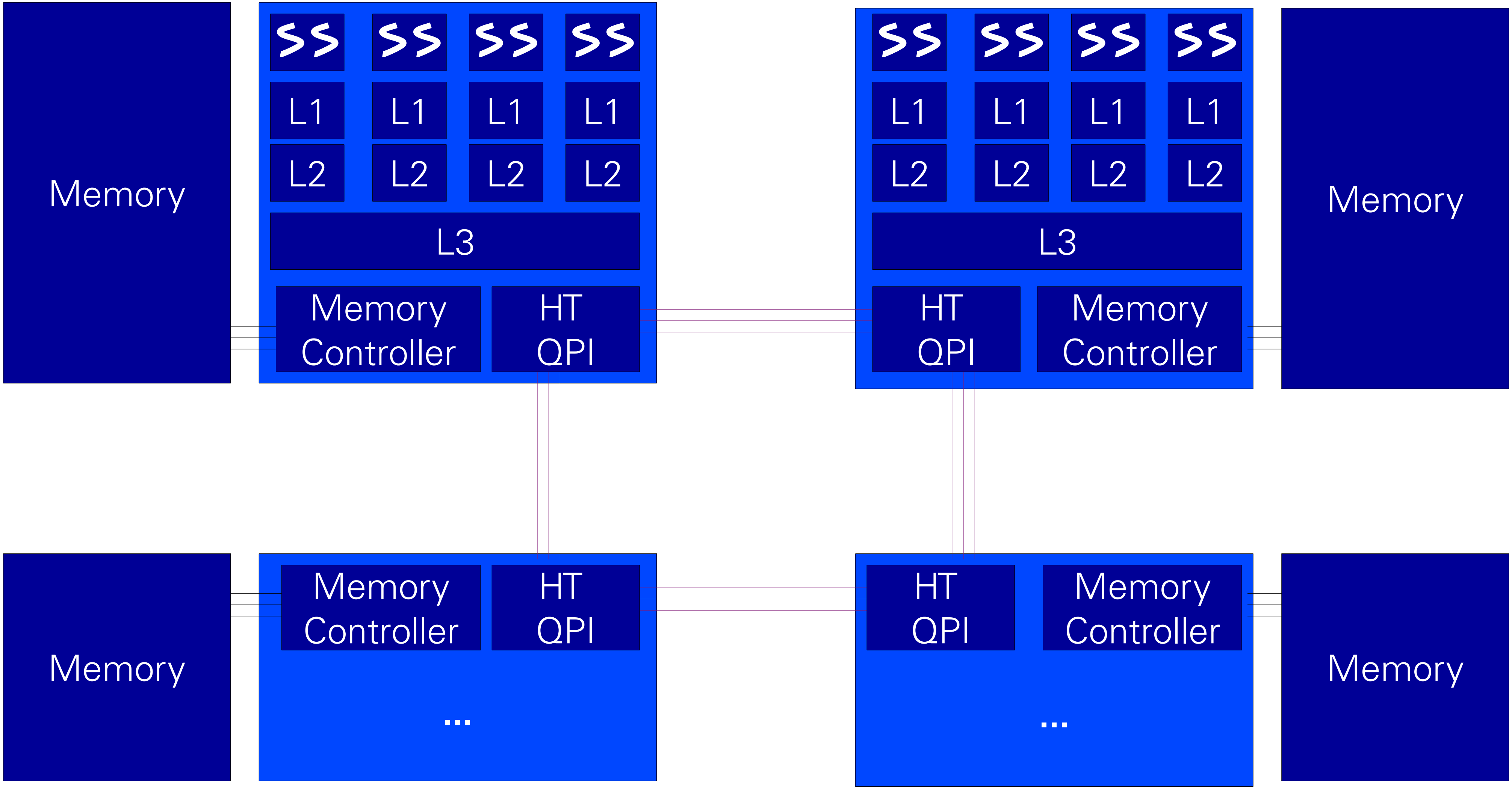
Migration Costs

- job-level migration
  - migration of running job implies pre-emption at source CPU
- task-level migration
  - job is already pre-empted
- direct costs
  - manipulate remote / global ready list
    - synchronization
  - fetch register state
- indirect costs
  - fetch active cache working set from remote cache
  - load remaining data from remote memory

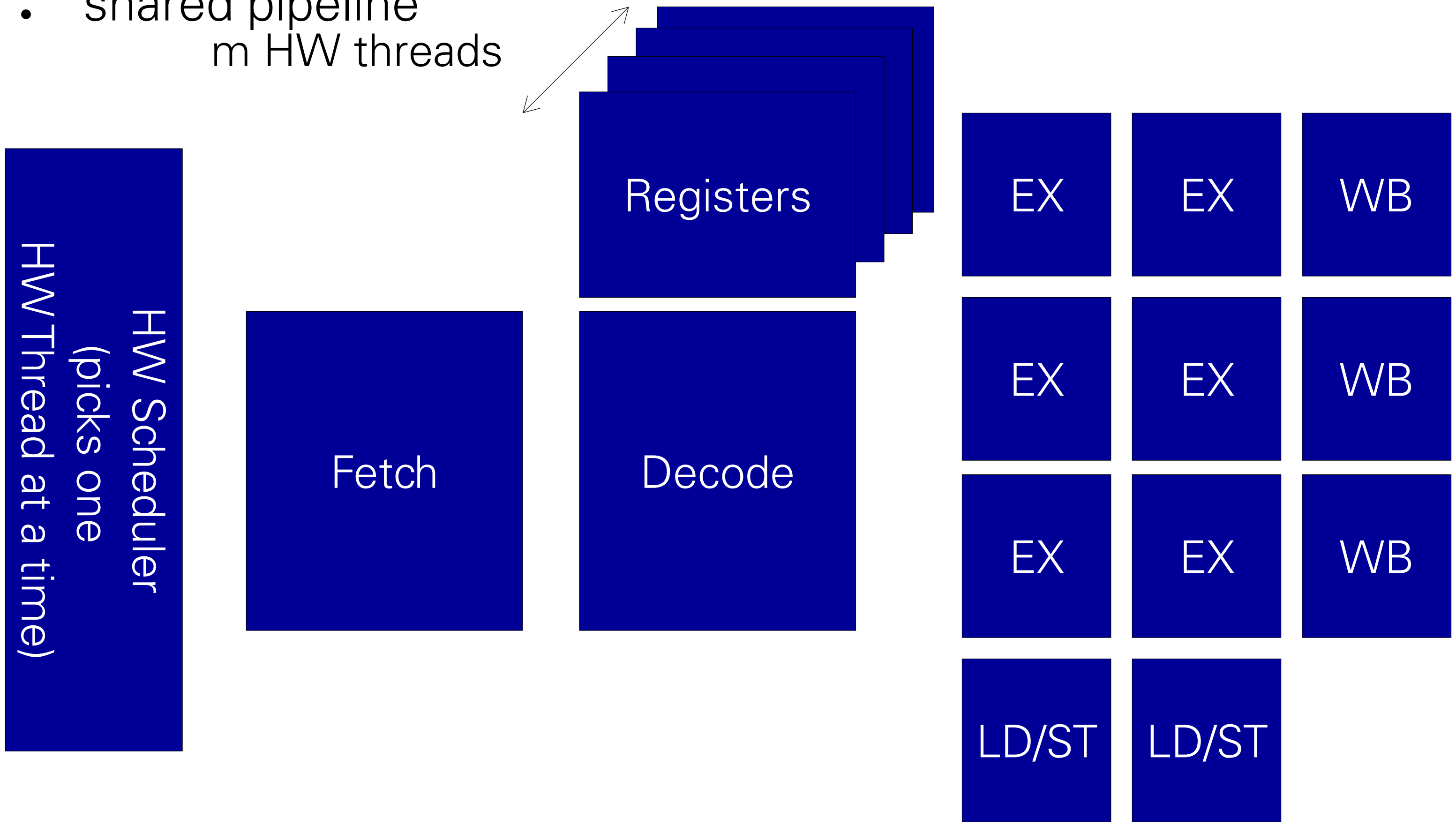
Multiprocessor Architectures

- AMD Opteron / Intel Core Duo: SMT + multi core + ccNuma



Multiprocessor Architectures

- Symmetric Multi-Threaded (SMT) Processors
  - m hardware threads
  - shared pipeline



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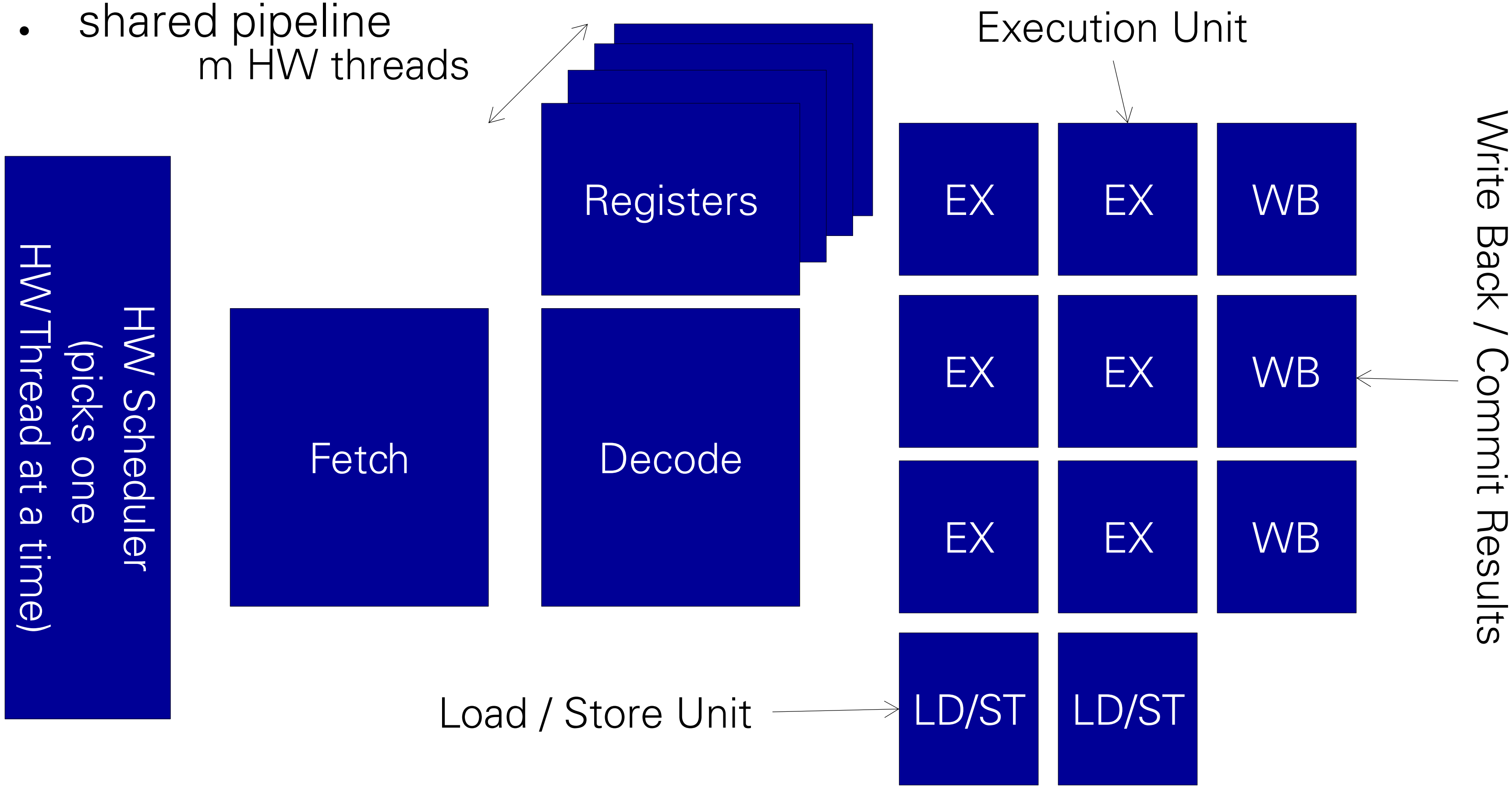
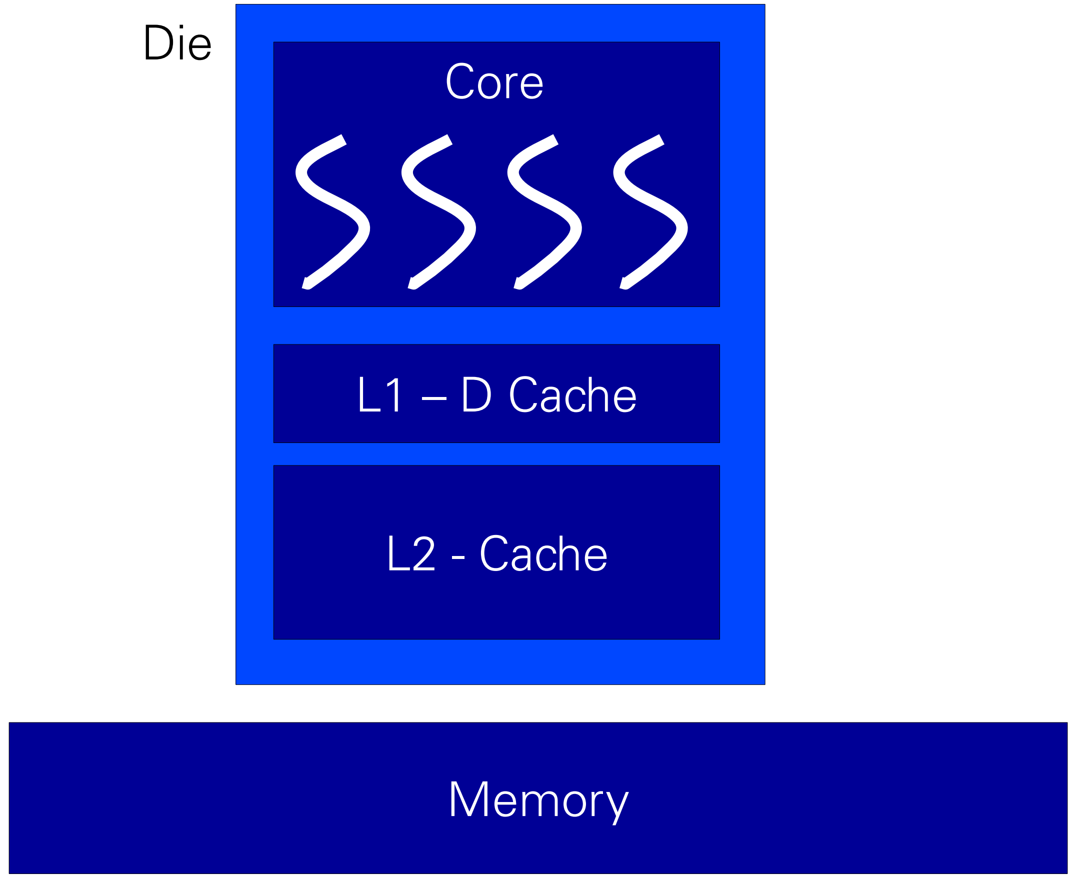


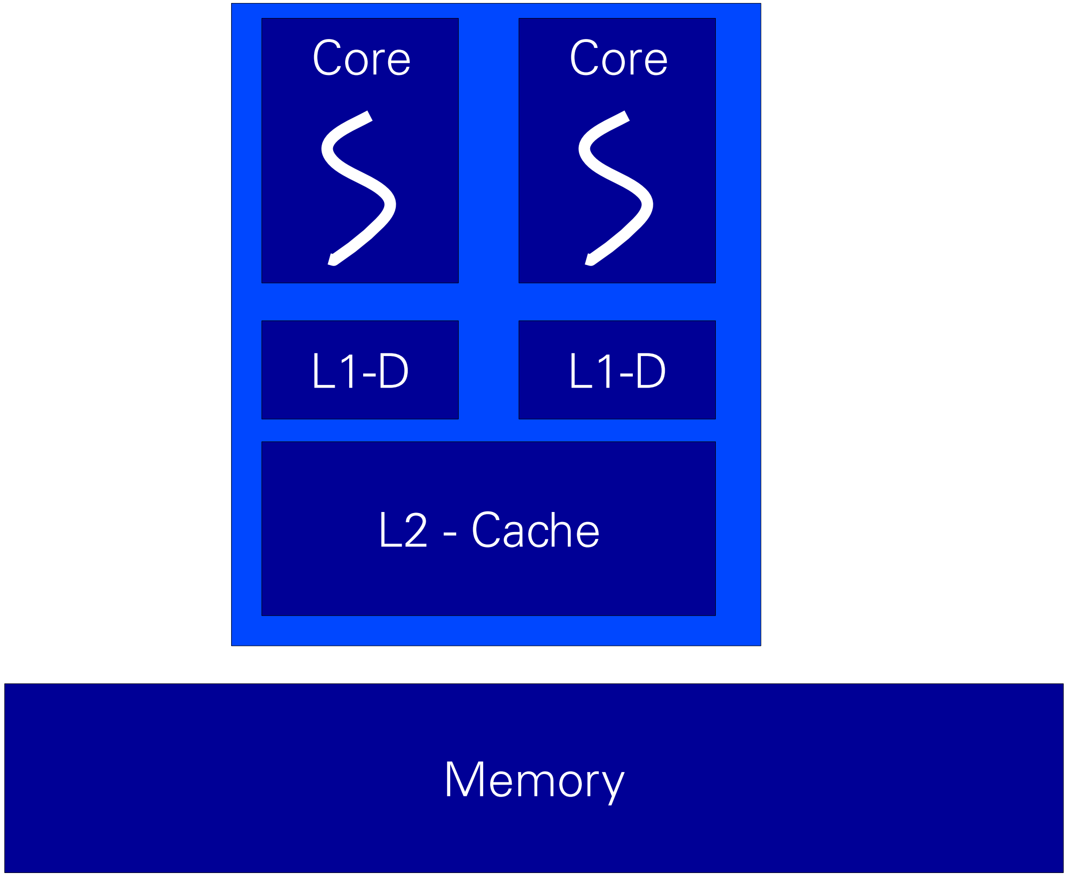
Multiprocessor Architectures

- Symmetric Multi-Threaded (SMT) Processors
  - operating system multiplexes n SW threads on m HW threads
  - caches + pipeline is shared => no indirect migration costs



Multiprocessor Architectures

- Multi-Core Processors
  - operating system multiplexes n SW threads on m cores
  - timing of last level cache dominates migration costs



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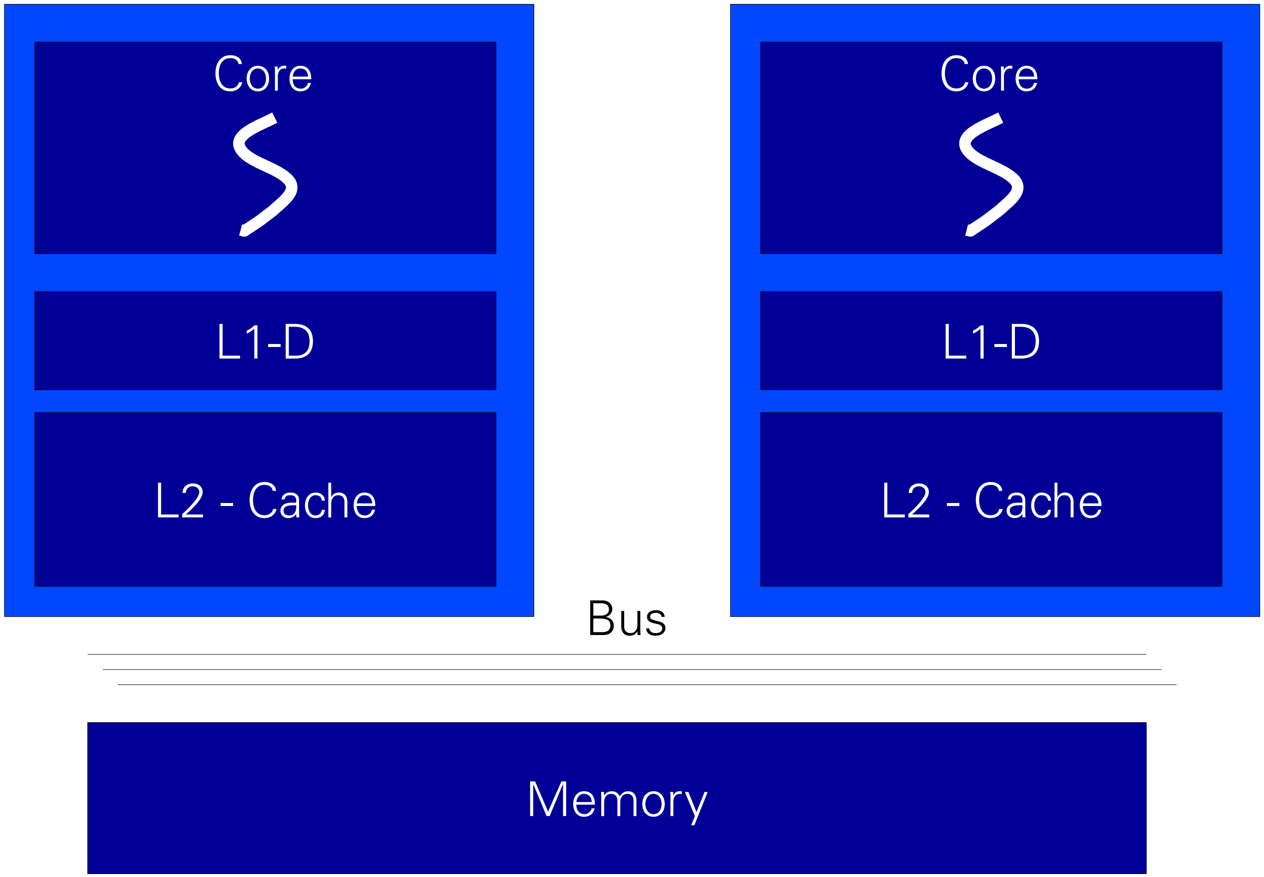
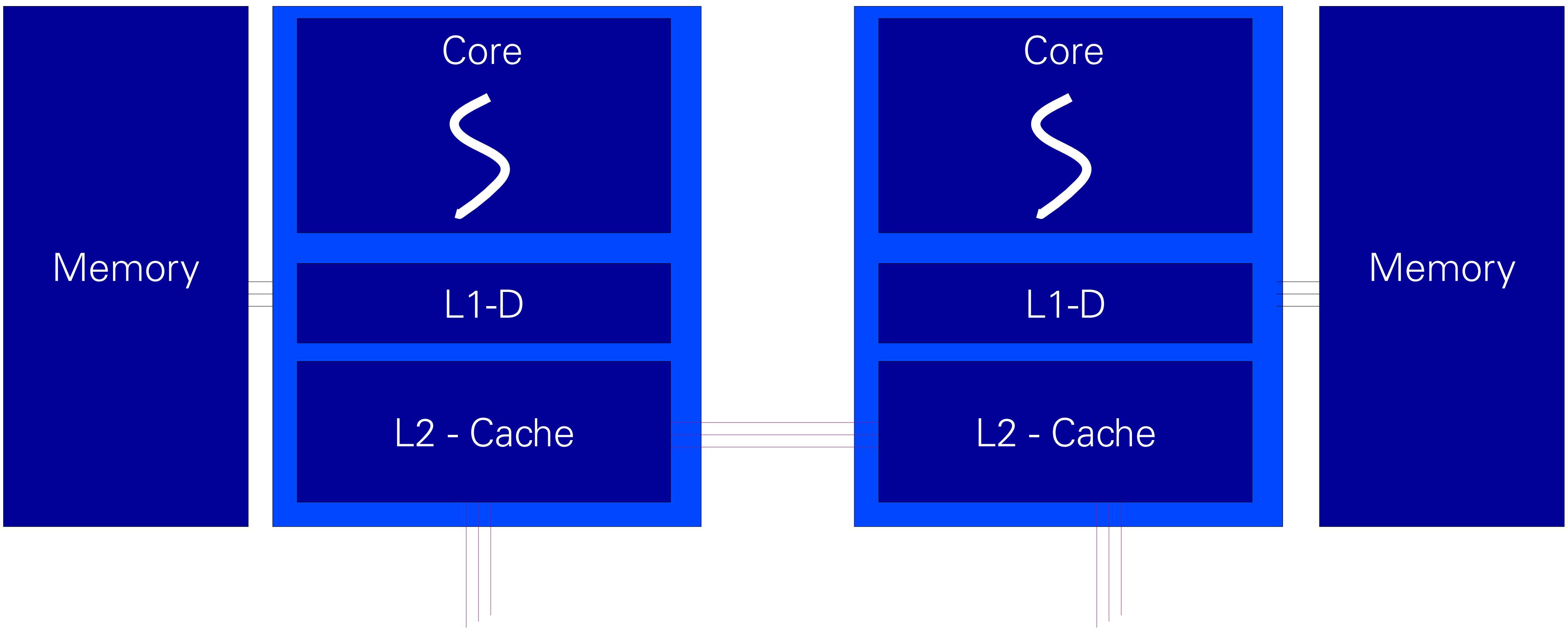


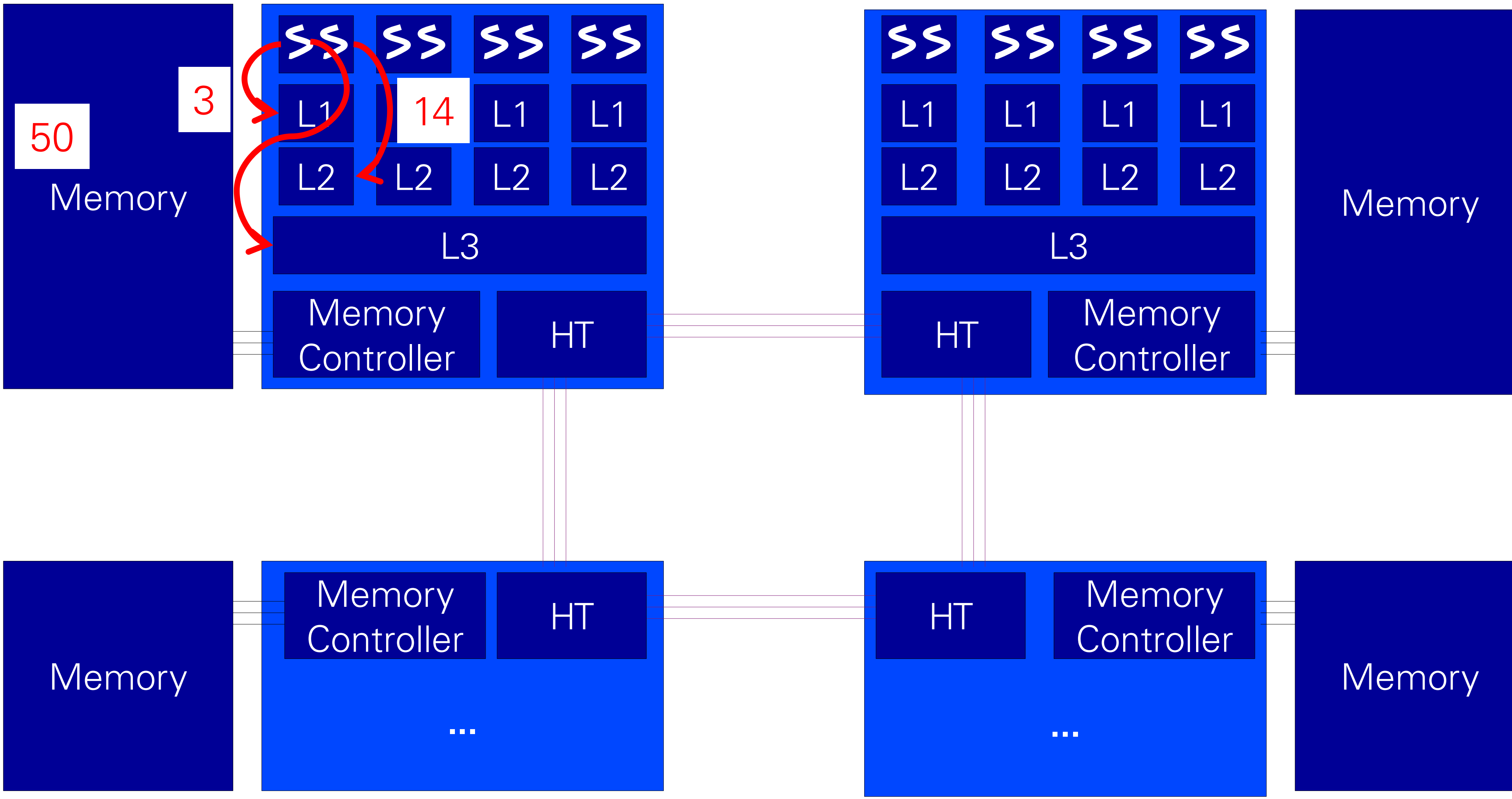
Multiprocessor Architectures

- (cache coherent) NUMA
  - like SMP
  - non-uniform memory access: fetch from remote memory



Multiprocessor Architectures

- AMD Opteron [Corey: OSDI '08]



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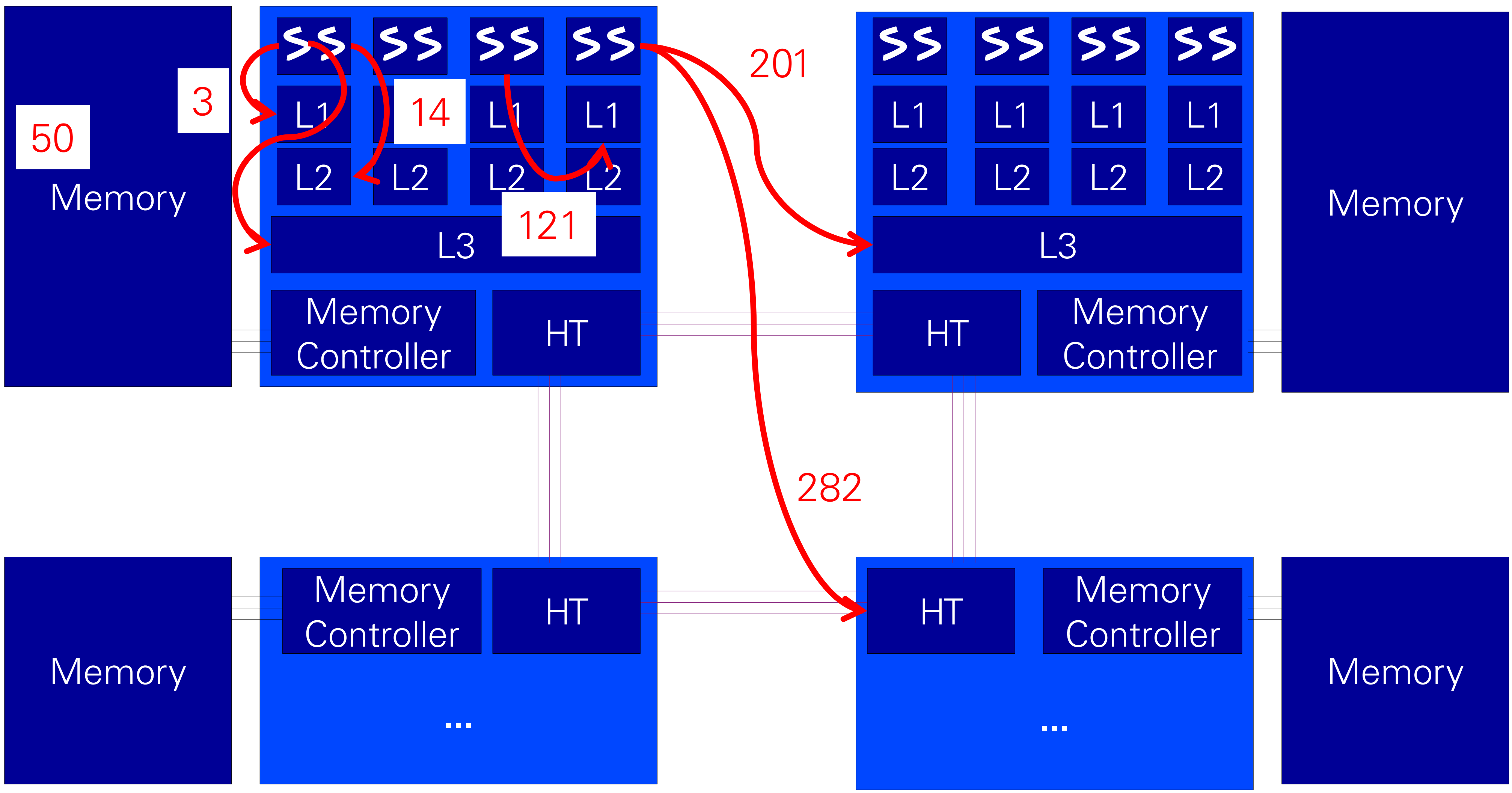

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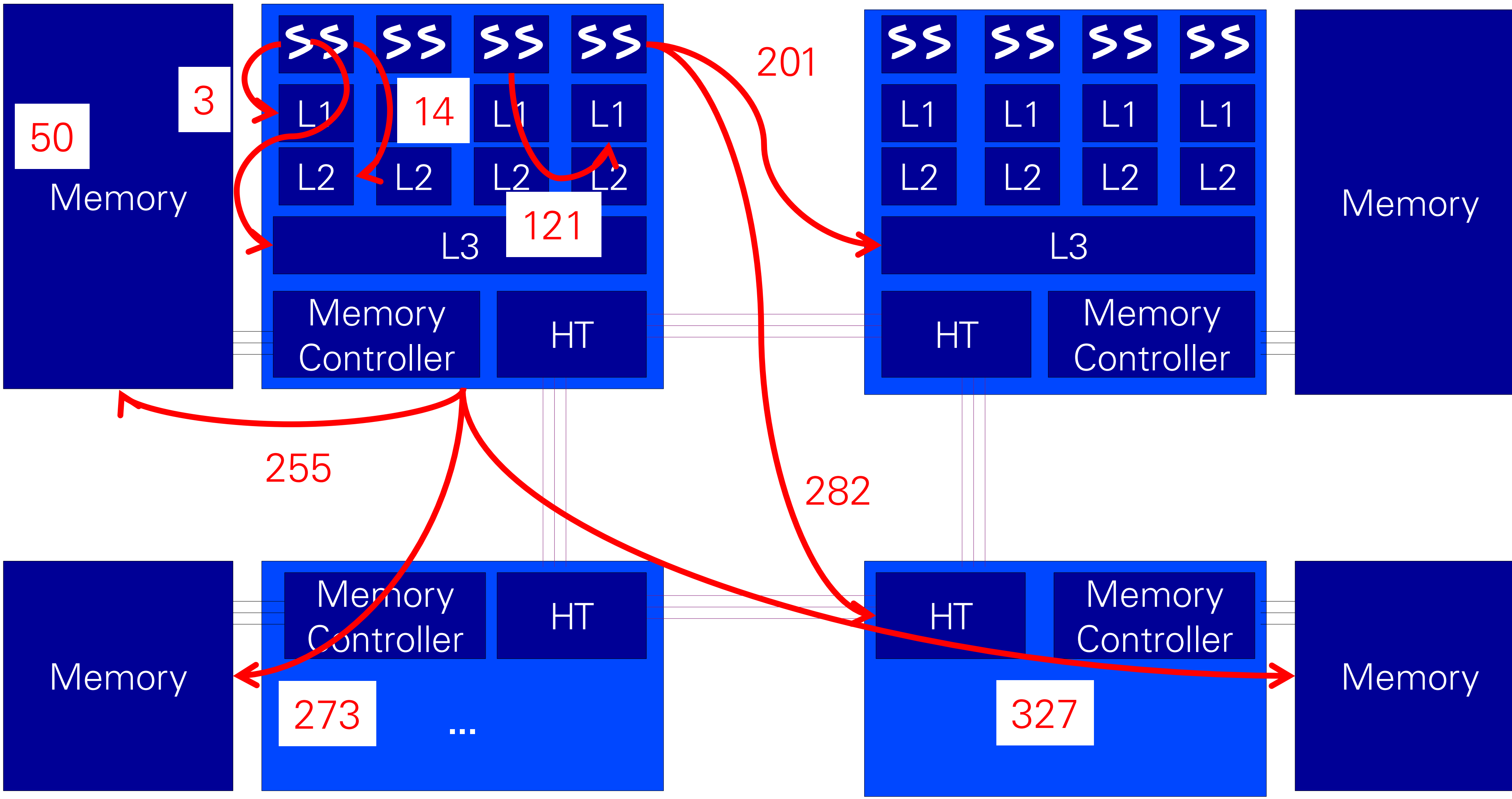
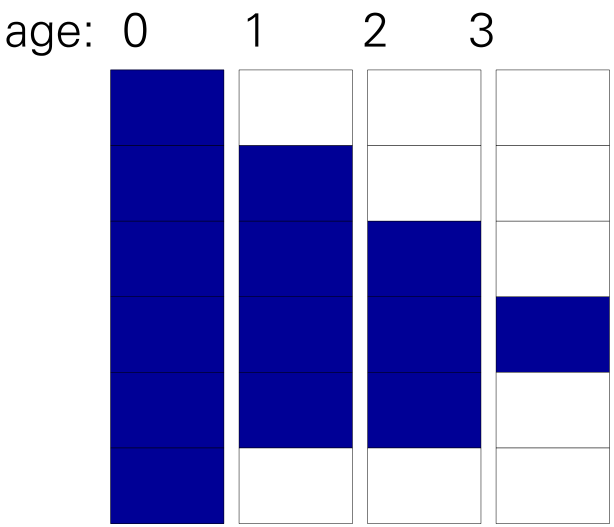


Migration Costs

- Active Cache Working Set
  - cachelines a thread would access again if it would run
  - varies over time
  - ages out after preemption



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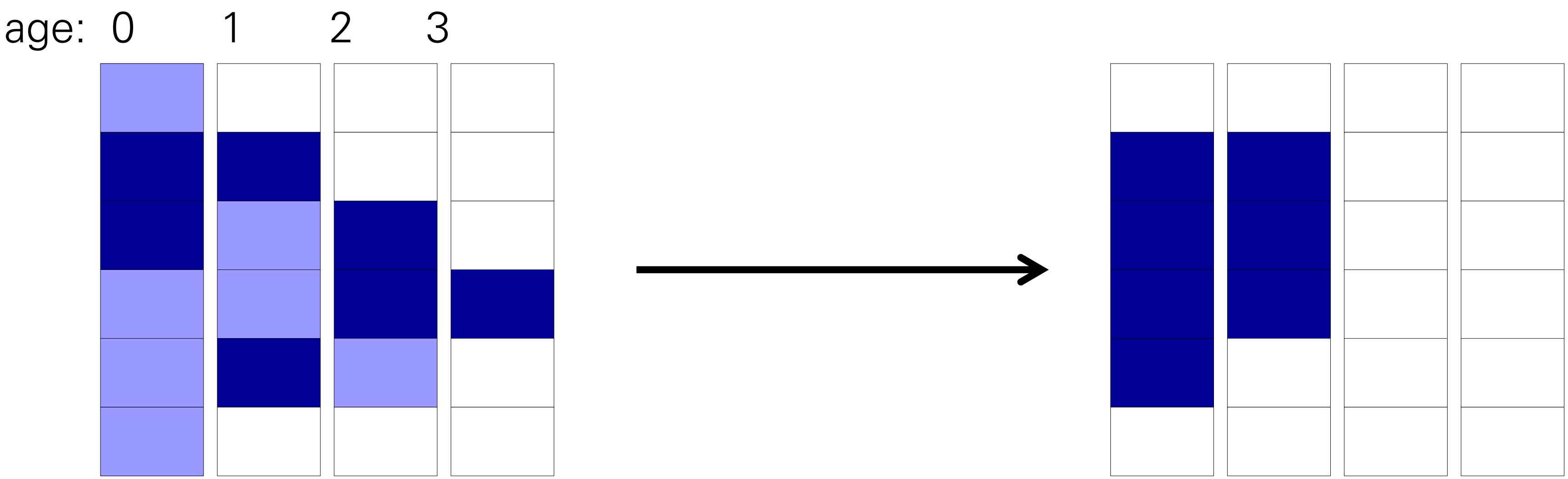

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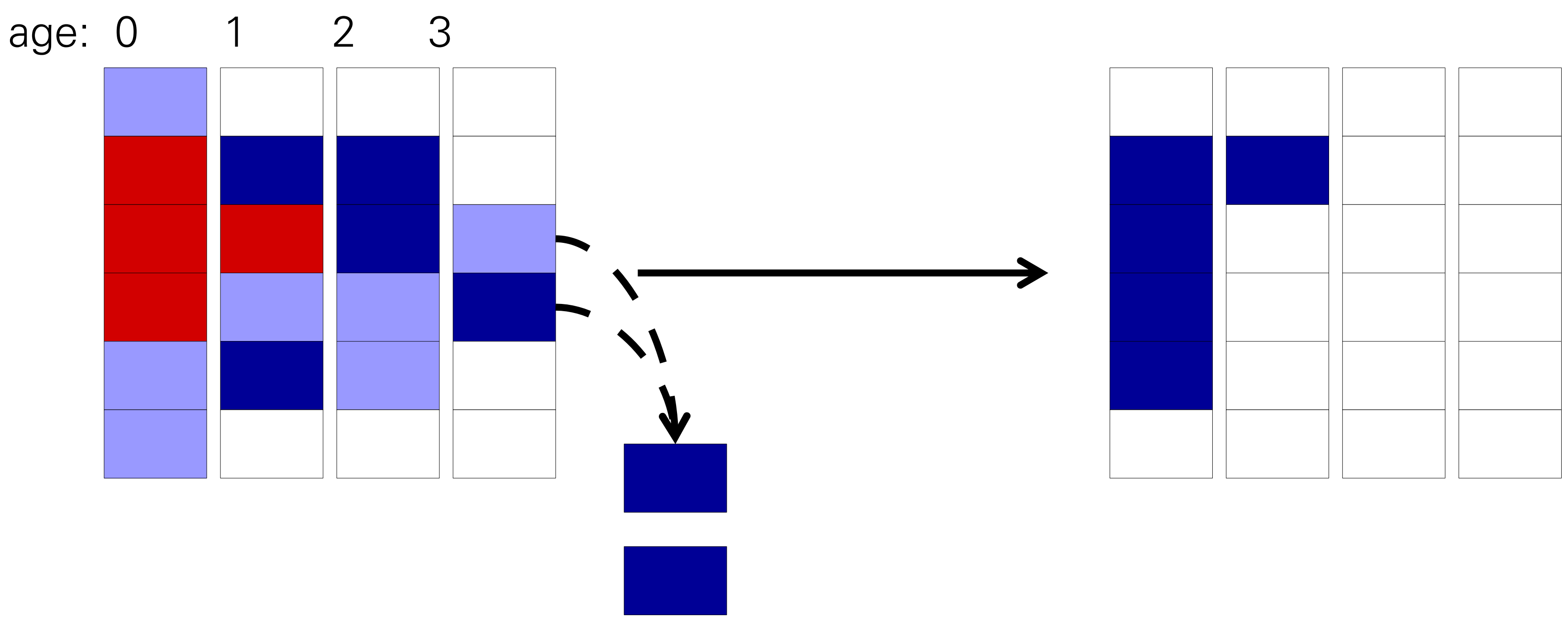
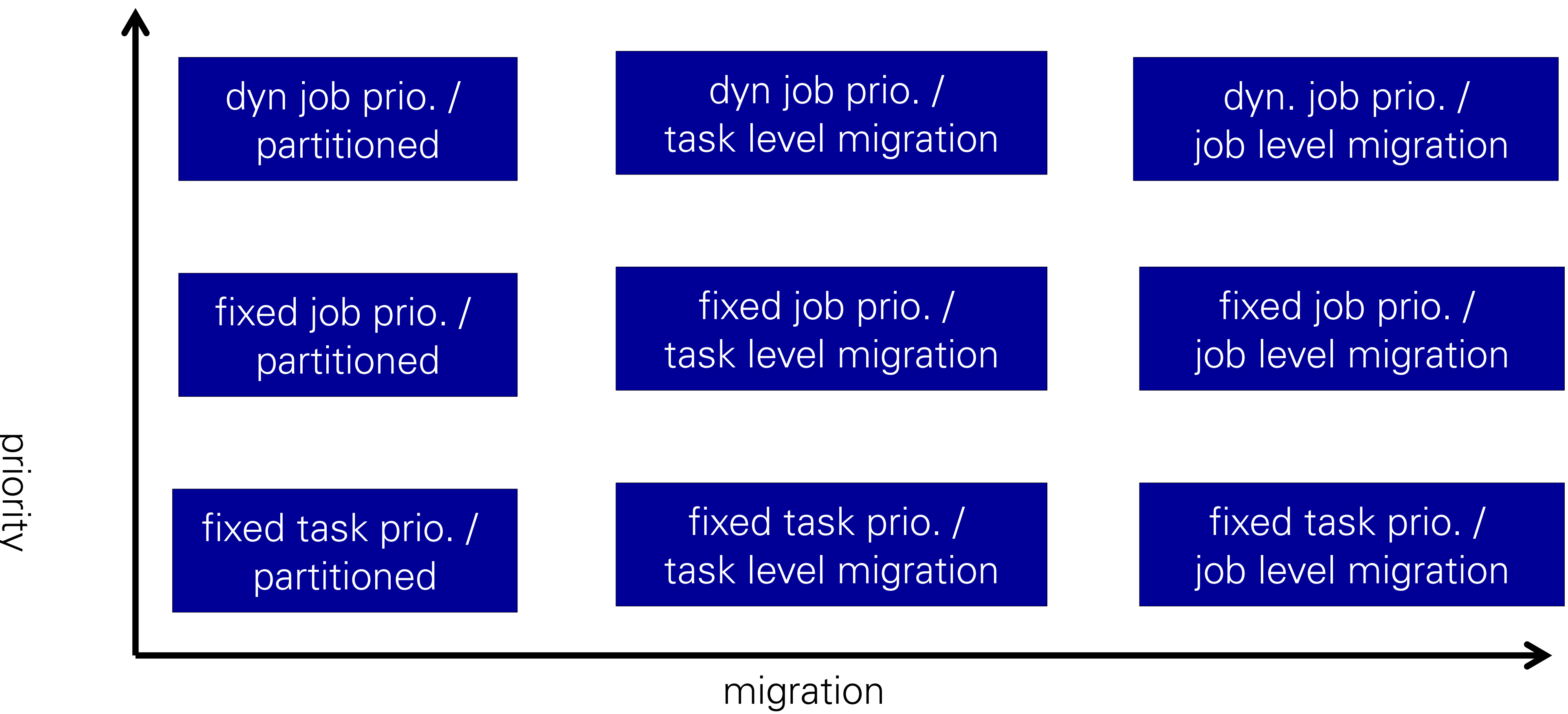


Migration Costs

- Summary
  - migration costs are highly architecture dependent
  - non-trivial to predict
  - may cause a significant delay when a thread resumes execution
- Assumption for the remainder of this lecture:
  - zero pre-emption and migration costs / attributed to WCET

Design Space of MP Scheduling



Design Space of MP Scheduling

Partitioned	Global	
dyn job prio. / partitioned	dyn job prio. / task level migration	dyn. job prio. / job level migration
fixed job prio. / partitioned	fixed job prio. / task level migration	fixed job prio. / job level migration
fixed task prio. / partitioned	fixed task prio. / task level migration	fixed task prio. / job level migration

Design Space of MP Scheduling

Relative ordering between classes of scheduling algorithms

dyn. job prio. / job level migration

dyn job prio. / task level migration

fixed job prio. / partitioned

dyn job prio. / partitioned

fixed job prio. / task level migration

fixed job prio. / job level migration

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Later in this lecture

Outline

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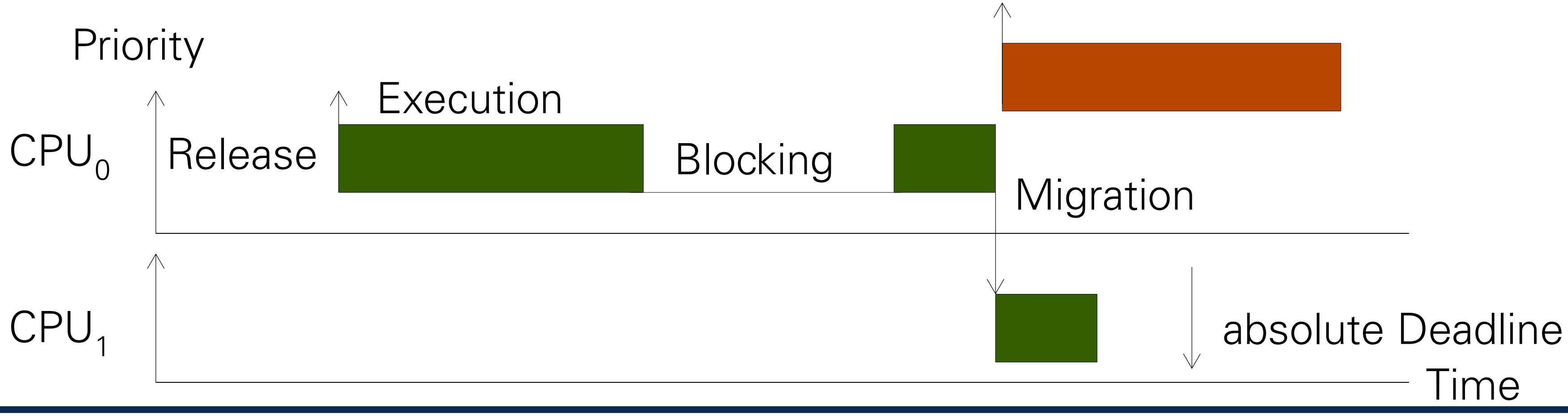
- Terminology, Notation and Assumptions
- Anomalies + Impossibility Results
- Partitioned Scheduling
- Global (Task-Lvl migration) Scheduling
  - G-FTP (e.g., G-RMS)
  - G-EDF
- Optimal MP Scheduling
- MP – Resource Access Protocols
- Open Research Issues

Terminology, Notation and Assumptions

- Periodic Tasks
  - Task $t_i = (P_i, D_i, C_i)$ P_i = const.
- Sporadic Tasks
  - P_i = Minimal Interrelease Time
- Deadlines
  - implicit deadline: $D_i = P_i$ (relative deadline = period)
  - constrained: $D_i \leq P_i$ (relative deadline < period)
  - arbitrary (deadline may be after period end)
- Utilization $U_i = \frac{C_i}{P_i}$
- Density $\partial_i = \frac{C_i}{min(D_i, P_i)}$

Terminology, Notation and Assumptions

- Assumptions for the remainder of this lecture
  - independent tasks
  - fully pre-emptible / migratable (negligible costs)
  - unlimited number of priorities
  - tasks are single threaded: a job can utilize only 1 CPU at a time
  - jobs do not block (shared resources later in this lecture)
  - pictures show schedules for 2 CPUs



Terminology: P-DMS / G-RMS / G-EDF

- Scheduling Algorithms:

Deadline Monotonic Scheduling:
prio inverse proportional to deadline

Rate Monotonic Scheduling:
prio inverse proportional to period

Earliest Deadline First:
job prio. inverse proportional to deadline

- P-DMS

G-RMS / G-EDF

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- P-DMS

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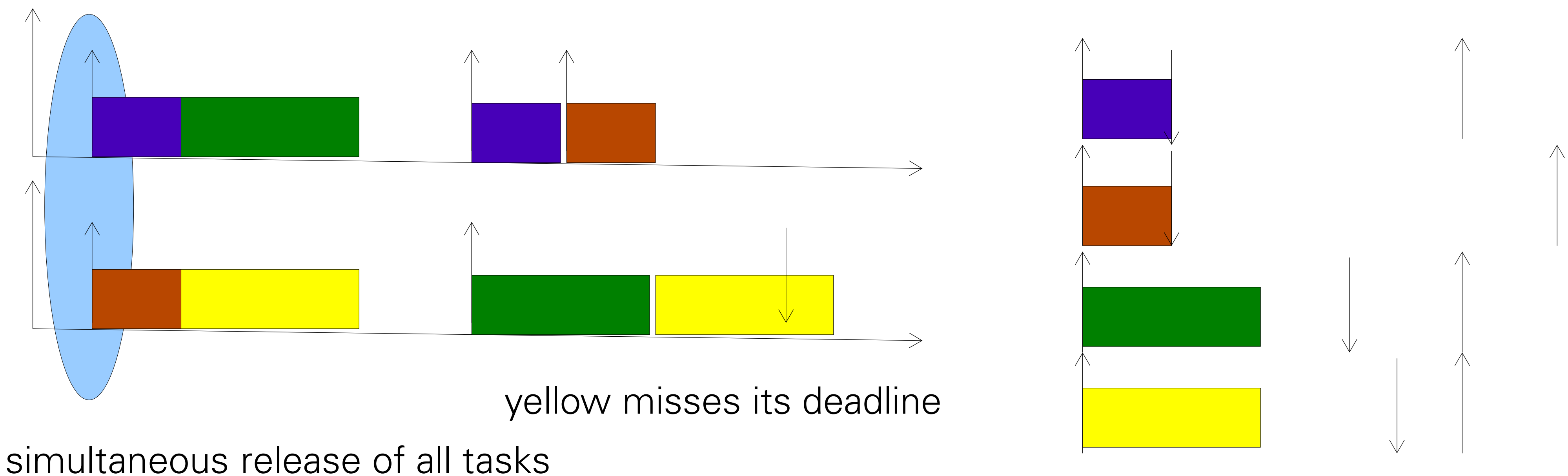
Global:
- threads may migrate to other CPUs
- scheduler picks thread from global ready queue
- accesses to ready queue must be synchronized

Partitioned:
- assign threads to processors
- scheduler picks threads from local (per CPU) ready queue
- no synchronization overhead for accessing the ready queue

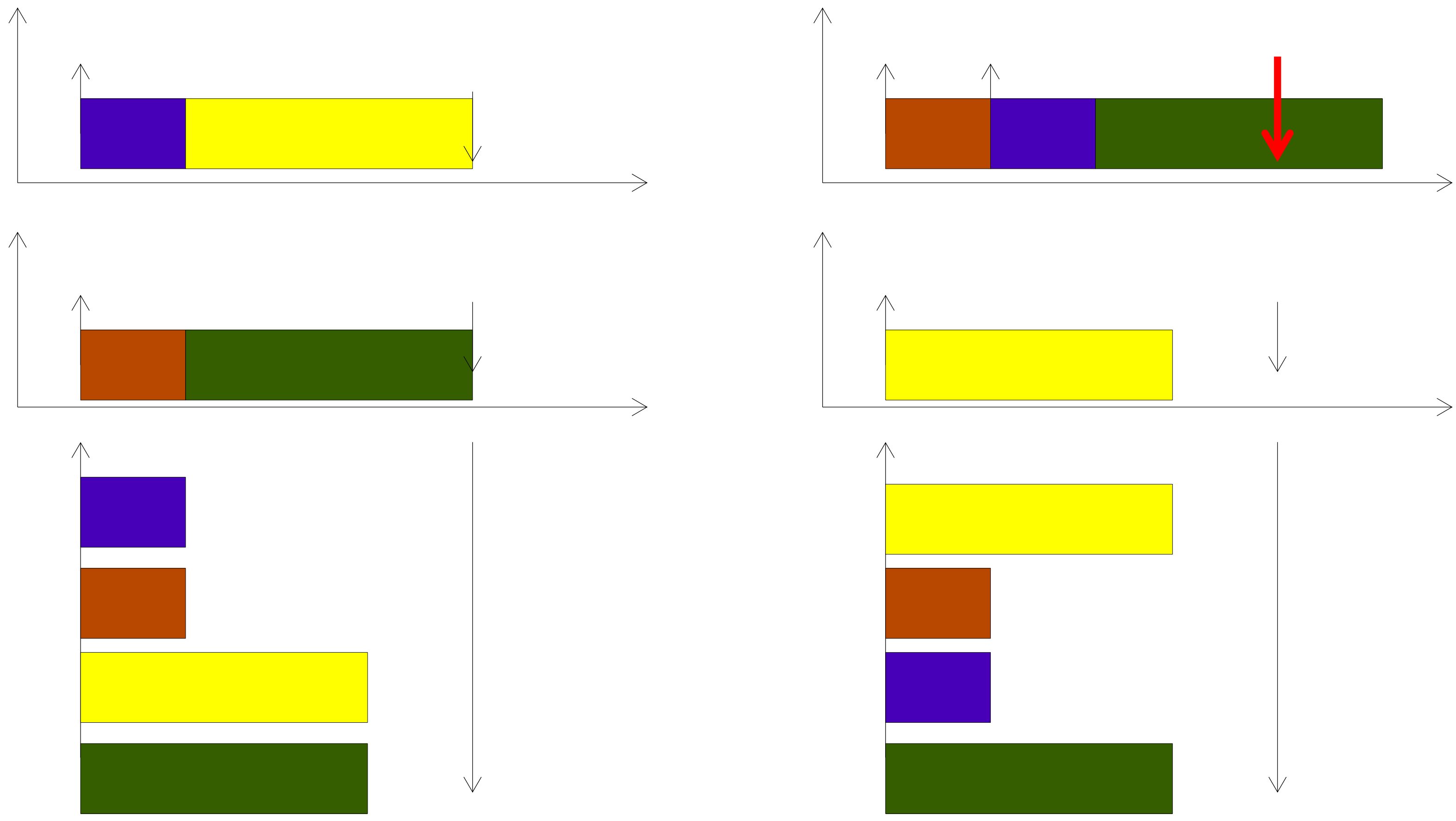
Anomalies

- Simultaneous Release is not Critical Instance [Lauzac '98]
  - longer response time in second period



Anomalies

- Response time (of green) depends not only on set of higher prioritized tasks but also on their relative priority ordering



Sustainability [Baruah '06]

- A schedulable workload remains schedulable if we
  - decrease the execution time of a task (predicability)
    - otherwise, WCET won't work as admission criterion
  - increase the minimal interrelease time (period) of a task
    - otherwise, more frequent recurrence is no safe approximation
  - increase the relative deadline of a task
    - otherwise, earlier deadline is no safe approximation

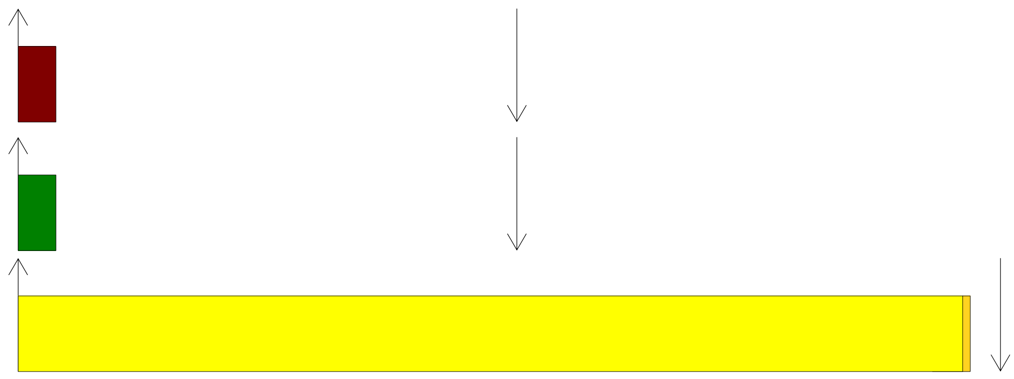
- G-FTP + G-EDF are not sustainable if #CPUs > 1

- all pre-emptive FJP / FTP algorithms are predictable

Fixed Job Priority Fixed Task Priority

Dhall Effect

- The utilization bound of Global EDF is as low as $U_{EDF} = 1 + e$
  - m tasks with short periods and infinitesimal low U_i (e.g., $U_i = e$)
  - 1 task with larger period and U_j close to 1 (e.g., $U_j > (2 – e) / 2$)



- Dhall Effect does not manifest if $U_i < 41\ \%$

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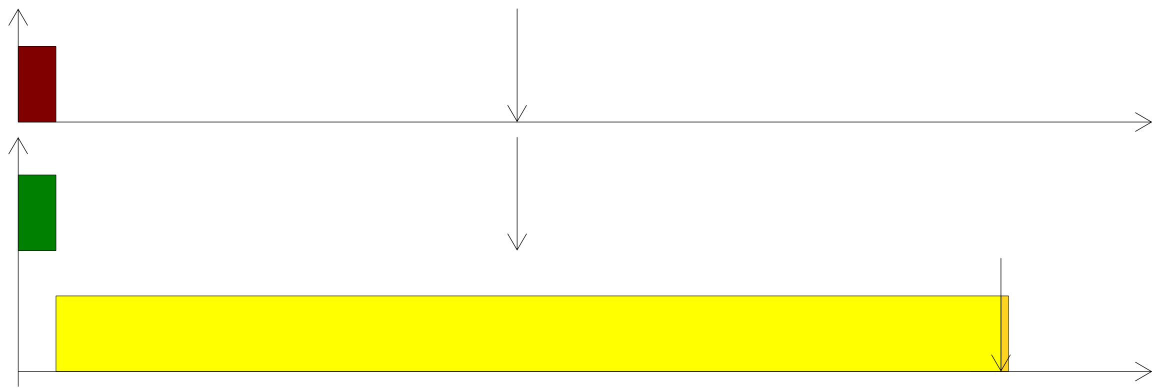

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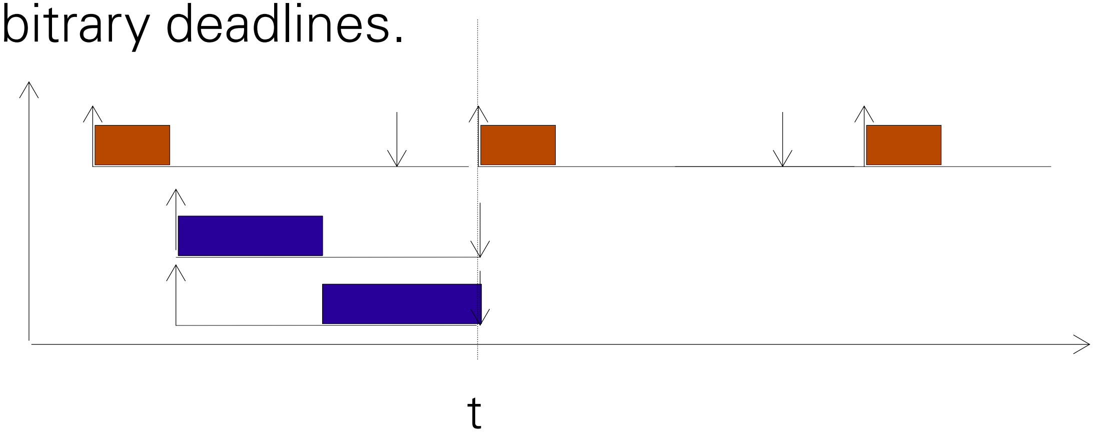
some Impossibility Results

- [Hong '88]
  - No optimal online MP scheduling algorithm for arbitrary jobs unless all jobs have the same relative deadline.
- [Dertouzos '89]
  - Even if execution times are known precisely
- [Fisher '07]
  - No optimal online algorithm for sporadic tasksets with constrained or arbitrary deadlines.



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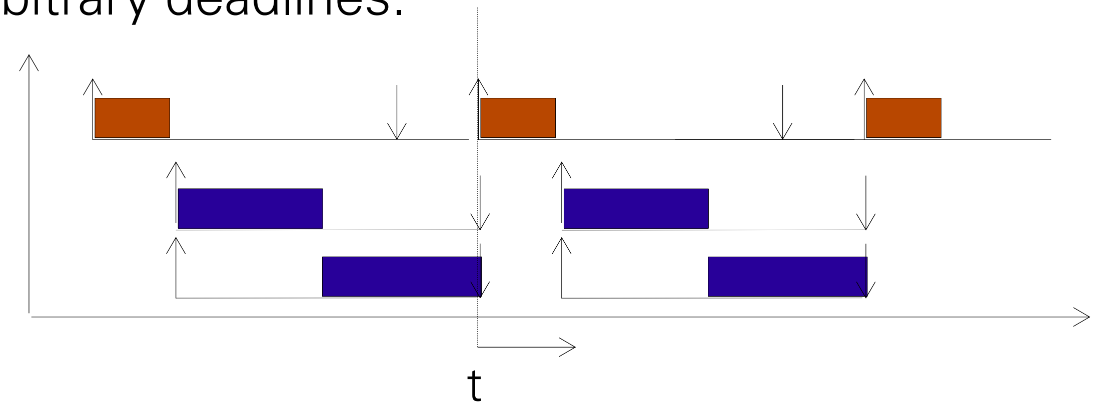
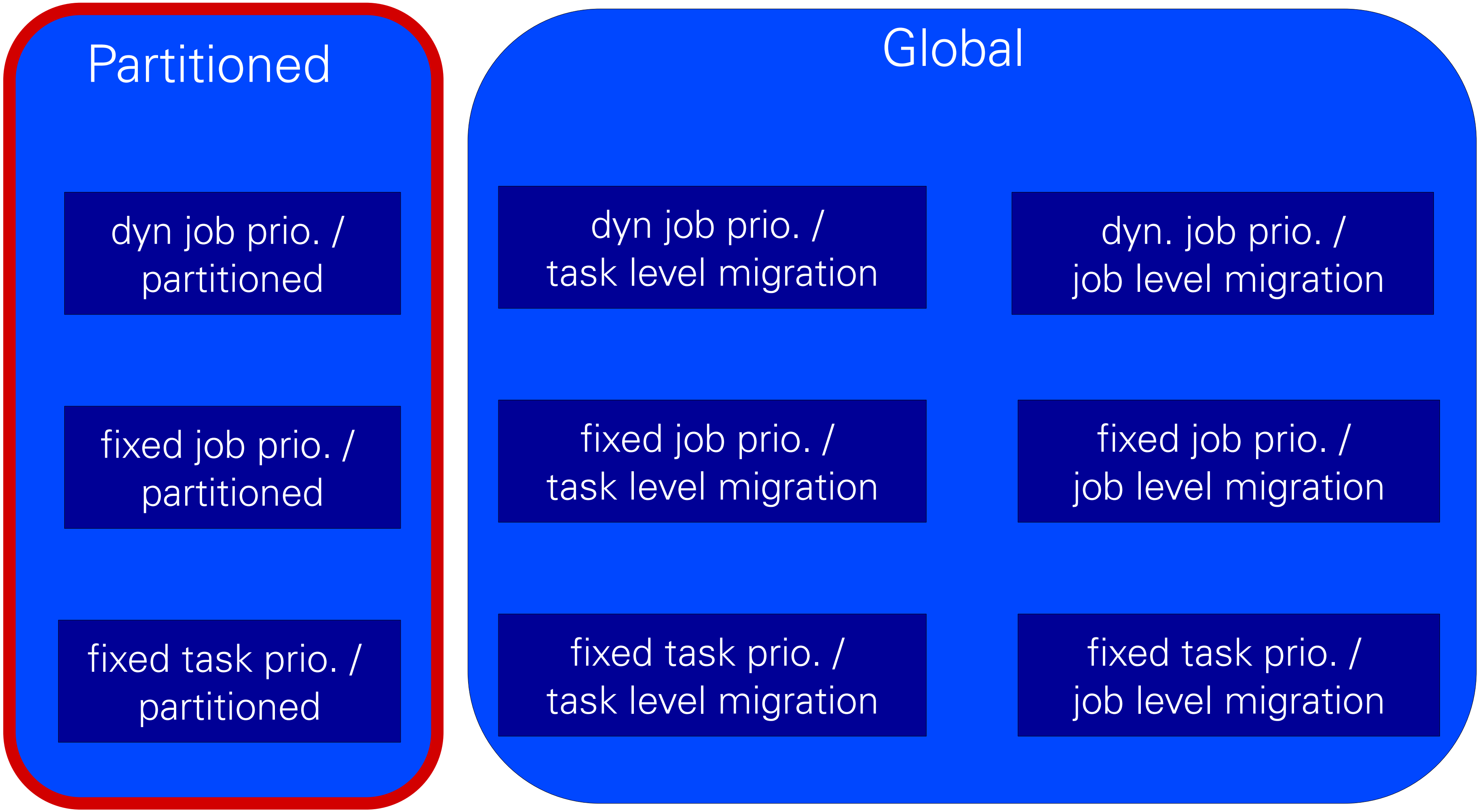
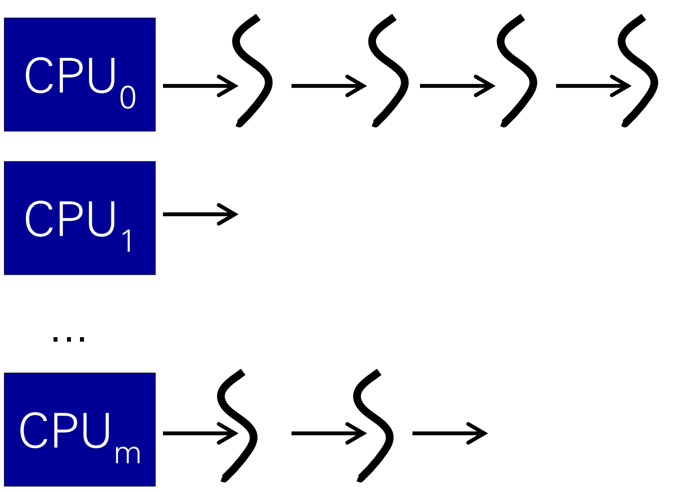


Partitioned Scheduling



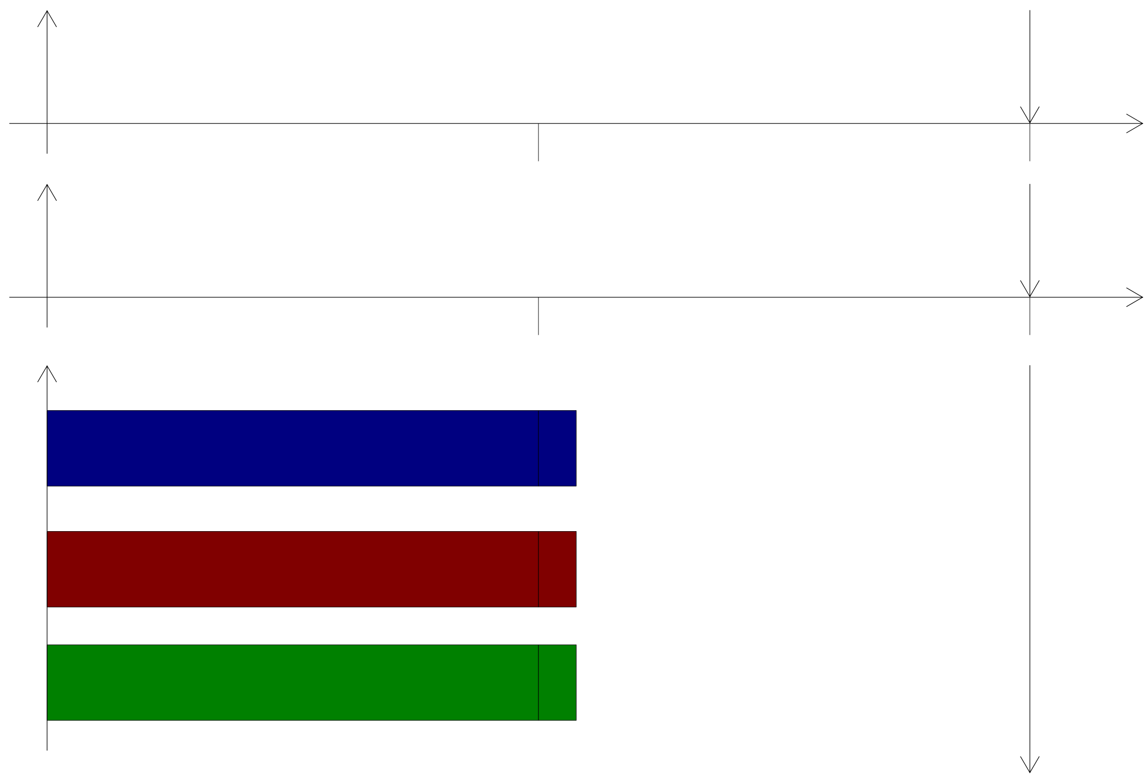
Partitioned Scheduling

- Split workload by allocating tasks to CPUs
- Run allocated task with UP scheduling algorithm
  - reap benefit of well known UP results
  - optimal task allocation is NP complete:
    - pack n tasks with density d_i on m CPUs with capacity $d_{max} = 1$
    - Bin-packing



Partitioned Scheduling

- Utilization bound for implicit deadline workloads [Anderson '01]



$$U_{opt} = \frac{m+1}{2}$$

No partitioning scheduling algorithm can produce a feasible schedule of m+1 tasks with execution time 1+e and period of 2 on m processors

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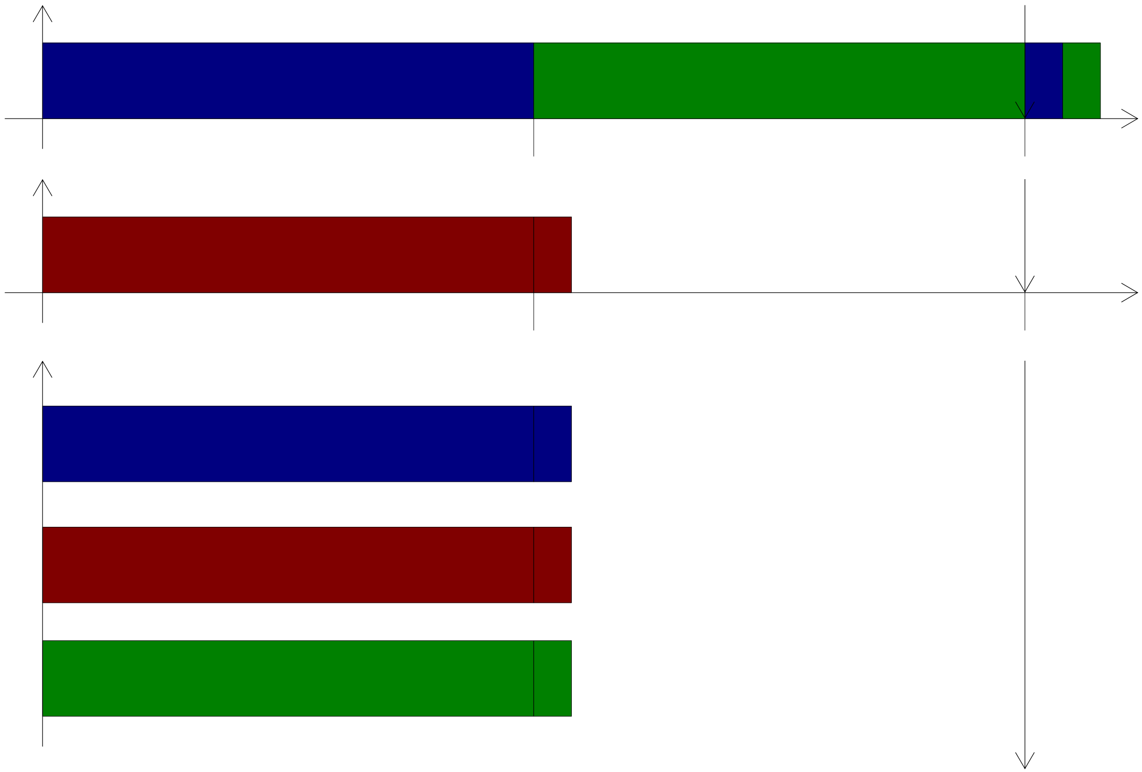

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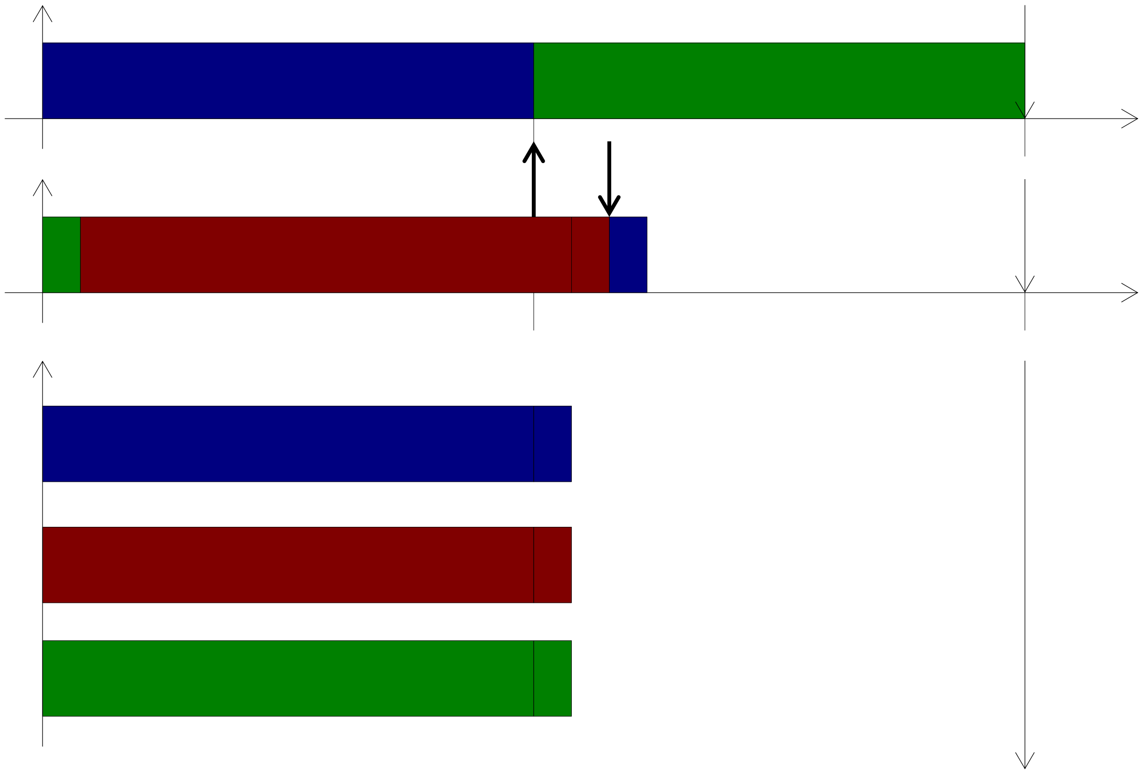

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Easy if blue and green can migrate to CPU_2

PDMS-HPTS-DS [Lakshmanan '09]

- Can we improve on Anderson's Utilization Bound?
  - by allowing a few jobs to migrate

- **PDMS** Partitioned Deadline Monotonic Scheduling
- **HPTS** Split Highest Priority Task
- **DS** Allocate according to Highest Density First

PDMS-HPTS-DS

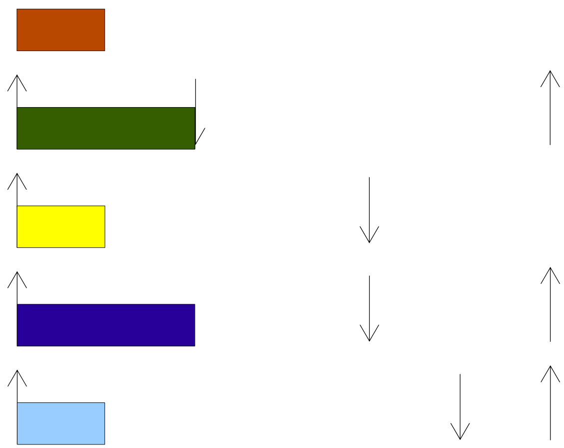
$\tau_1 = (4,3,1)$

$\tau_2 = (6,2,2)$

$\tau_3 = (4,4,1)$

$\tau_4 = (6,4,2)$

$\tau_5 = (6,5,1)$



$u_1 = 0.25 \quad \delta_1 = 1/3 = 0.33$

$u_2 = 0.33 \quad \delta_2 = 1$

$u_3 = 0.25 \quad \delta_3 = 1/4 = 0.25$

$u_4 = 0.33 \quad \delta_4 = 1/2 = 0.5$

$u_5 = 0.16 \quad \delta_5 = 1/5 = 0.2$

$u_{sum} = 1.33 \;\Rightarrow\; u_{sum} / 2 = 0.66\%$

CPU_0

CPU_1

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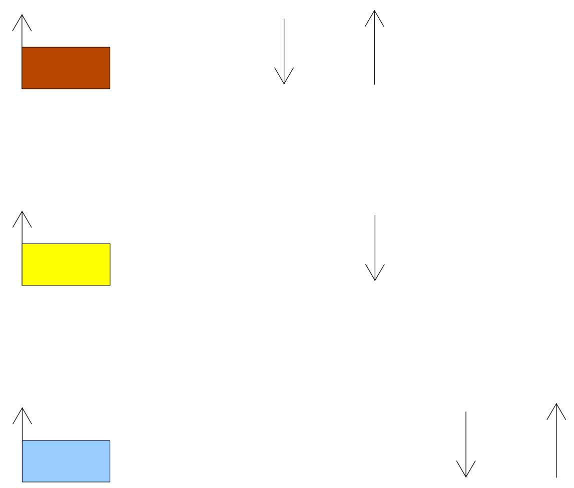

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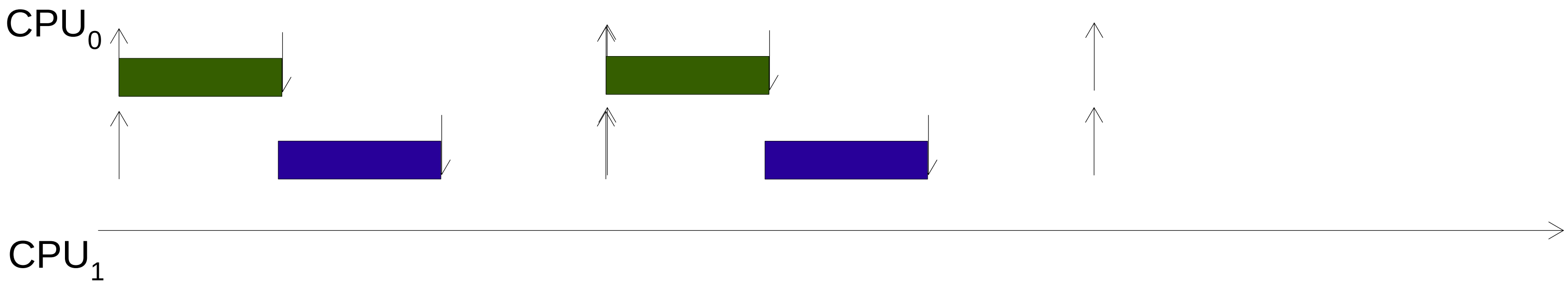

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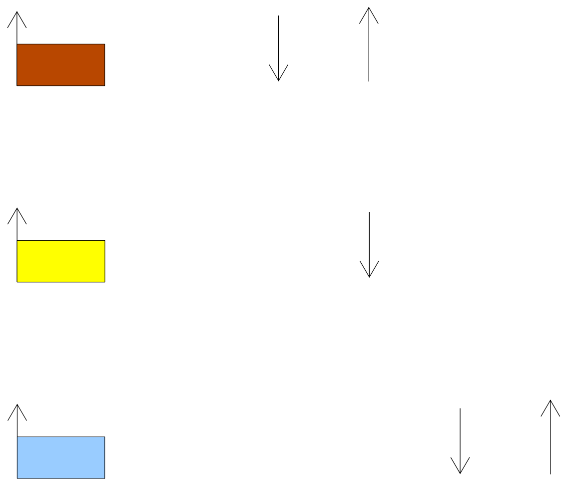

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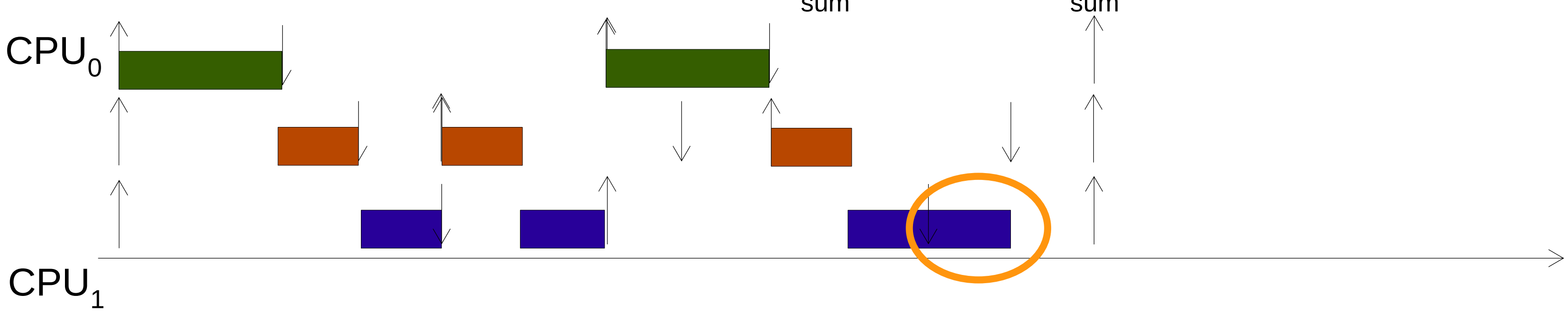

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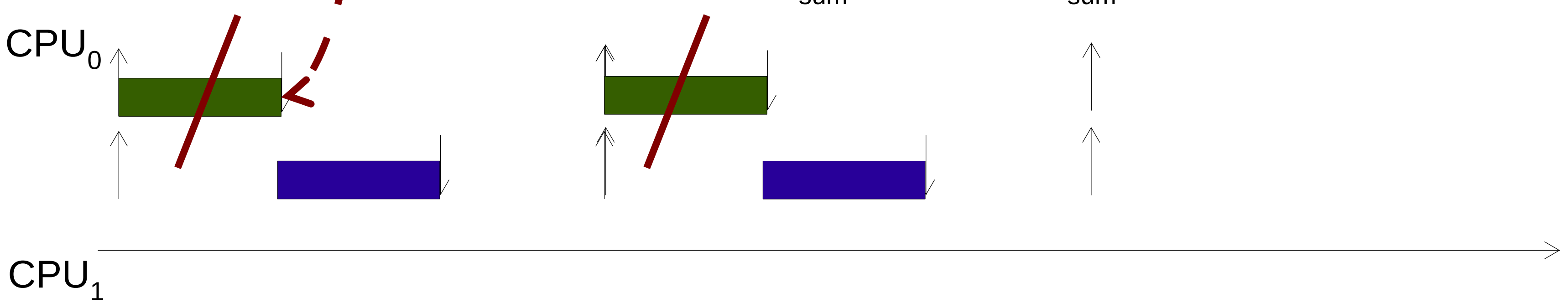

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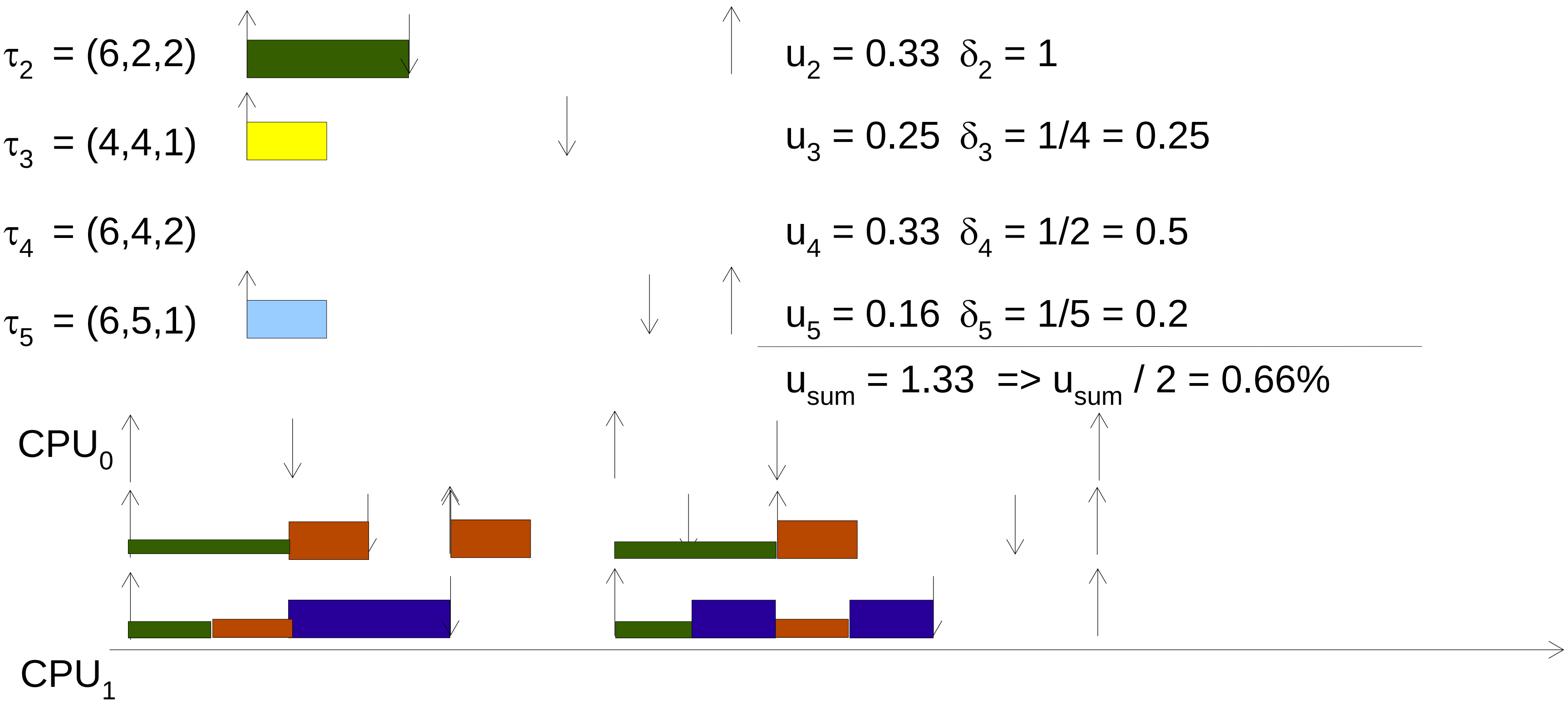

PDMS-HPTS-DS

Splitting HP Task into D'' – R' = D'' = C'
=> deadline of τ'' maximized

τ_1 = (4,3,1)
τ_2' = (6,2,1)
τ_2''= (5,1,1)
τ_3 = (4,4,1)

τ_4 = (6,4,2)

τ_5 = (6,5,1)

$u_2 = 0.33 \quad \delta_2 = 1$

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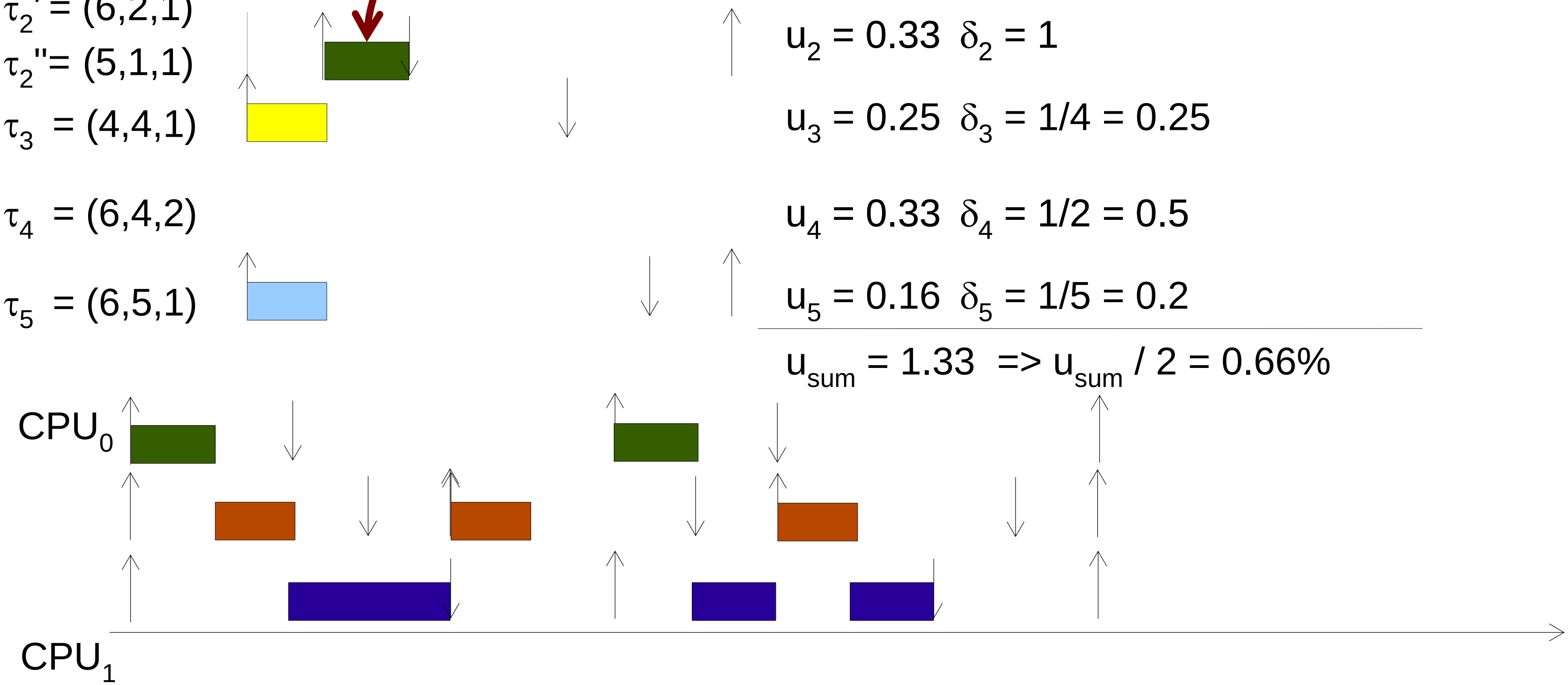
$u_5 = 0.16 \quad \delta_5 = 1/5 = 0.2$

$u_{sum} = 1.33 \Rightarrow u_{sum} / 2 = 0.66\%$



PDMS-HPTS-DS

$\tau_1 = (4,3,1)$

$\tau_2' = (6,2,1)$

$\tau_2'' = (5,1,1)$

$\tau_3 = (4,4,1)$

$\tau_4 = (6,4,2)$

$\tau_5 = (6,5,1)$

$u_1 = 0.25 \quad \delta_1 = 1/3 = 0.33$

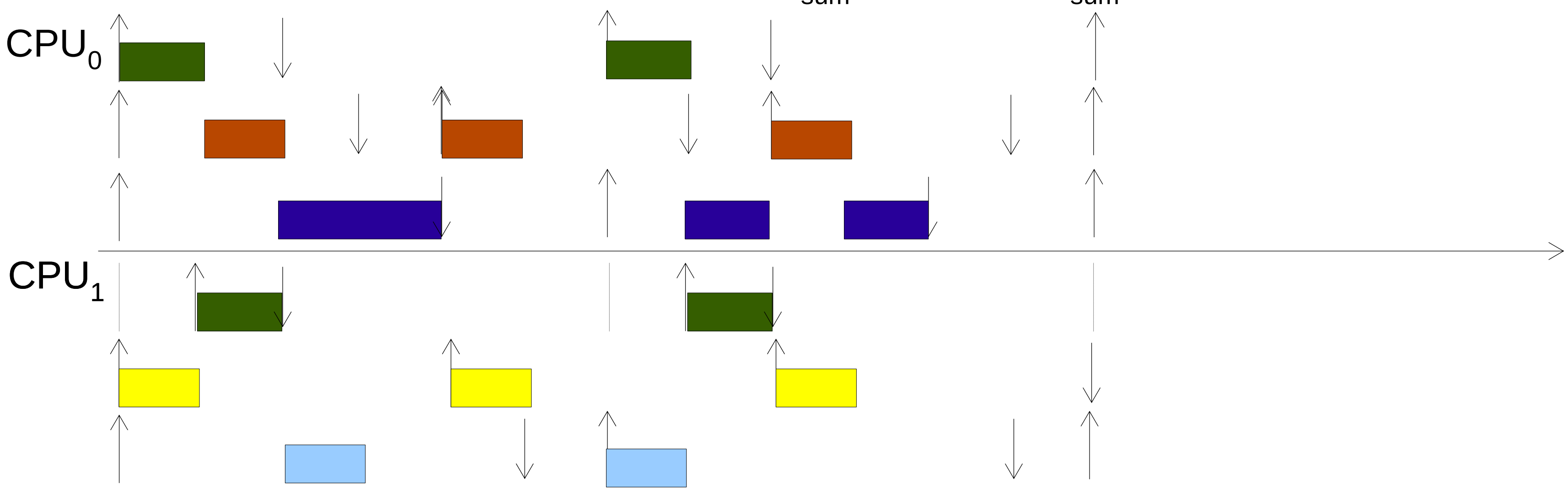
$u_2 = 0.33 \quad \delta_2 = 1$

$u_3 = 0.25 \quad \delta_3 = 1/4 = 0.25$

$u_4 = 0.33 \quad \delta_4 = 1/2 = 0.5$

$u_5 = 0.16 \quad \delta_5 = 1/5 = 0.2$

$u_{sum} = 1.33 \Rightarrow u_{sum} / 2 = 0.66\%$



PDMS-HPTS-DS

- $U_{PDMS\text{-}HPTS\text{-}DS}$ = 69.3 % if all tasks have a utilization U_i < 41%

Global Scheduling

Partitioned

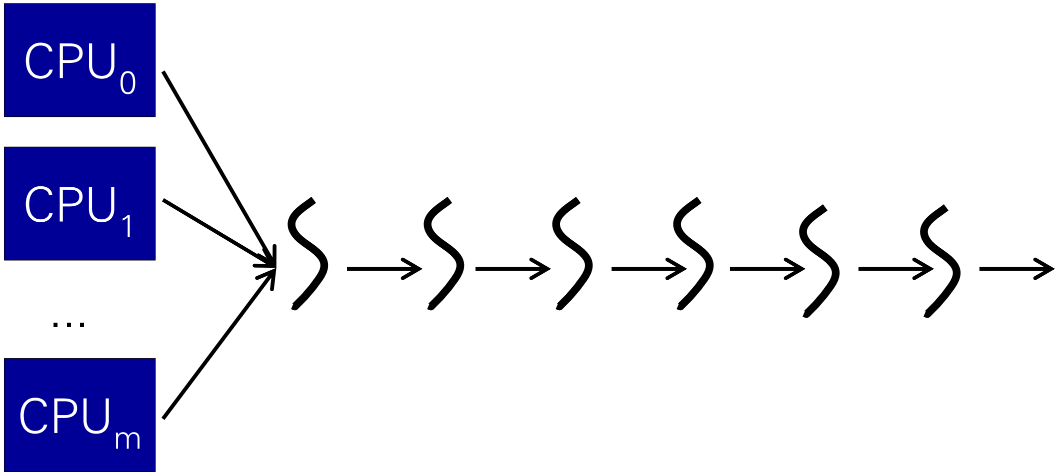
- dyn job prio. / partitioned
- fixed job prio. / partitioned
- fixed task prio. / partitioned

Global

- dyn job prio. / task level migration
- fixed job prio. / task level migration
- fixed task prio. / task level migration
- dyn. job prio. / job level migration
- fixed job prio. / job level migration
- fixed task prio. / job level migration

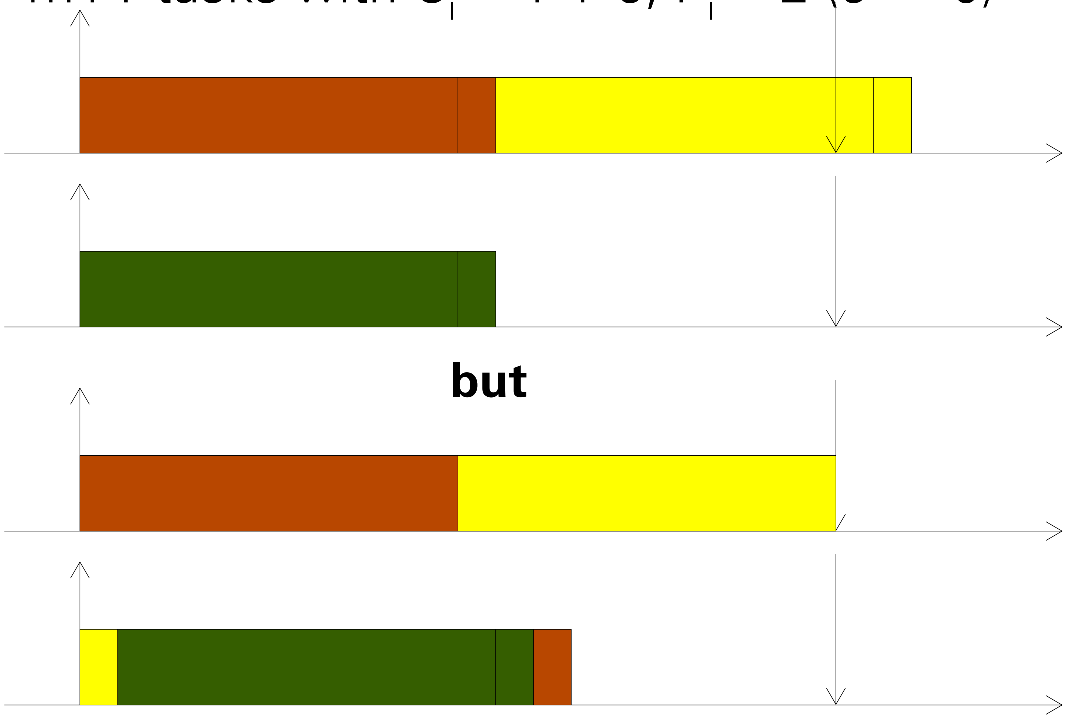
Global Scheduling

- Always pick the ready jobs of the m most "important" tasks
- A task may migrate
  - When a new job of a task is released it may receive a different CPU; once started, a job is no longer migrated
- No need for allocation / load balancing
  - Load balancing is automatic



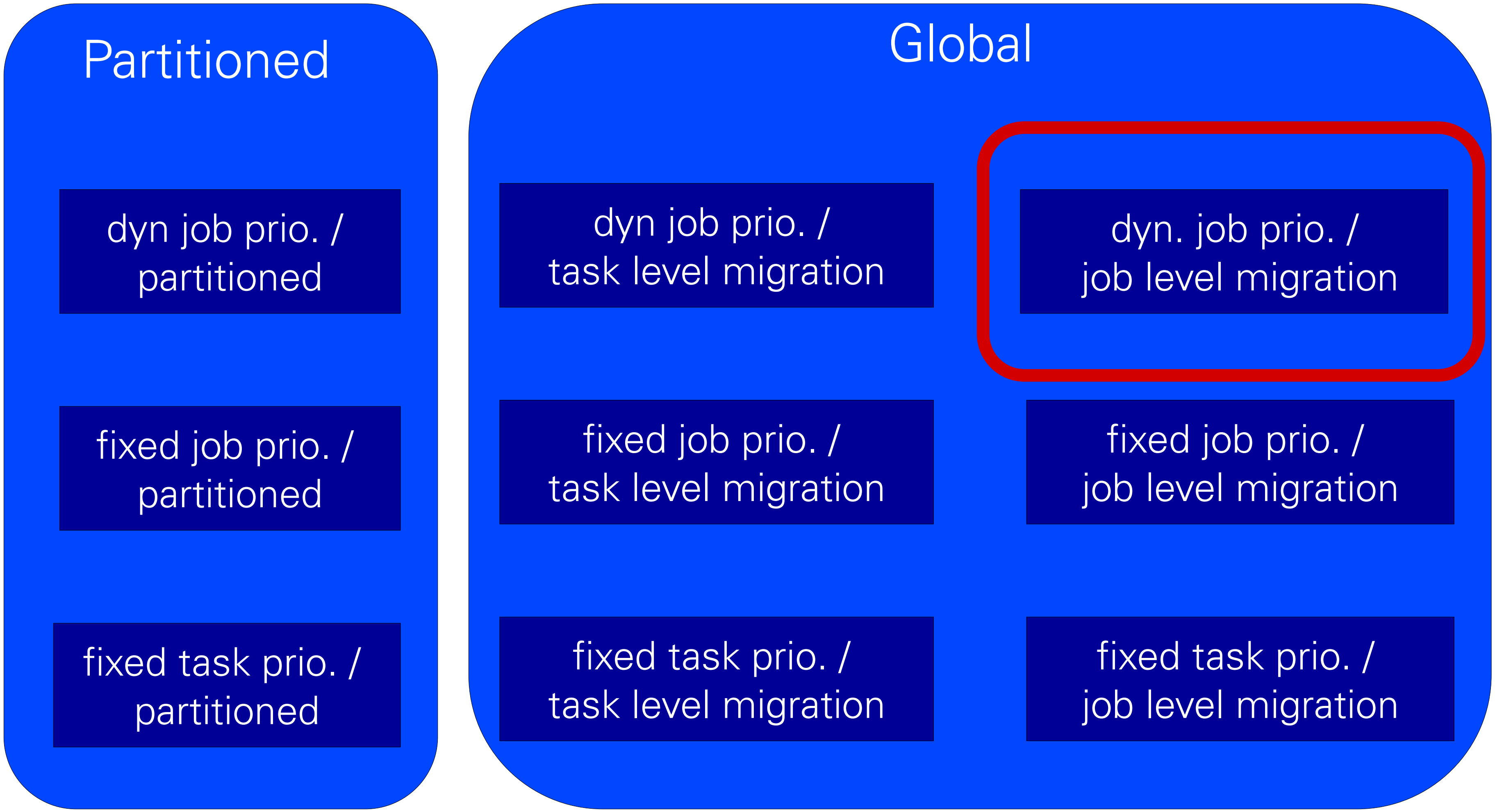
Global Scheduling – Utilization Bound

- Utilization bound for global fixed-job priority algorithms
  - on m CPUs, G-FJP algorithms cannot schedule m+1 tasks with $C_i = 1 + e$, $P_i = 2$ ($e \to 0$)



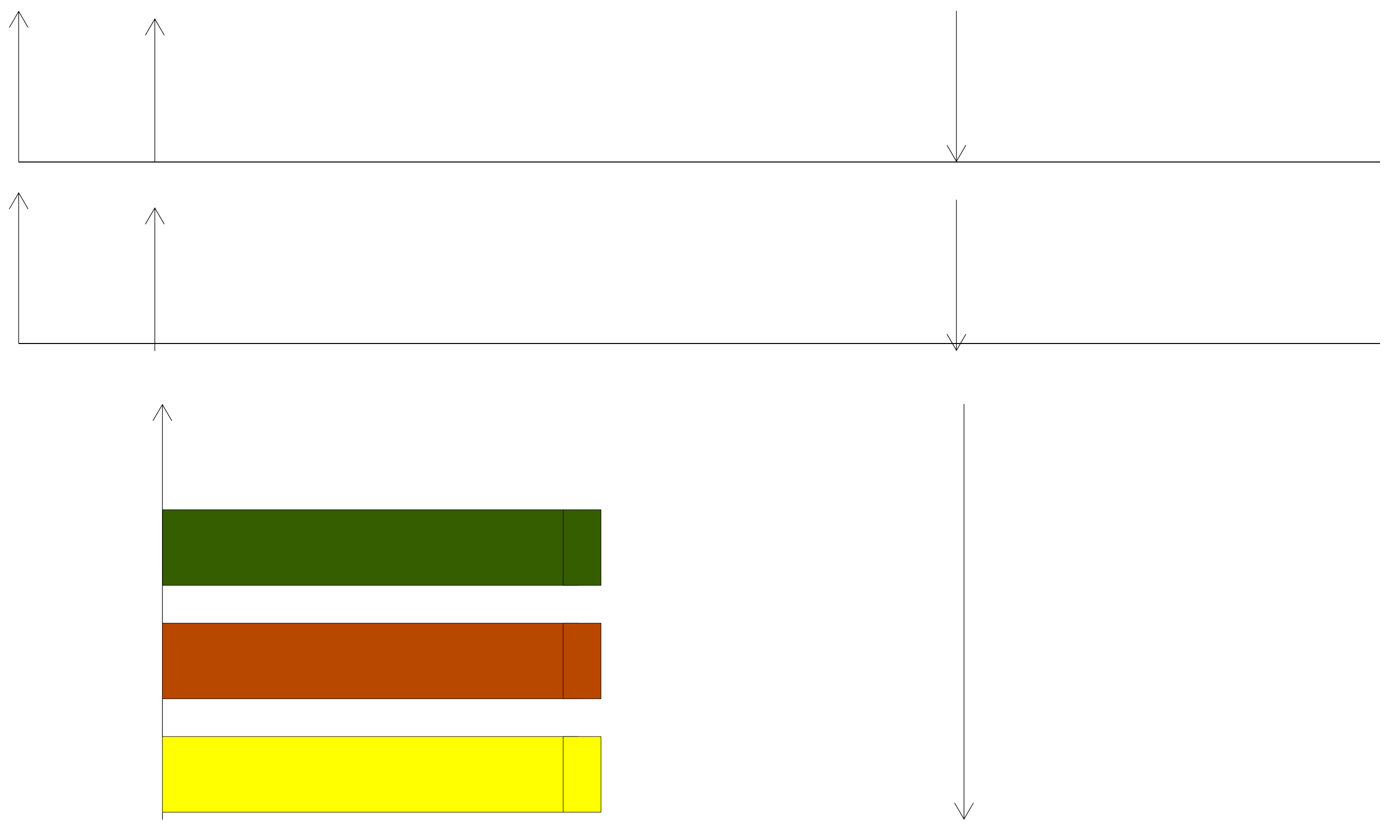
- $U_{OPT} = \lim_{e \to 0} \frac{(m+1)(1+e)}{2} = \frac{m+1}{2}$

Global Scheduling - Job Level Migration



PFAIR [Baruah '96]

- Divide timeline into equal length quanta
- At each quanta of length t, allocate tasks to processors such that the accumulated processor time is either $\lceil tu_i \rceil$ or $\lfloor tu_i \rfloor$



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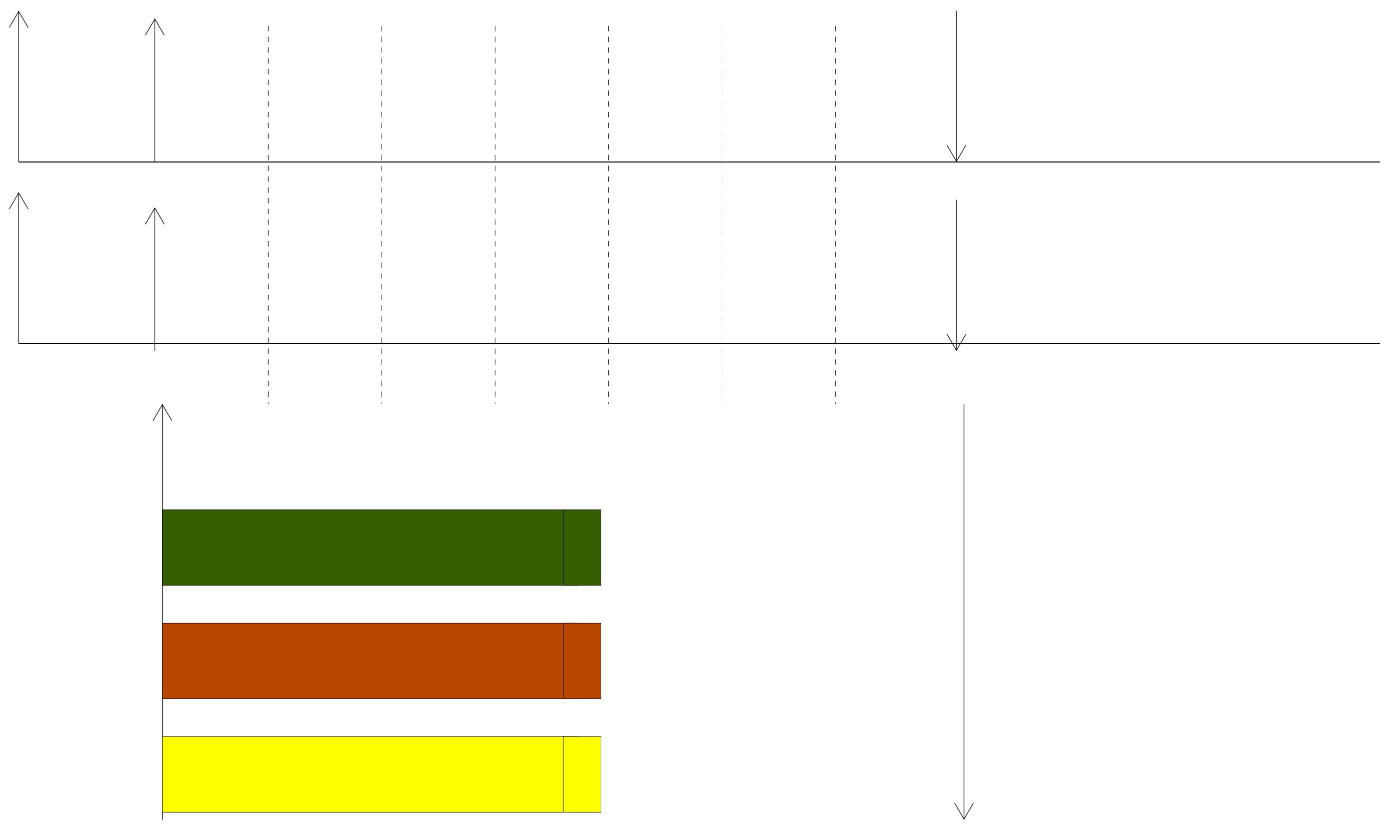

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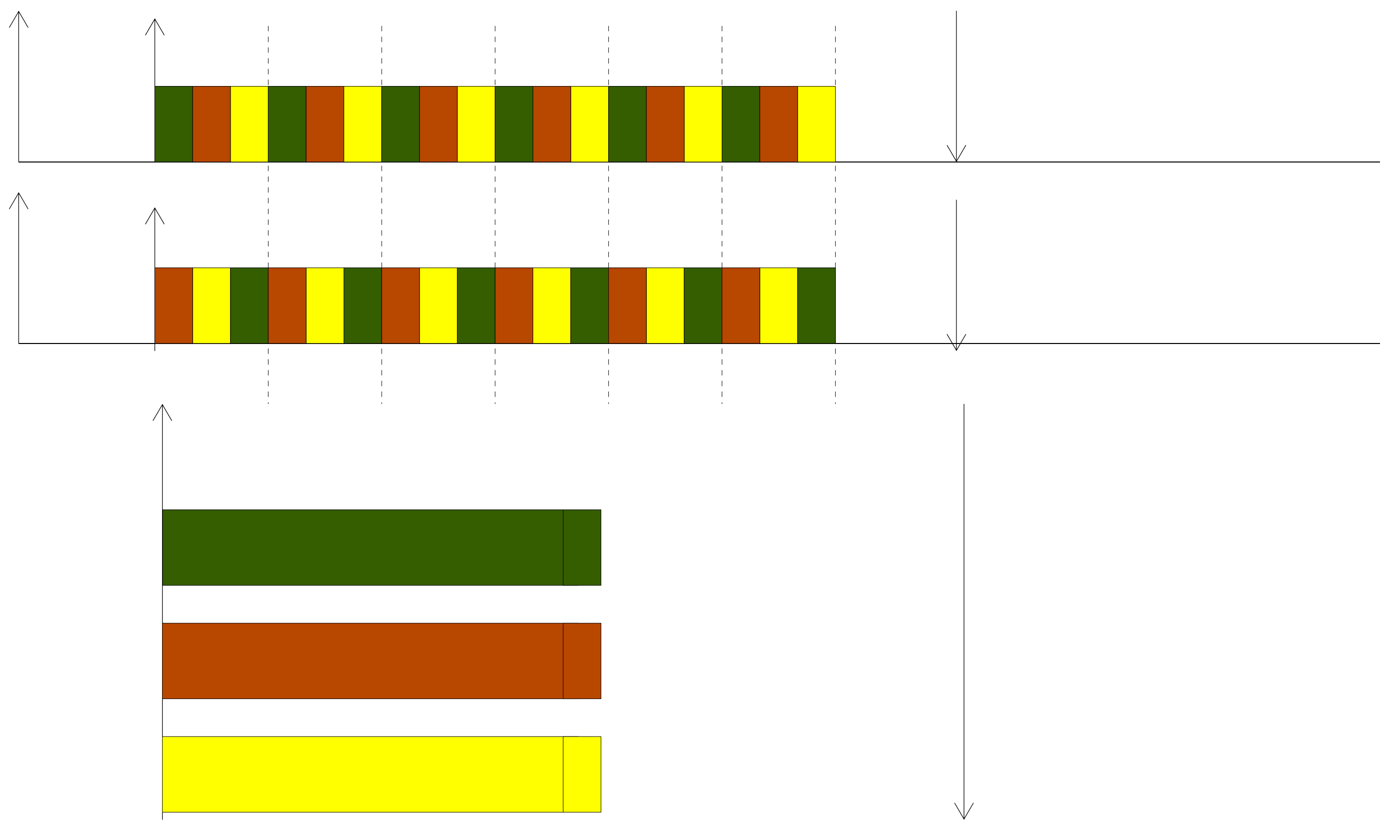

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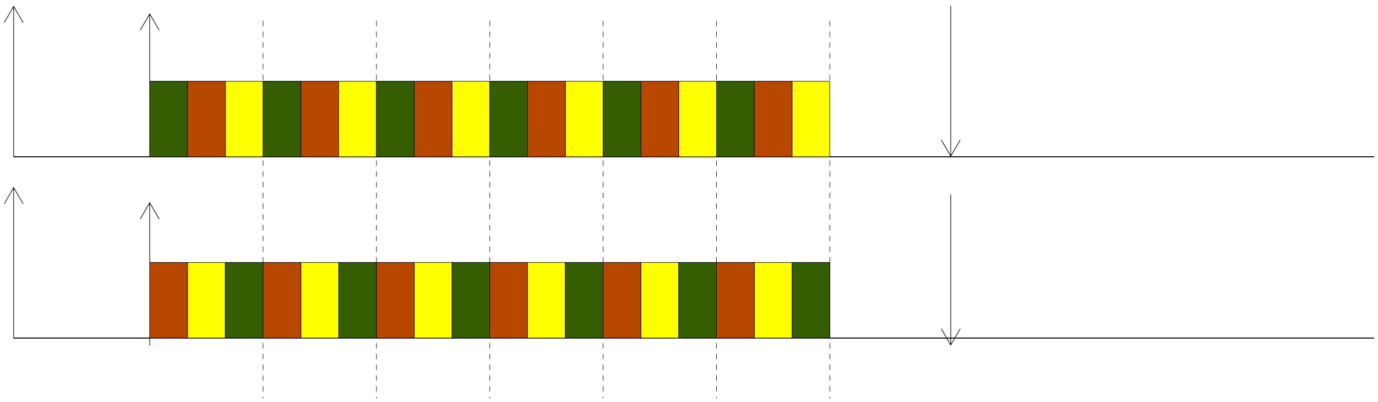


- PFAIR is optimal for periodic implicit deadline tasksets: $U_{OPT} = m$
- Very high preemption and migration costs

DP-Fair [Brandt '10]

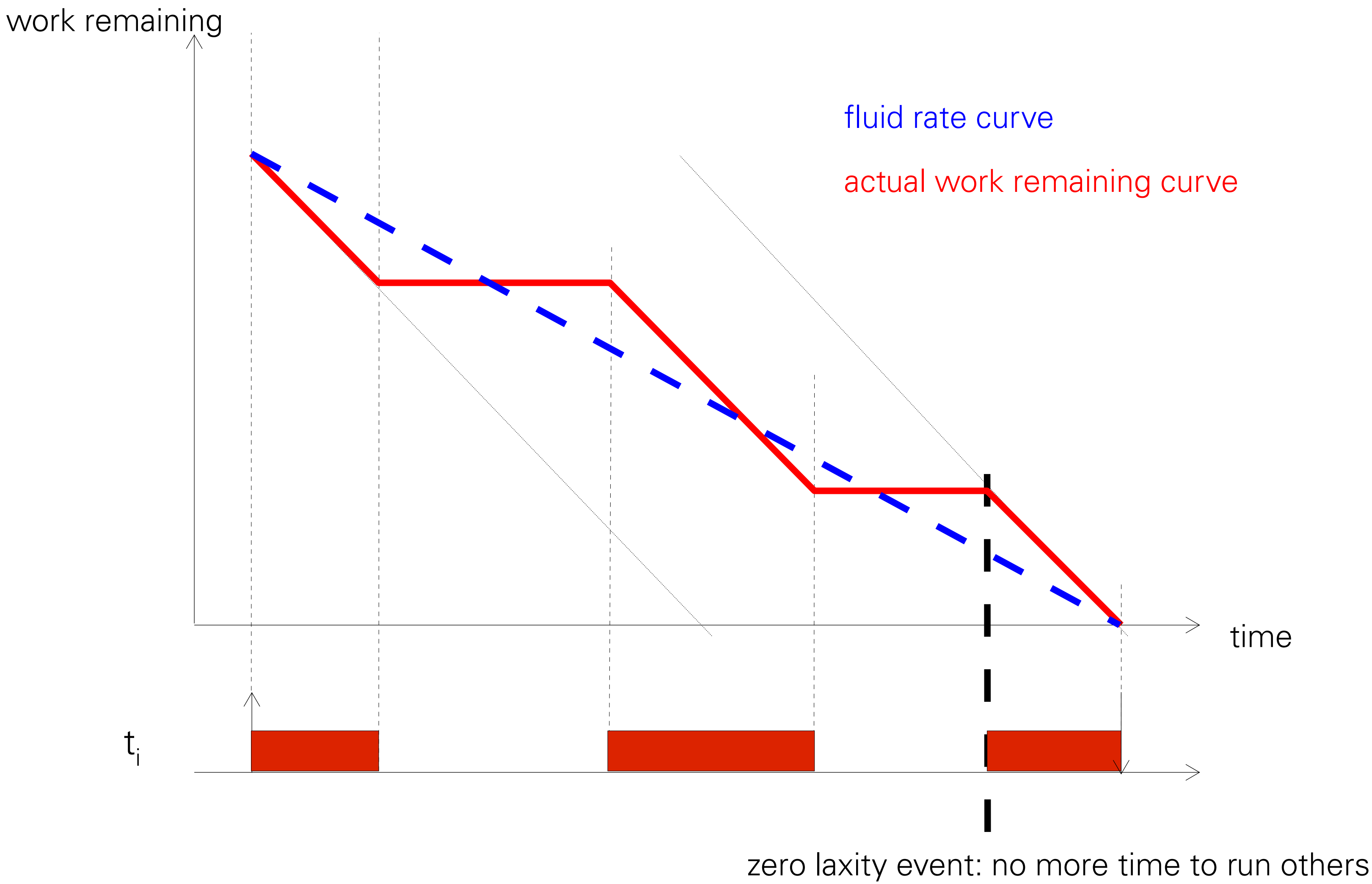
- DP-Fair
  - Optimal scheduler for periodic implicit deadline tasksets with a minimal number of preemptions / migrations?
  - Recall [Hong '88]:
    - No optimal MP scheduling algorithm for arbitrary tasksets if not all tasks have the same relative deadline

  =>

  - deadline partitioning
    - any task's deadline becomes a deadline for all tasks
  - always run zero laxity jobs
    - laxity = time to deadline – remaining execution time
    - zero laxity => job may miss its deadline if it is not run
  - jobs who twine themselves around the ***fluid rate curve*** are somehow in good shape

DP-Fair [Brandt '10]

- Fluid Rate Curve

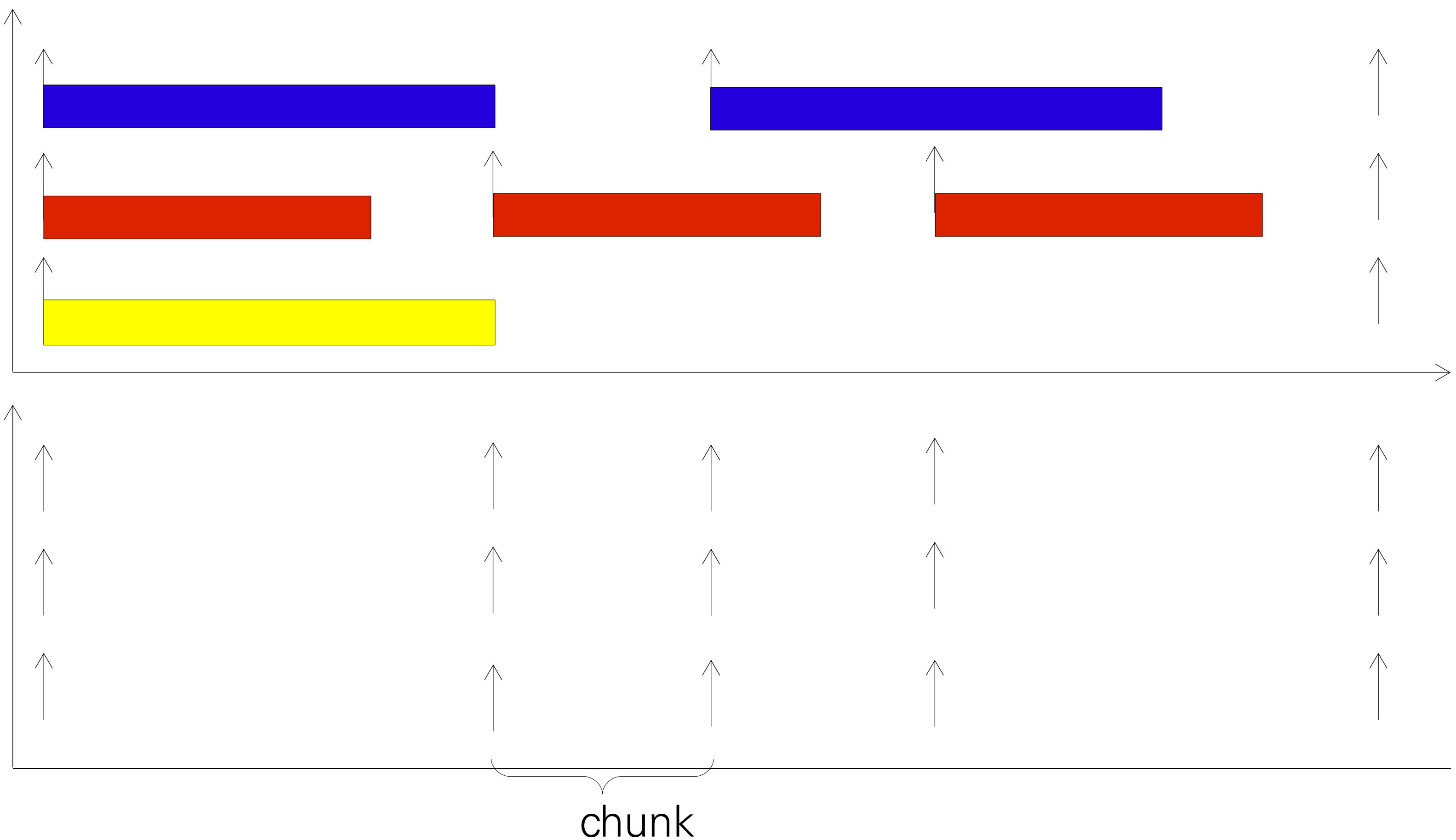


DP-Fair [Brandt '10]

- DP-Fair:
  - a family of optimal, deadline partitioning scheduling algorithms
  - Split timeline into chunks according to job deadlines
  - Allocate work to a chunk proportional to U_i
    - local execution time: $C^l_{i,j}=(t_{j+1} - t_j)\ U_i$
  - Rule 1: run all jobs with zero local laxity
    - jobs with remaining local execution time = time to end of chunk
  - Rule 2: do not run jobs for more than $C^l_{i,j}$
  - Rule 3: split up idle time proportional to length of chunk
    - allocate at most $S\ (t_{j+1} - t_j)$ idle time to chunk j

DP-Fair [Brandt '10]

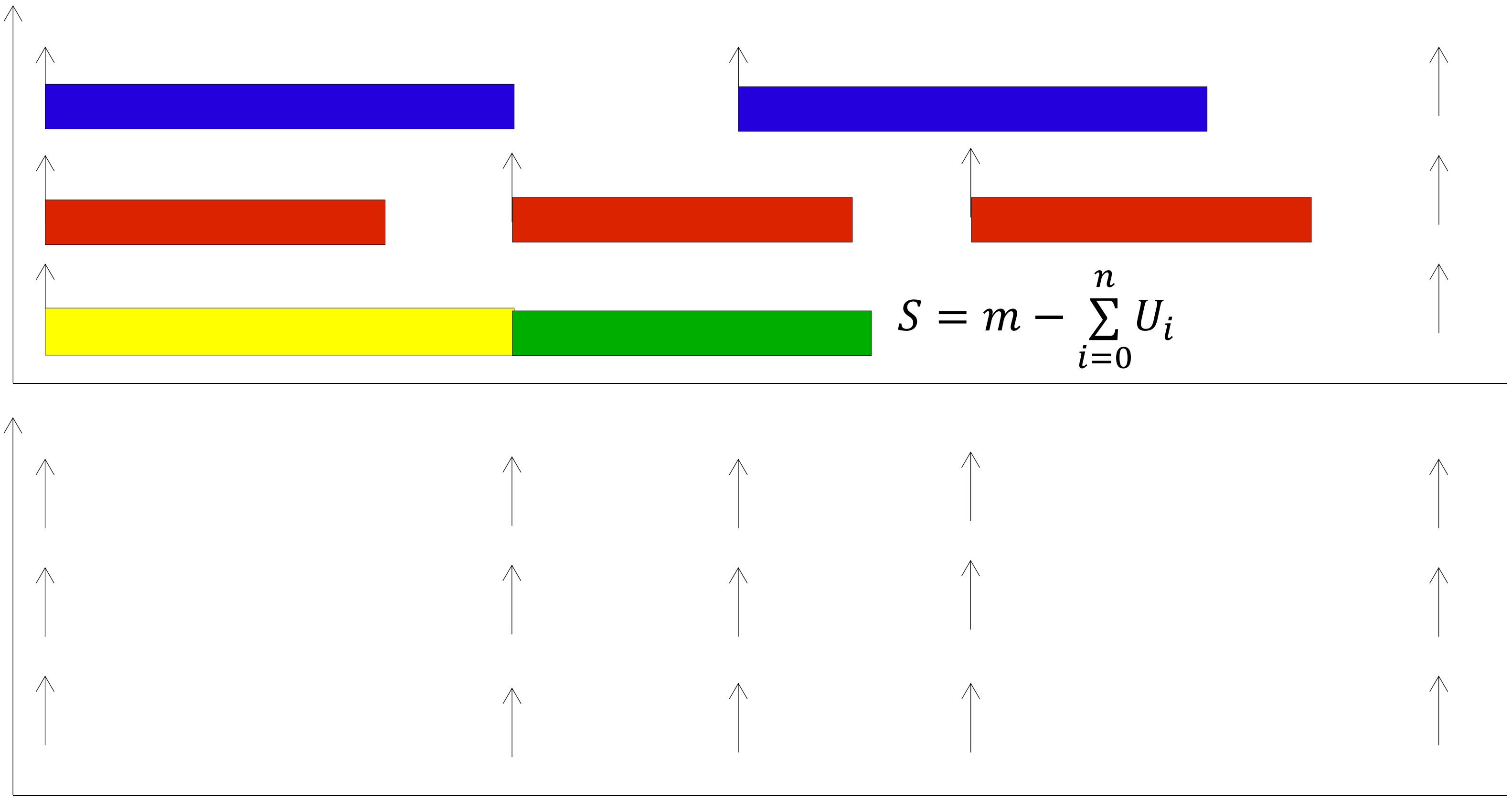
- Deadline partitioning



Introduce additional releases / deadlines for all jobs whenever there is such an event for one job in the original schedule => chunks

DP-Fair [Brandt '10]

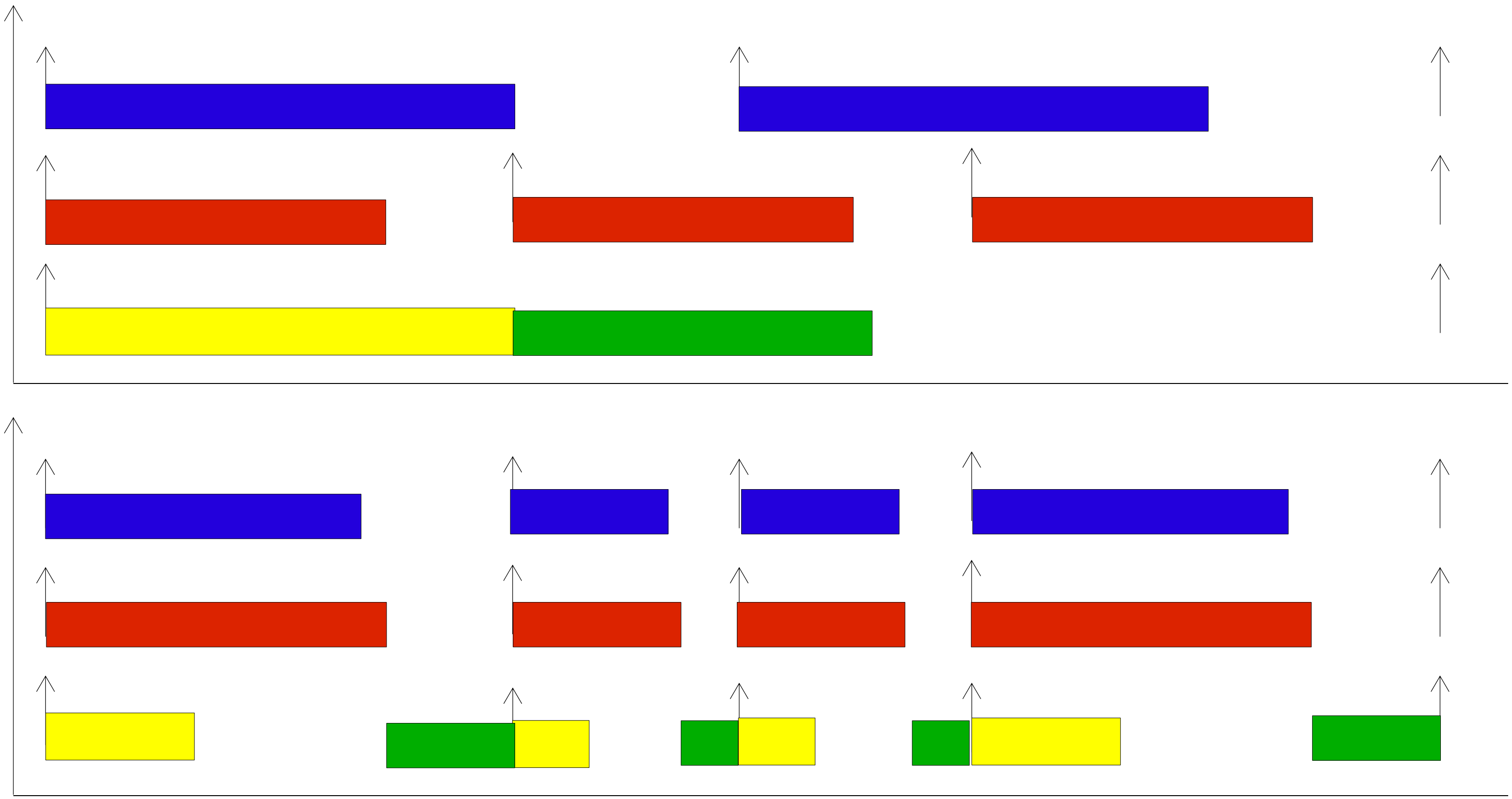
- Idle time



Treat idle time as just another job to schedule.

DP-Fair [Brandt '10]

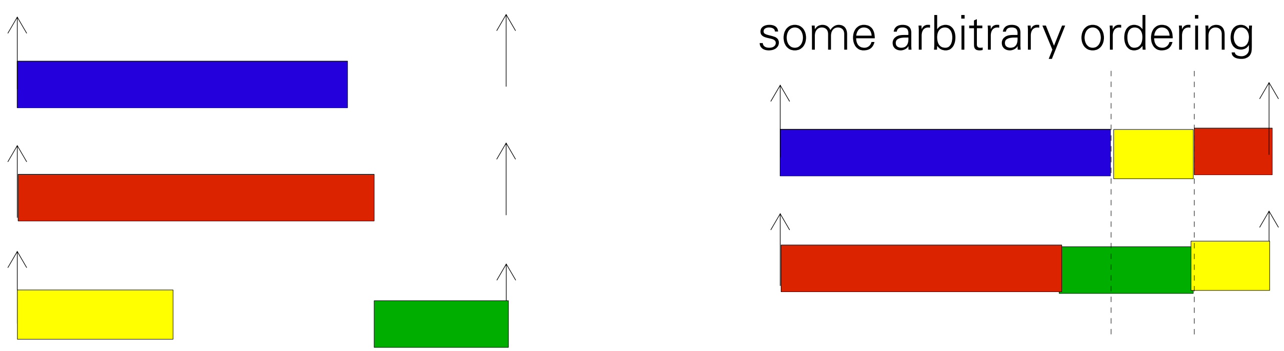
- Allocate work proportional to U_i

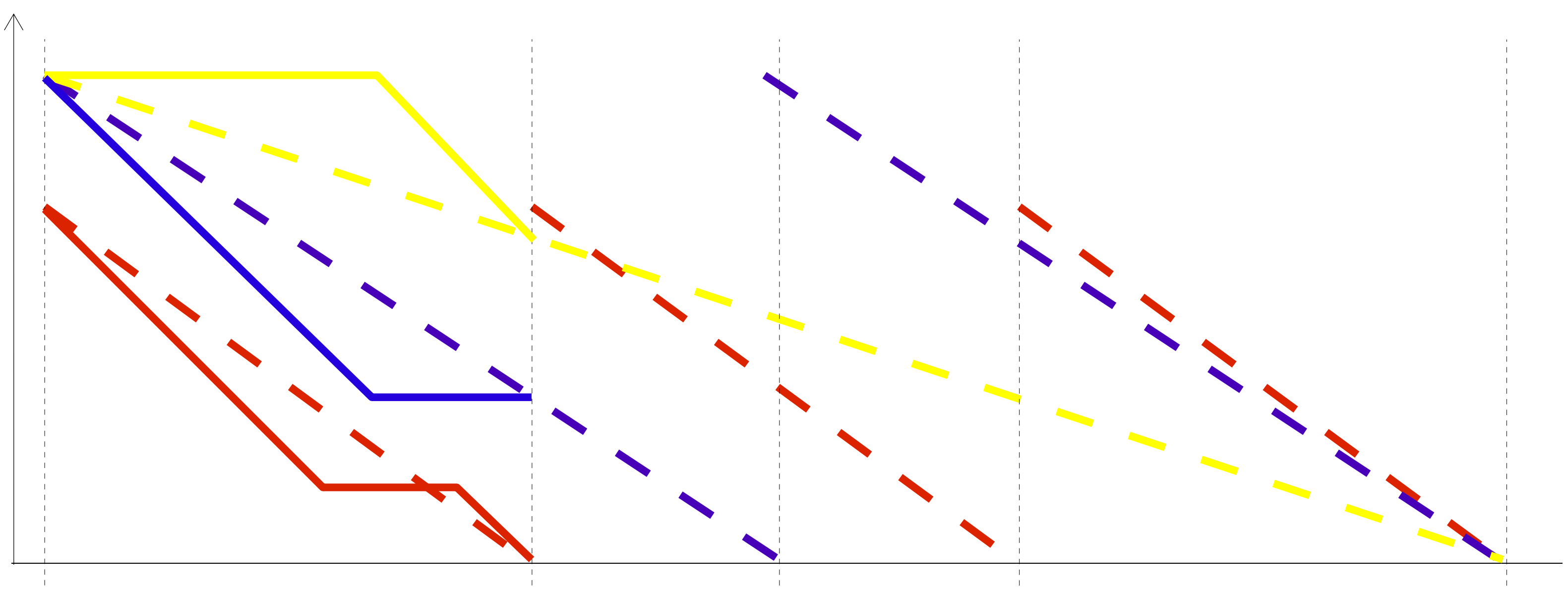


Allocate execution (and idle) time of a job proportionally to its utilization
=> amount of time that this job must run in a given chunk

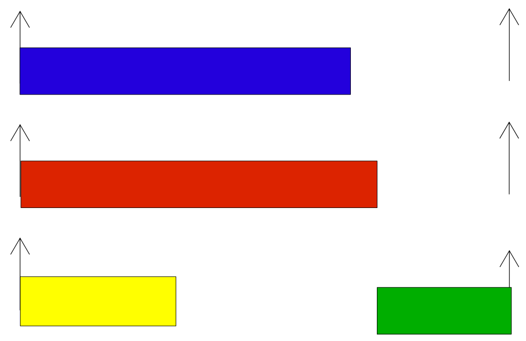
DP-Fair [Brandt '10]

- Jobs hit their fluid rate curve at the end of each chunk



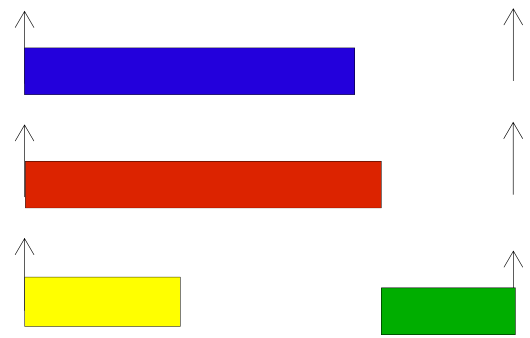


DP-Wrap – a DP-Fair Scheduler



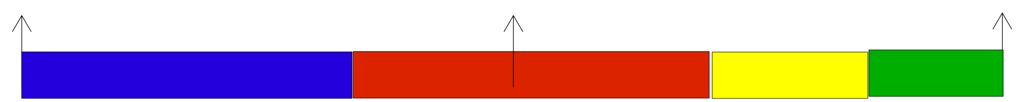
Work allocated to a chunk:
find a schedule

DP-Wrap – a DP-Fair Scheduler



Work allocated to a chunk:
find a schedule

arrange jobs consecutively



DP-Wrap – a DP-Fair Scheduler

Work allocated to a chunk:
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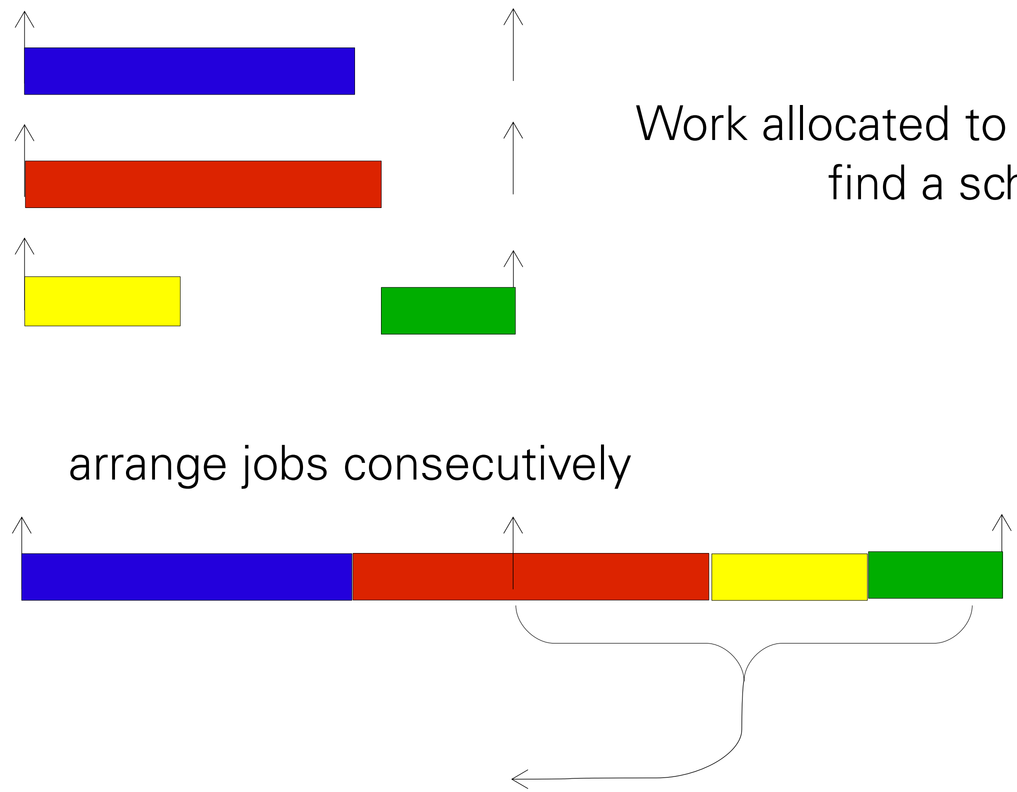
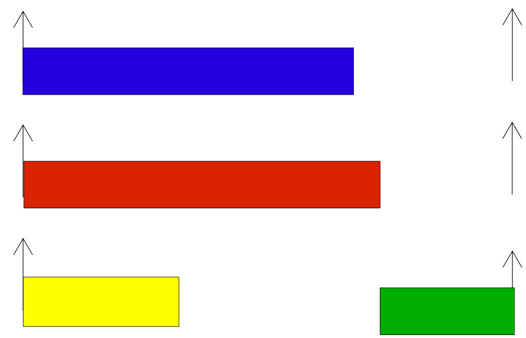
arrange jobs consecutively



wrap around to obtain schedule for 2nd CPU, ...

DP-Wrap – a DP-Fair Scheduler



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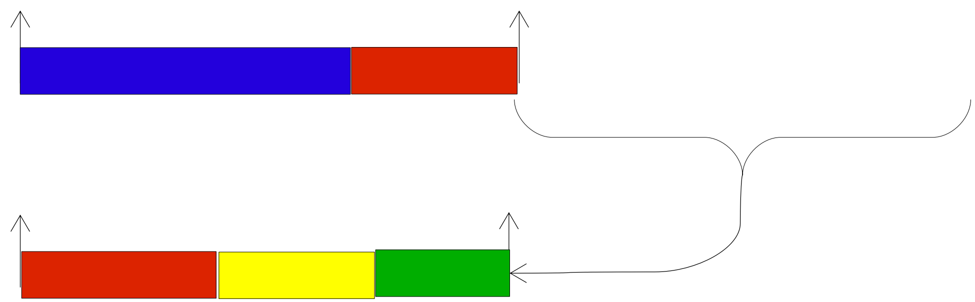
find a schedule

arrange jobs consecutively



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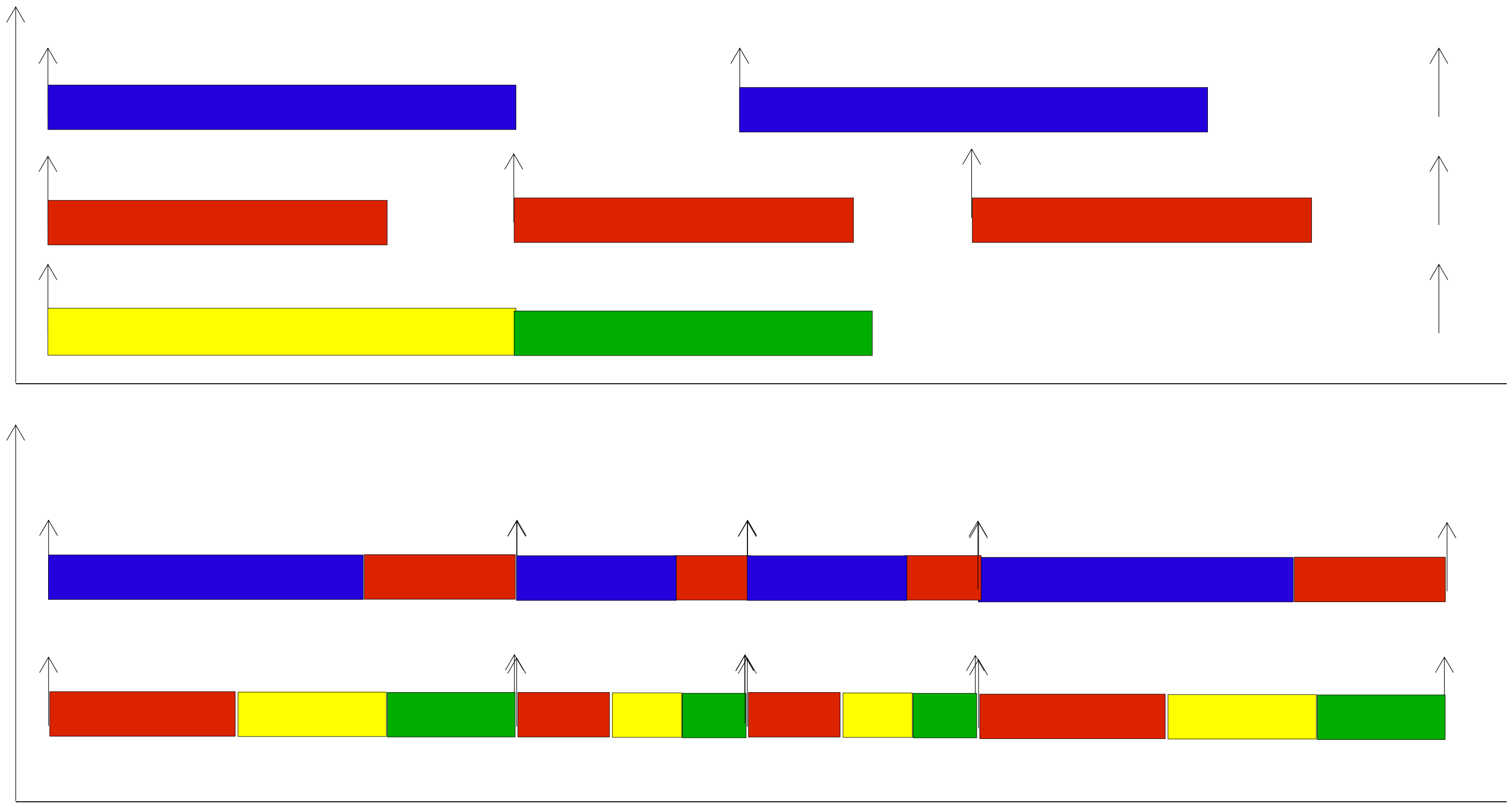
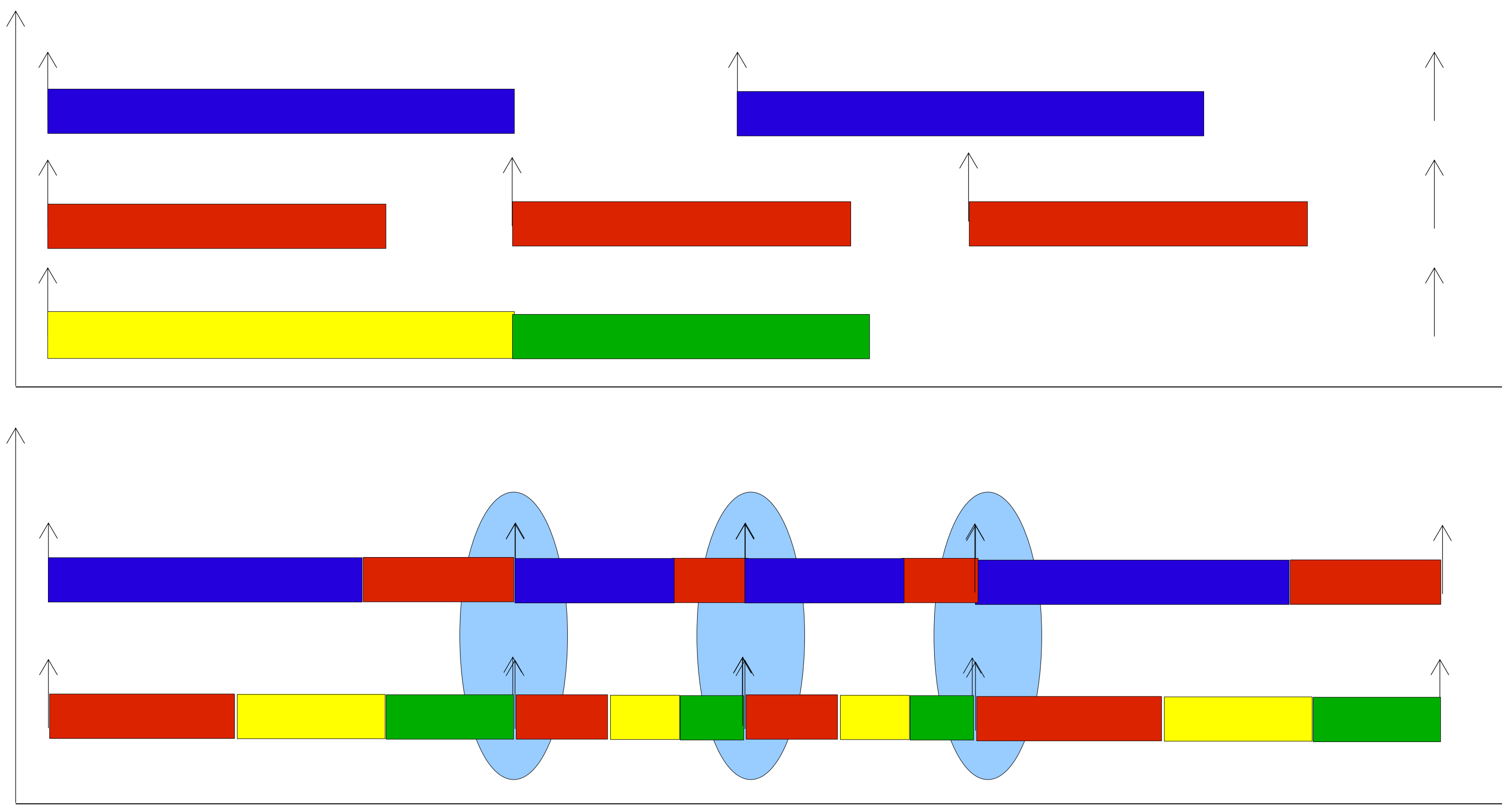
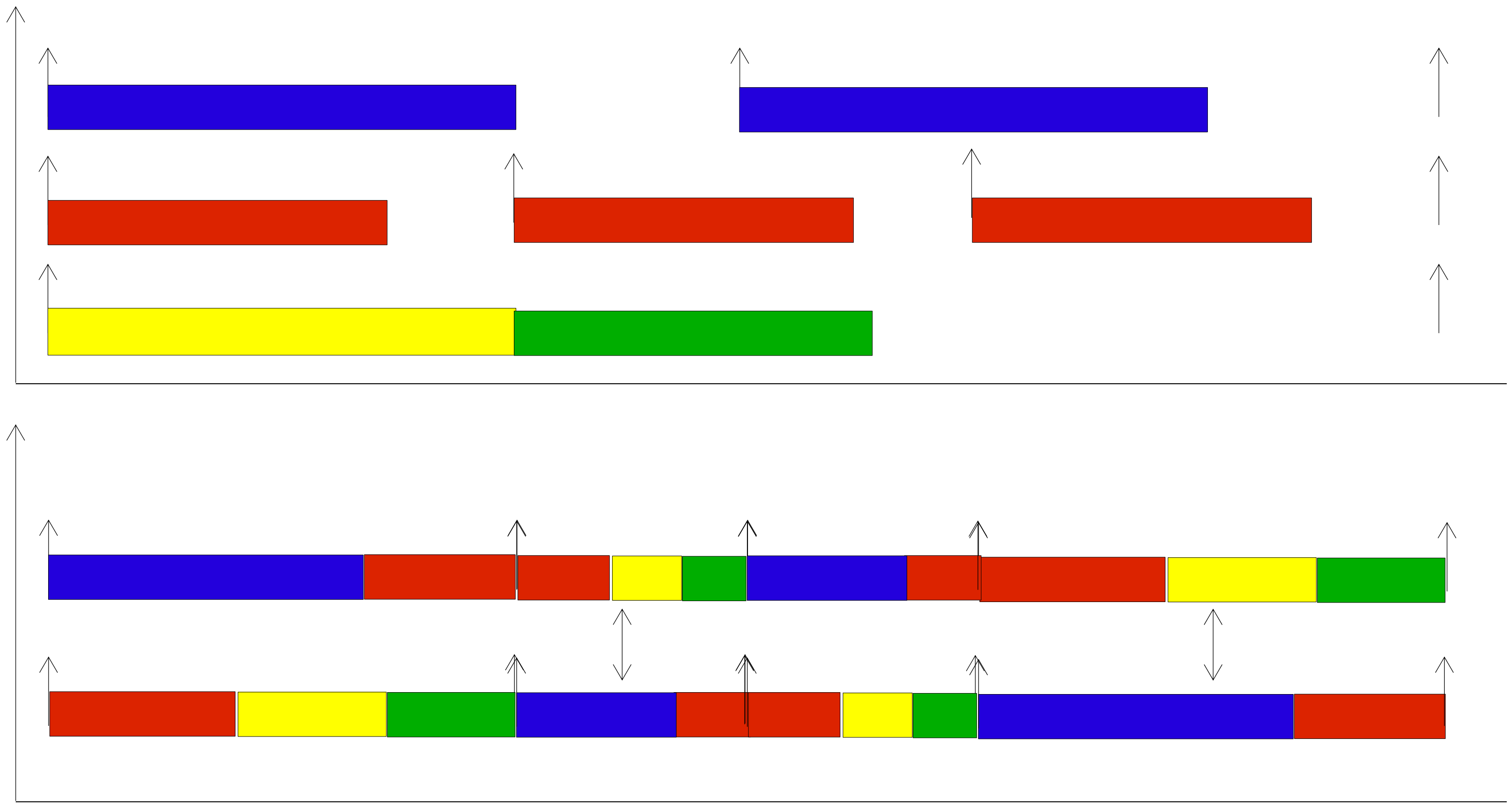


DP-Wrap – a DP-Fair Scheduler



Unnecessary migration of red task at chunk boundaries
=> mirror processor assignment of every second chunk

DP-Wrap (mirrored)

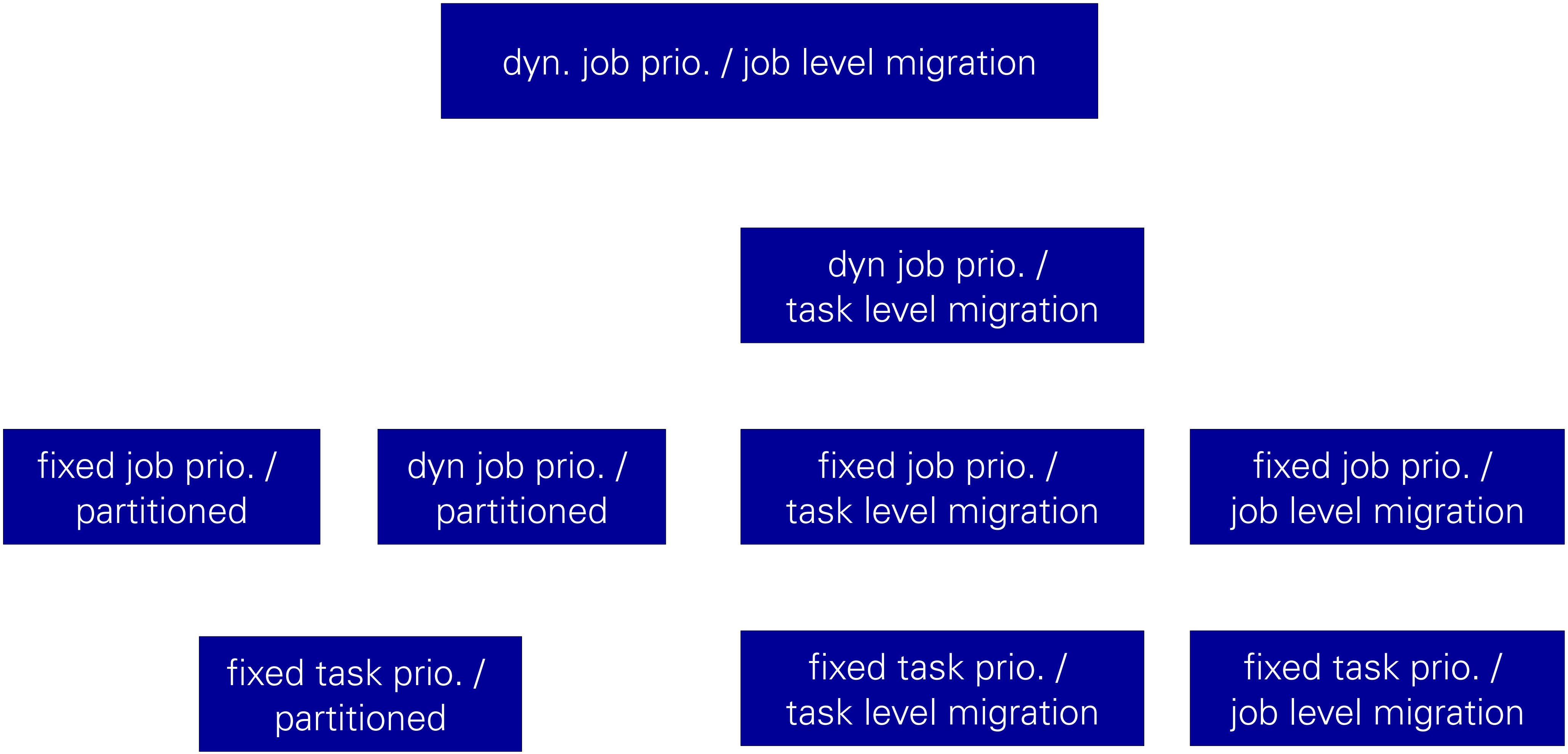


m – 1 migrations per chunk
n – 1 context switches per chunk

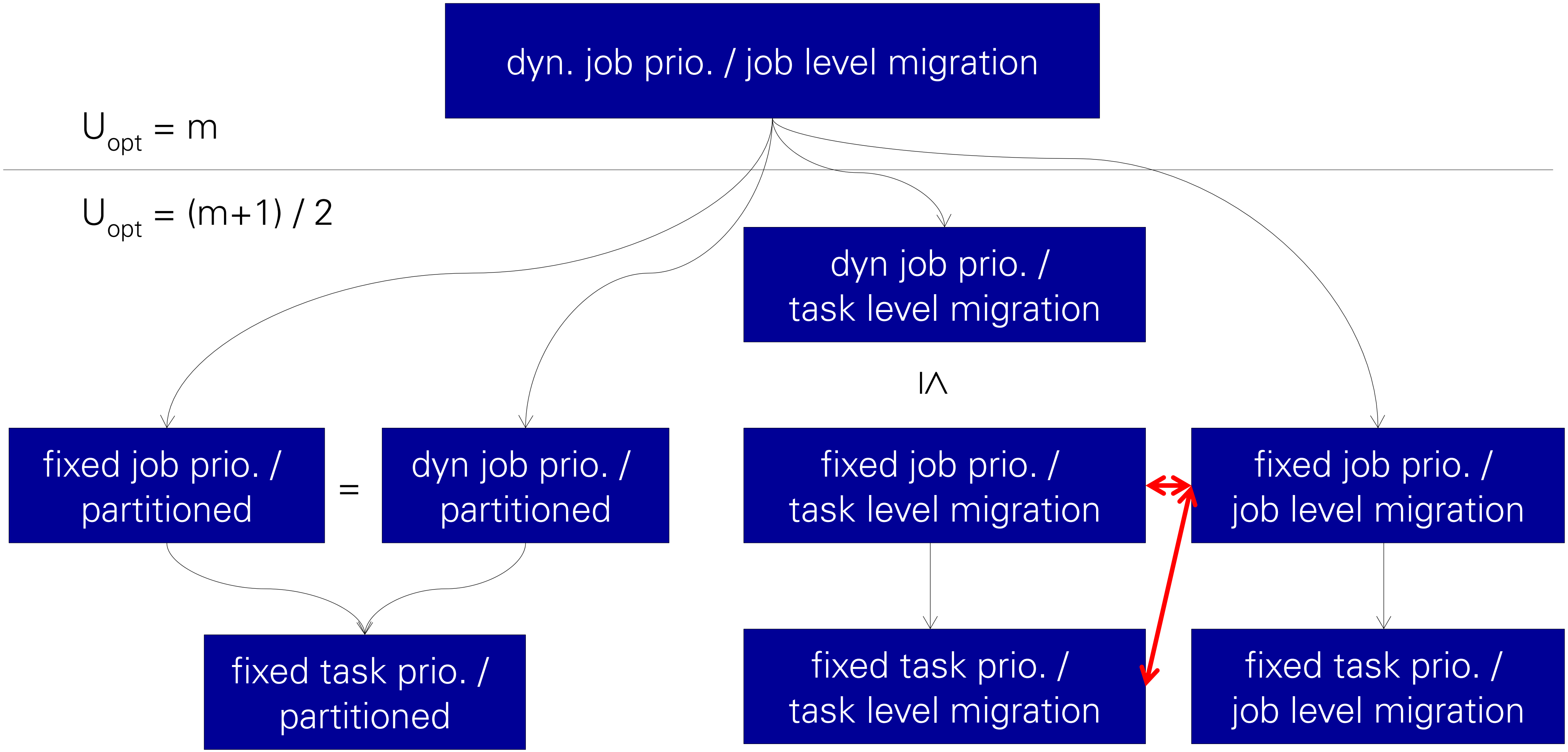
Design Space of MP Scheduling

dyn job prio. / partitioned	dyn job prio. / task level migration	dyn. job prio. / job level migration
fixed job prio. / partitioned	fixed job prio. / task level migration	fixed job prio. / job level migration
fixed task prio. / partitioned	fixed task prio. / task level migration	fixed task prio. / job level migration

Design Space of MP Scheduling



Design Space of MP Scheduling



A → B => A can schedule any taskset that B can schedule and more
A ↔ B => dominance is not yet known

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  - G-EDF
- Optimal MP Scheduling
- MP – Resource Access Protocols
- Open Research Issues

MP Resource Access Protocols

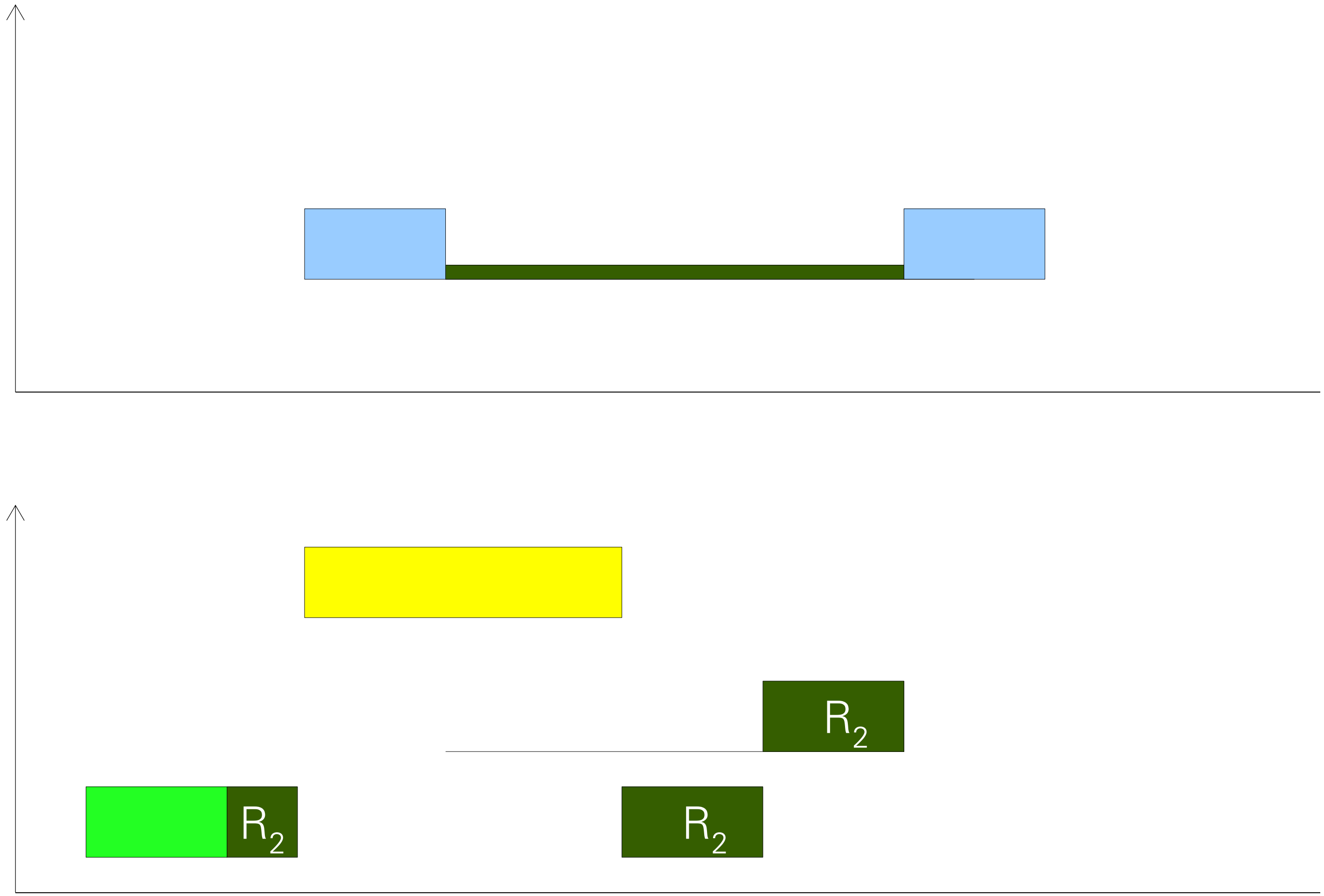
- UP:
  - Basic Priority Ceiling Protocol BPCP
  - Stack Resource Protocol SRP (Ceiling Priority Protocol CPP)
    - bounded priority inversion: | CS |
    - BPCP does not influence unrelated threads
- General Idea:
  - run UP protocol on every CPU of MP system
- Ceiling Priority i of Resource R_i: $\hat{R}_i$ = max prio(t_j)
  - here, priorities have a global meaning
- System Ceiling $\hat{S}$ = max $\hat{R}_i$ of held resources
- Synchronization Processor: CPU on which R_i is executed

MP Resource Access Protocols

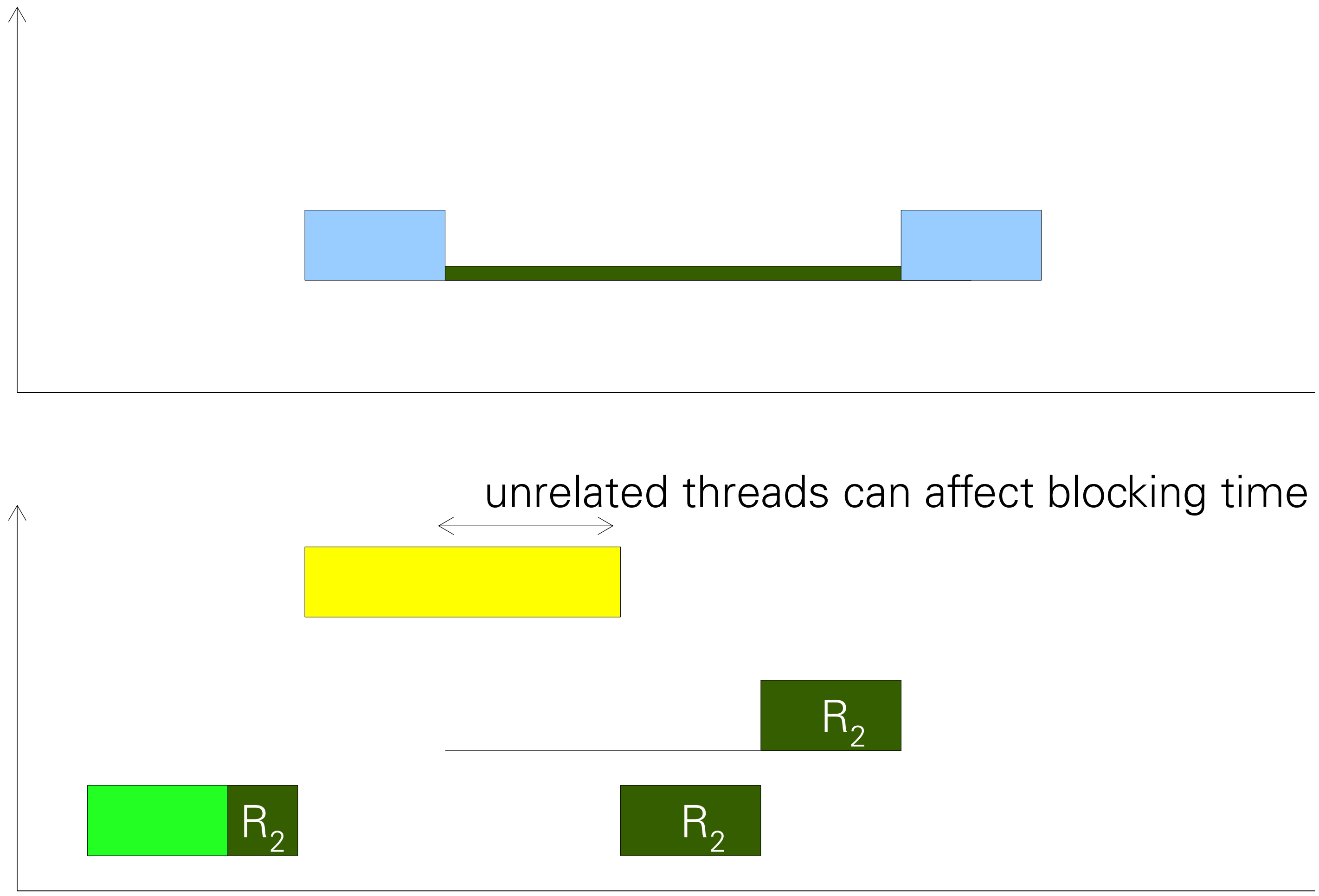
- UP-BPCP in a nutshell
  - resource holders inherits priority from blocked threads
  - resource granted if prio(t_j) > $\hat{S}$
  - only the resource holder, which holds a resource with $\hat{R}_i = \hat{S}$ receives additional resources

- UP-SRP (actually UP-CPP) in a nutshell
  - resource holder runs at max $\hat{R}_i$ of held resources
    => only higher prioritized threads may run (acquire resources)

MPCP – first try

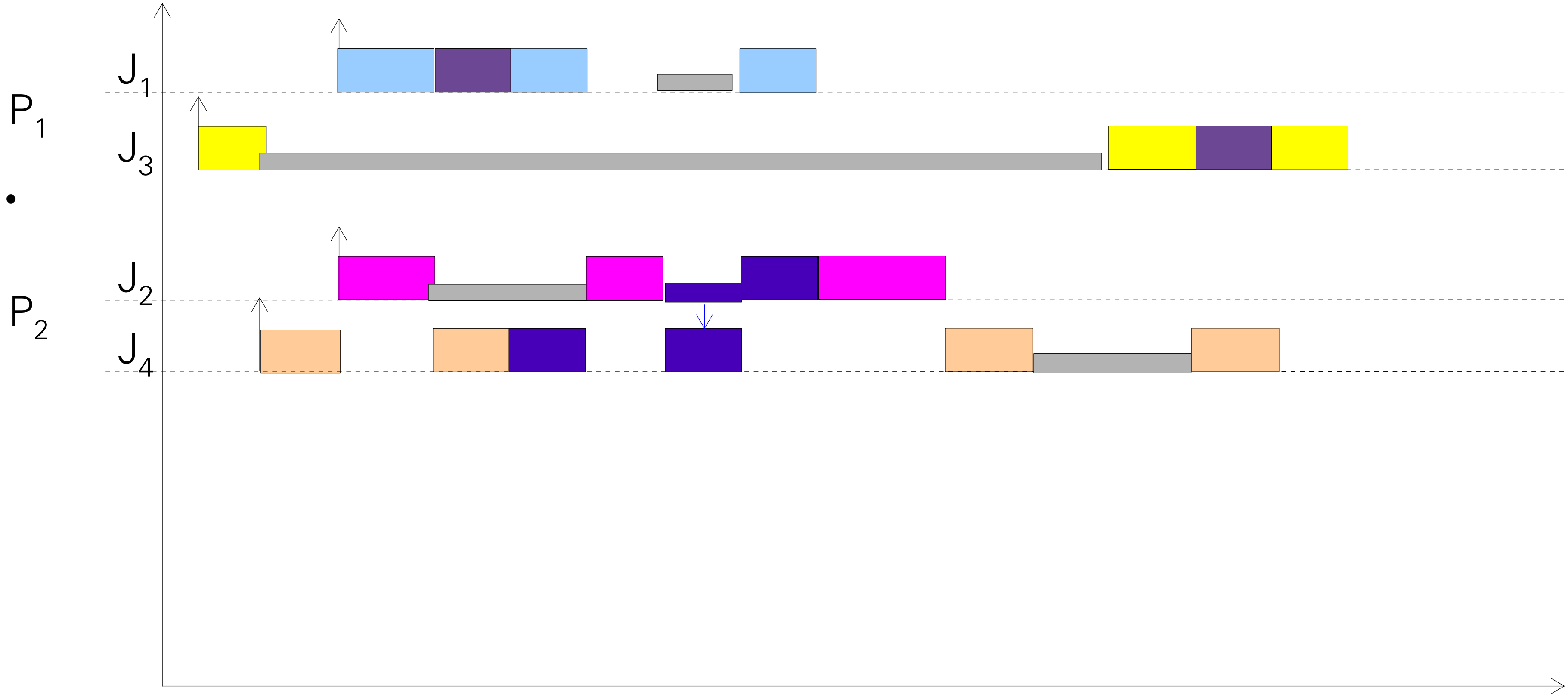


MPCP – first try



MP Priority Ceiling Protocol (MPCP)

- Run the priority ceiling protocol on each processor
- Treat global resources as jobs with same relative but strictly higher priority than other threads on the sync. CPU



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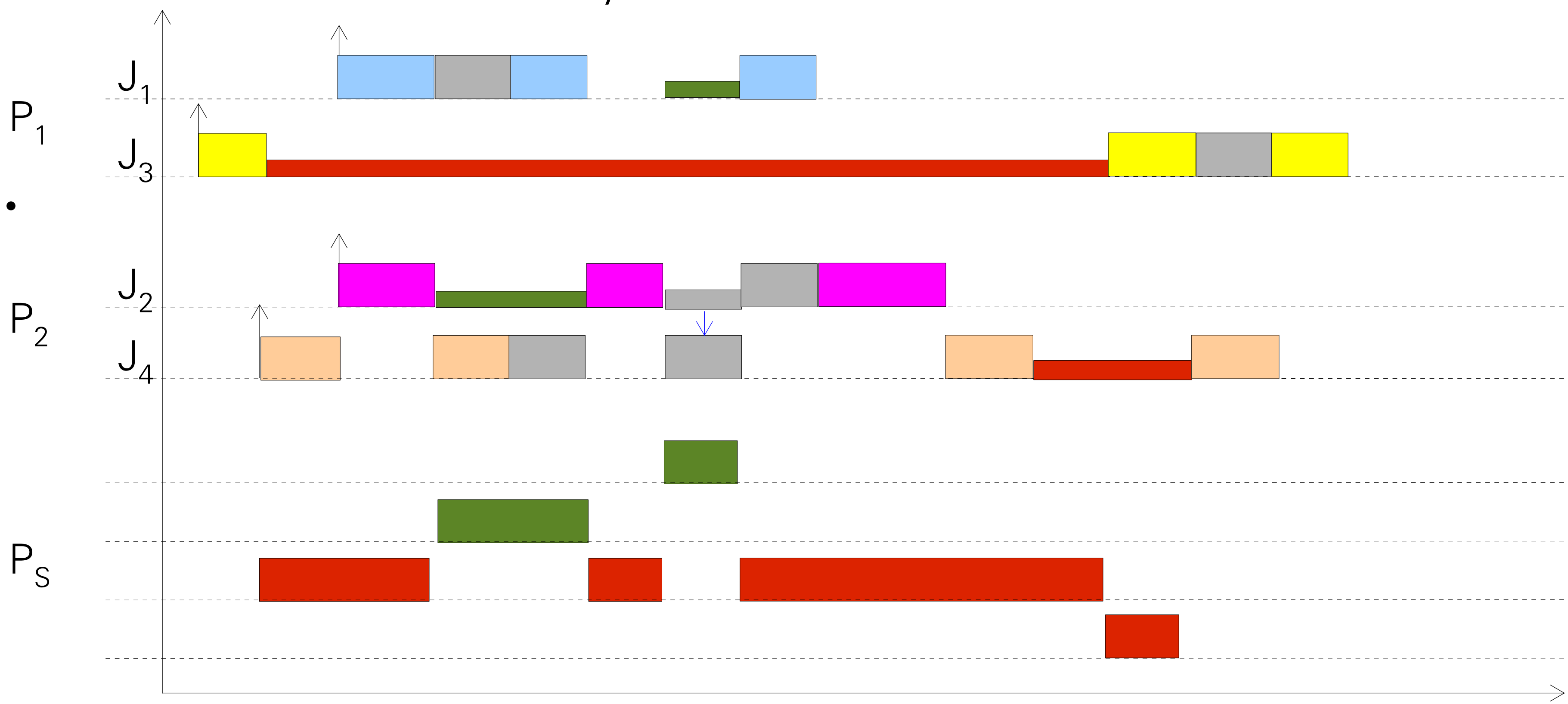

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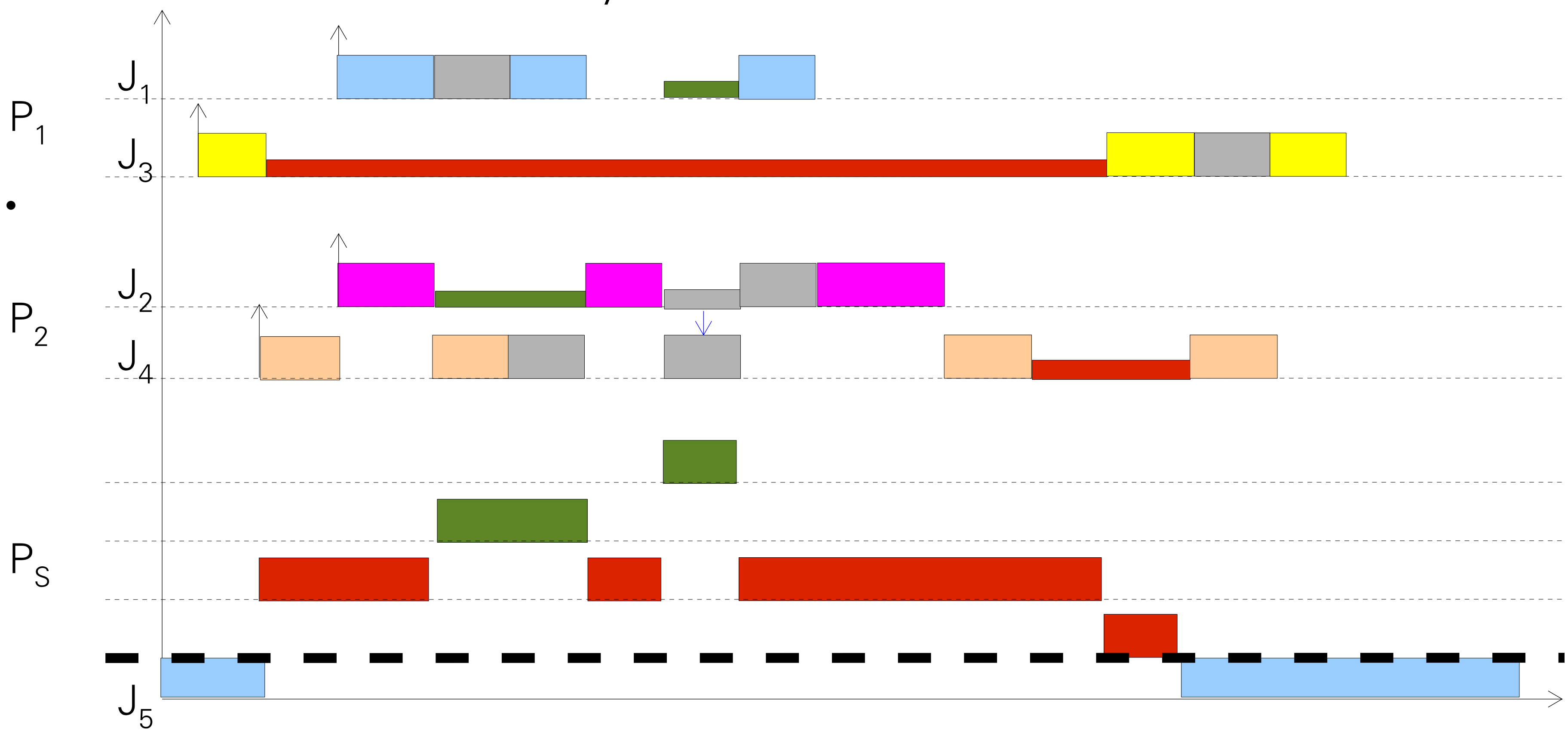
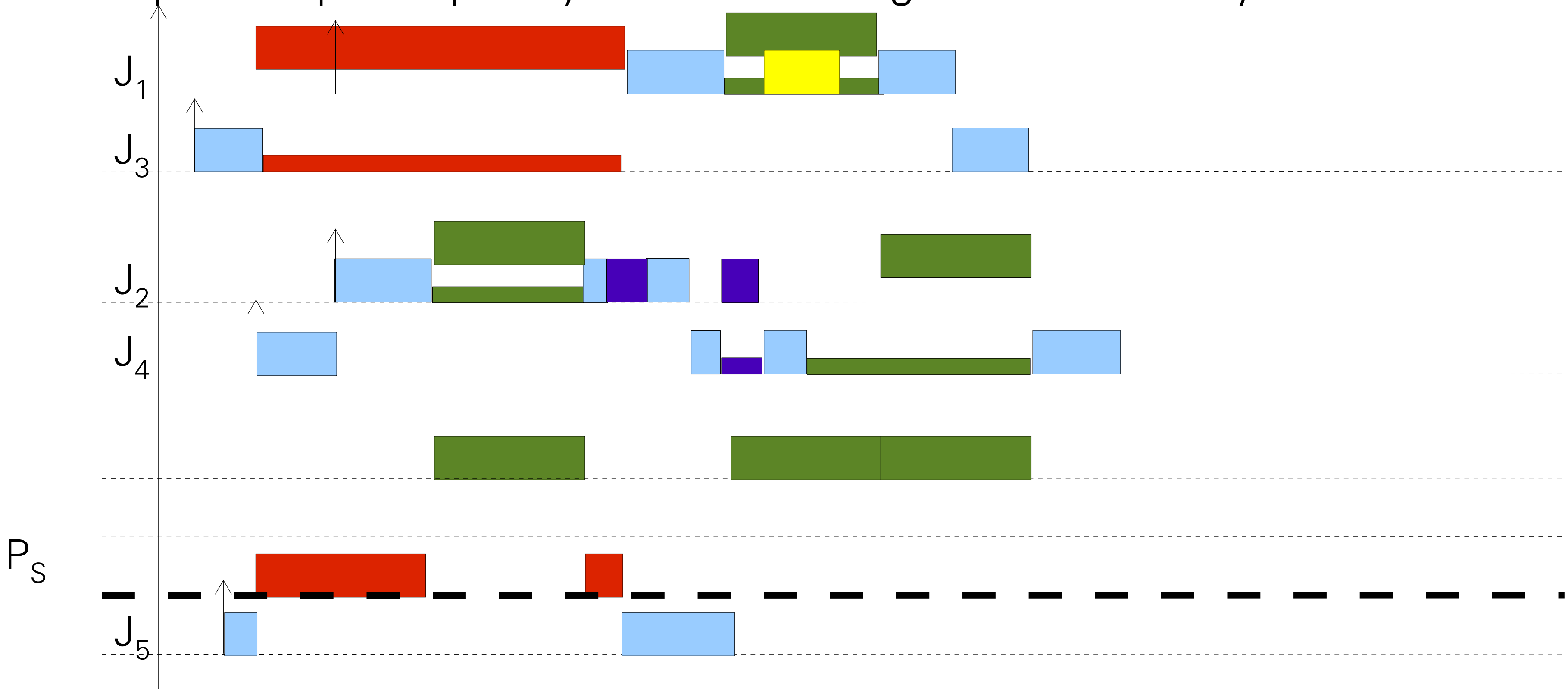


MP Stack-Resource Protocol (MSRP)

- SRP on every CPU
- Spin non-preemptively while executing a GCS on the sync. CPU



FMLP [Block]

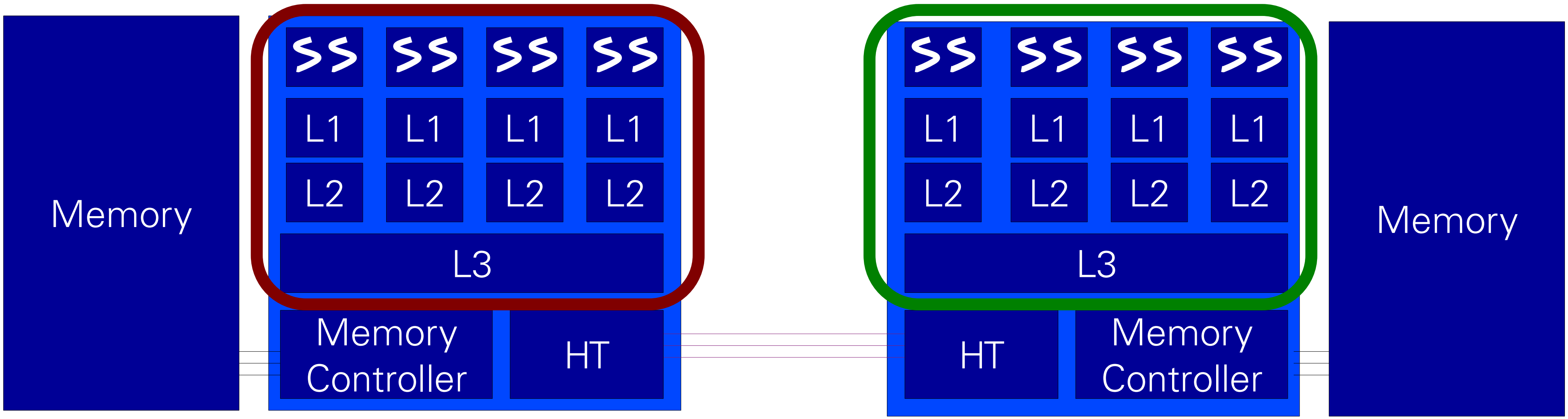
- **Flexible Multiprocessor Locking Protocol**
  - works with global scheduling
  - access short resources non-preemptively (busy wait if blocked)
  - block on Semaphore if long resource is busy
    - Resource holder inherits priority
  - resource groups to avoid deadlocks

Performance

- [Gai '03]:
  - MSRP typically outperforms MPCP for short + typically local CSs
- [Brandenburg '08]:
  - comparison of blocking (FMLP) vs. lock-free vs. wait-free
  - non-blocking are preferable for small + simple CSs
  - wait-free / spin-based are preferable for long CSs
  - spin-based almost always outperforms suspension-based algorithms SRP on every CPU

Locking for Clustered Scheduling

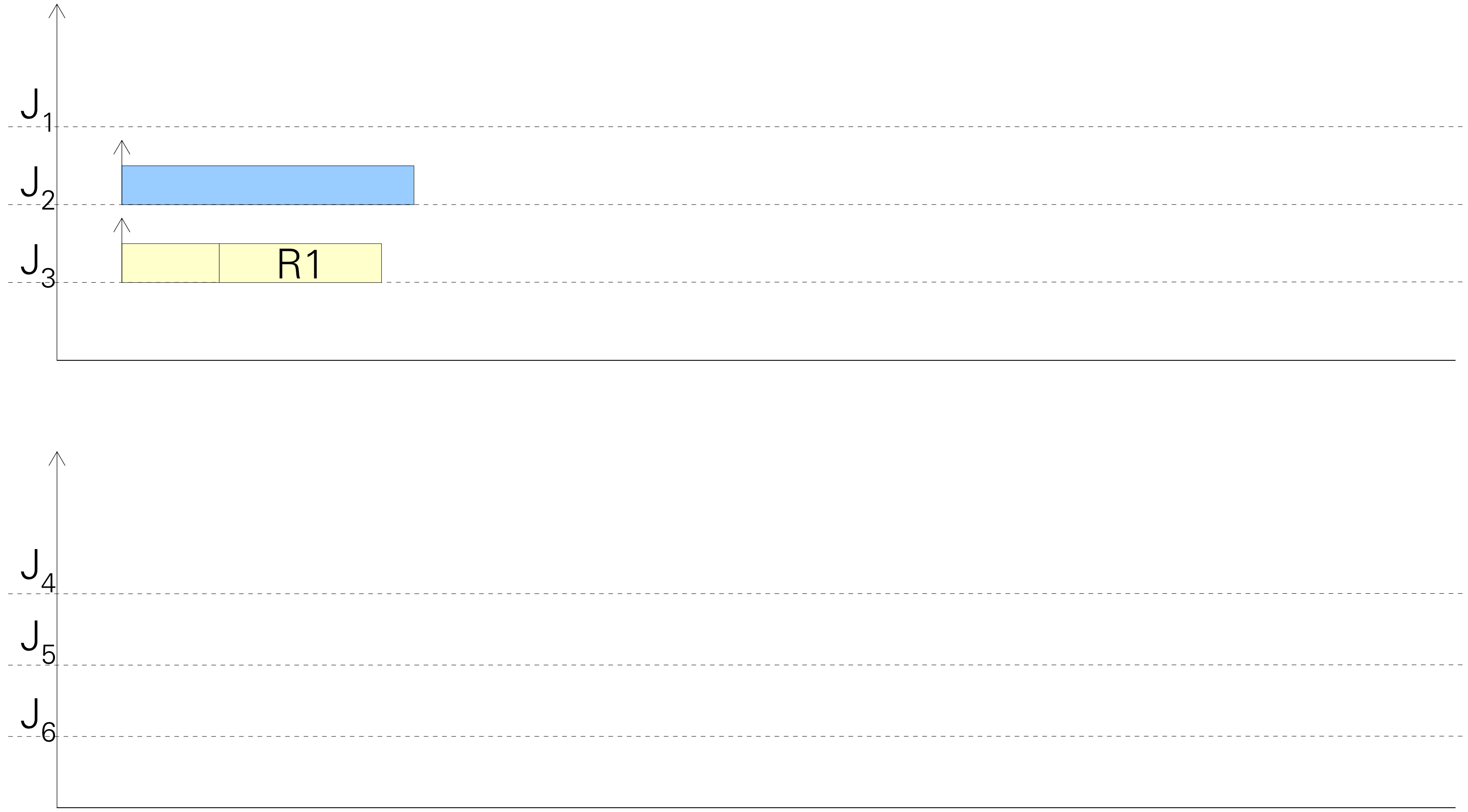
- [Brandenburg '11]:
  - clustered scheduling: global within the cluster; partitioned in between



- Idea:
  - Every task helps out resource holders for a bounded time
  - Only the n-highest prioritized threads may acquire resources

Locking for Clustered Scheduling

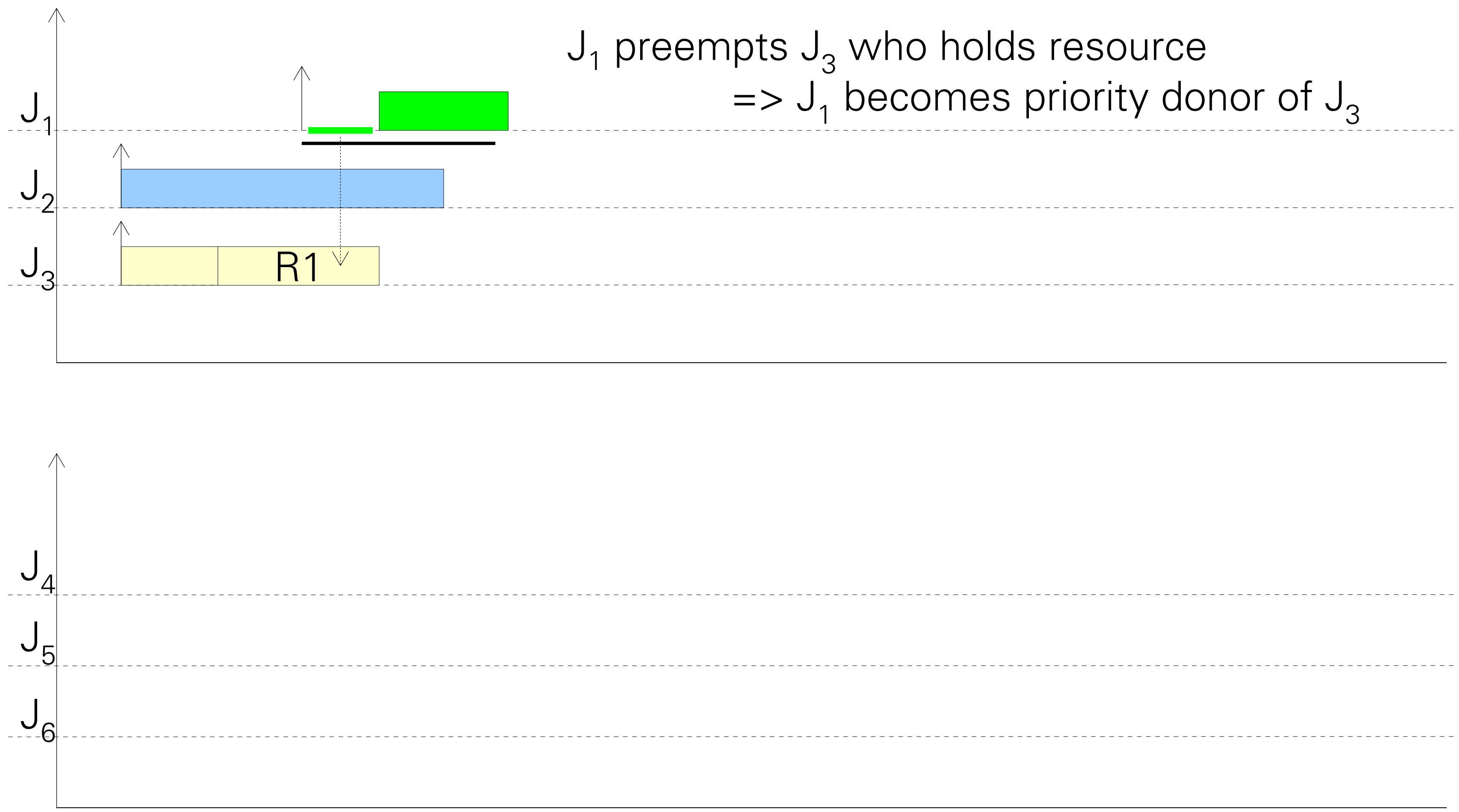
- 2 clusters; 2 cores each; 3 jobs / cluster



Locking for Clustered Scheduling

- 2 clusters; 2 cores each; 3 jobs / cluster

J_1 preempts J_3 who holds resource
=> J_1 becomes priority donor of J_3



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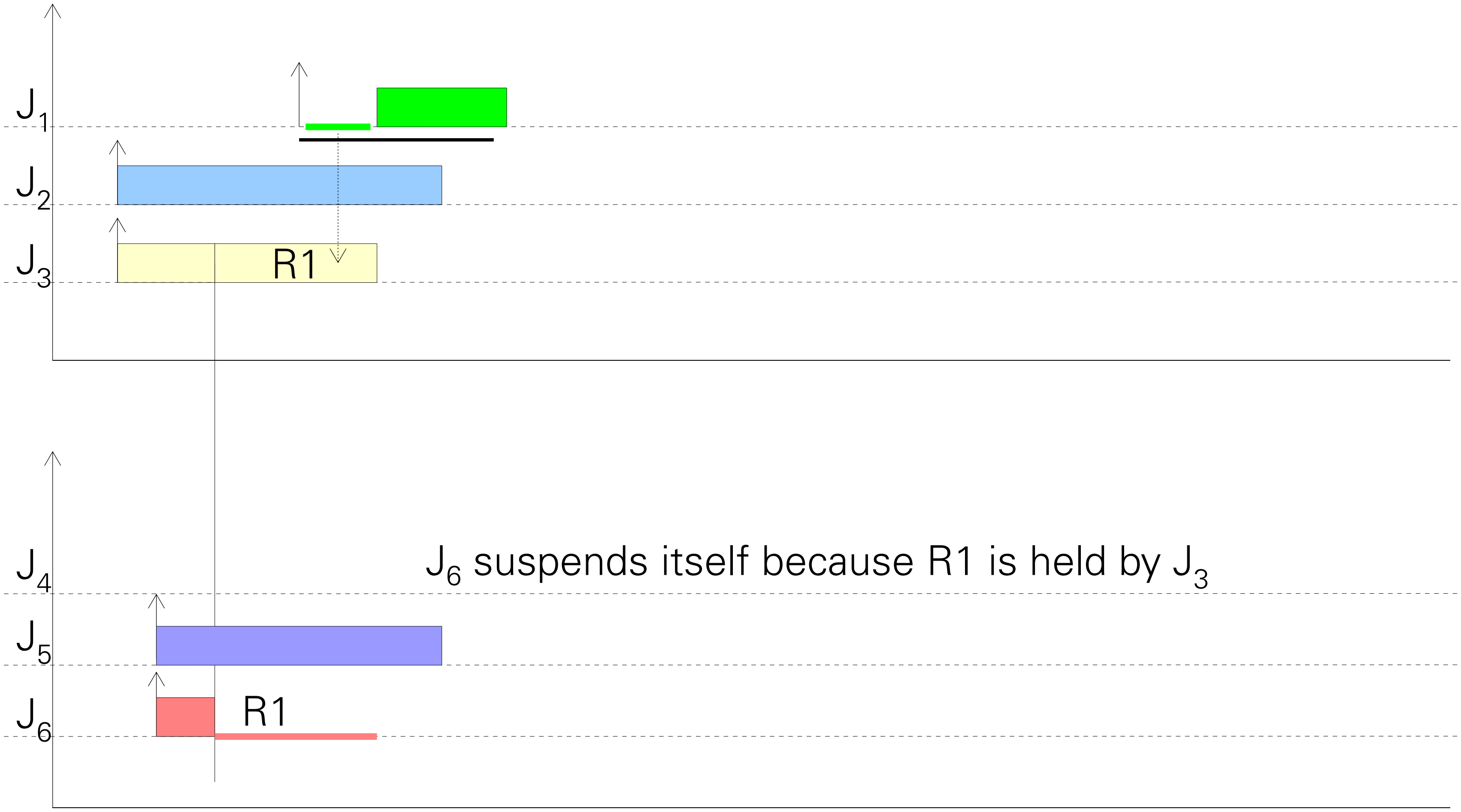

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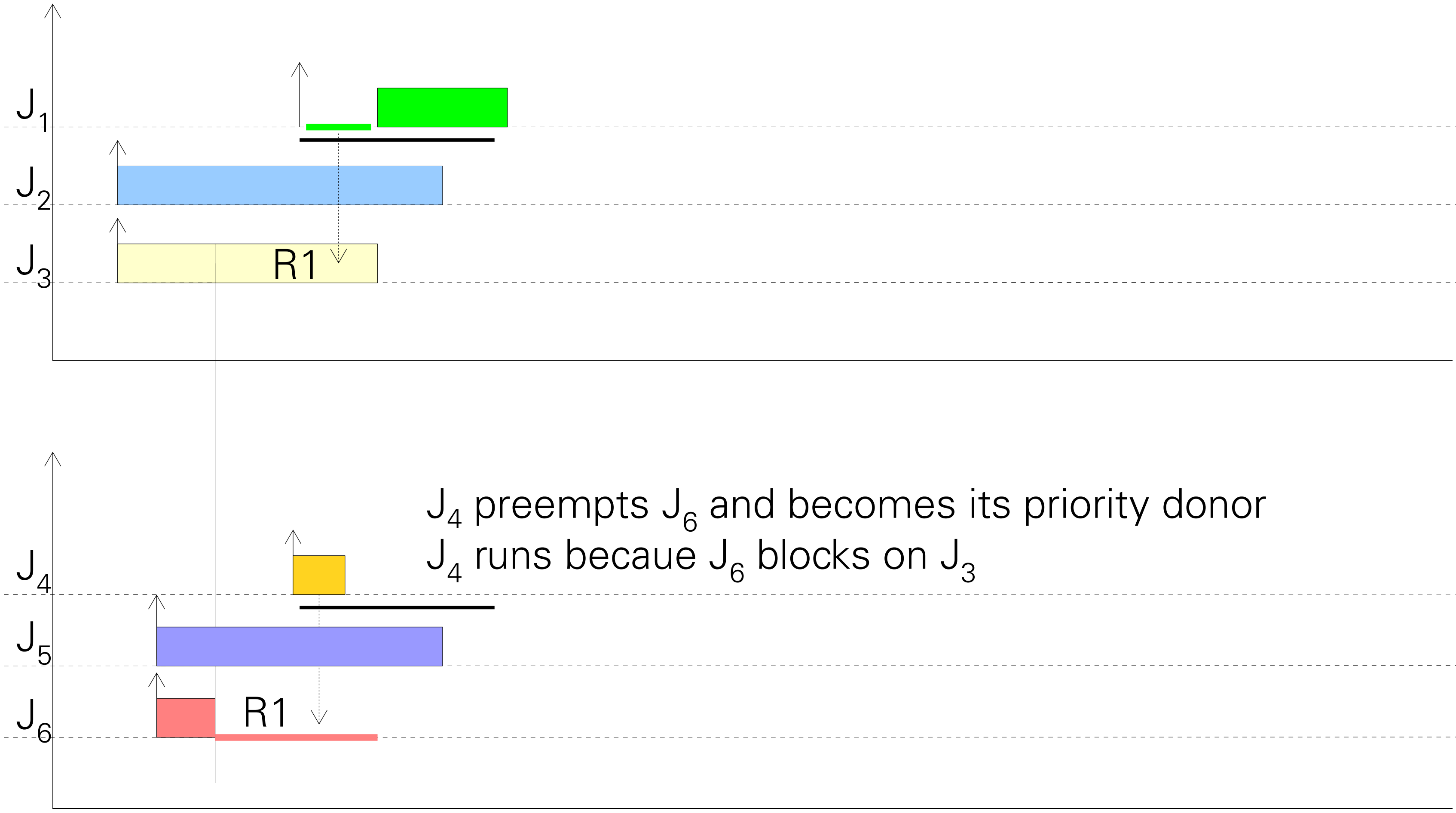

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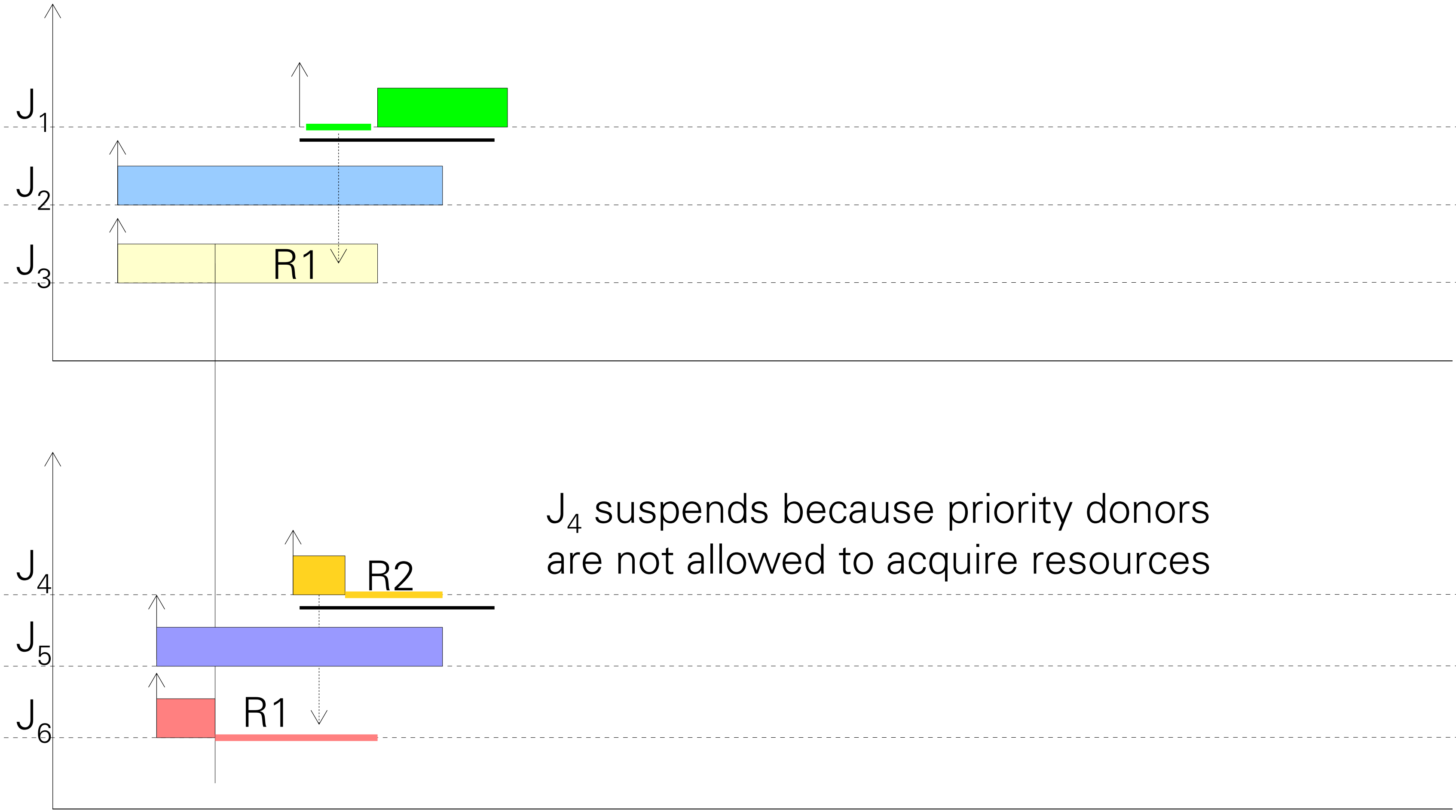

J_4 suspends because priority donors are not allowed to acquire resources

Locking for Clustered Scheduling

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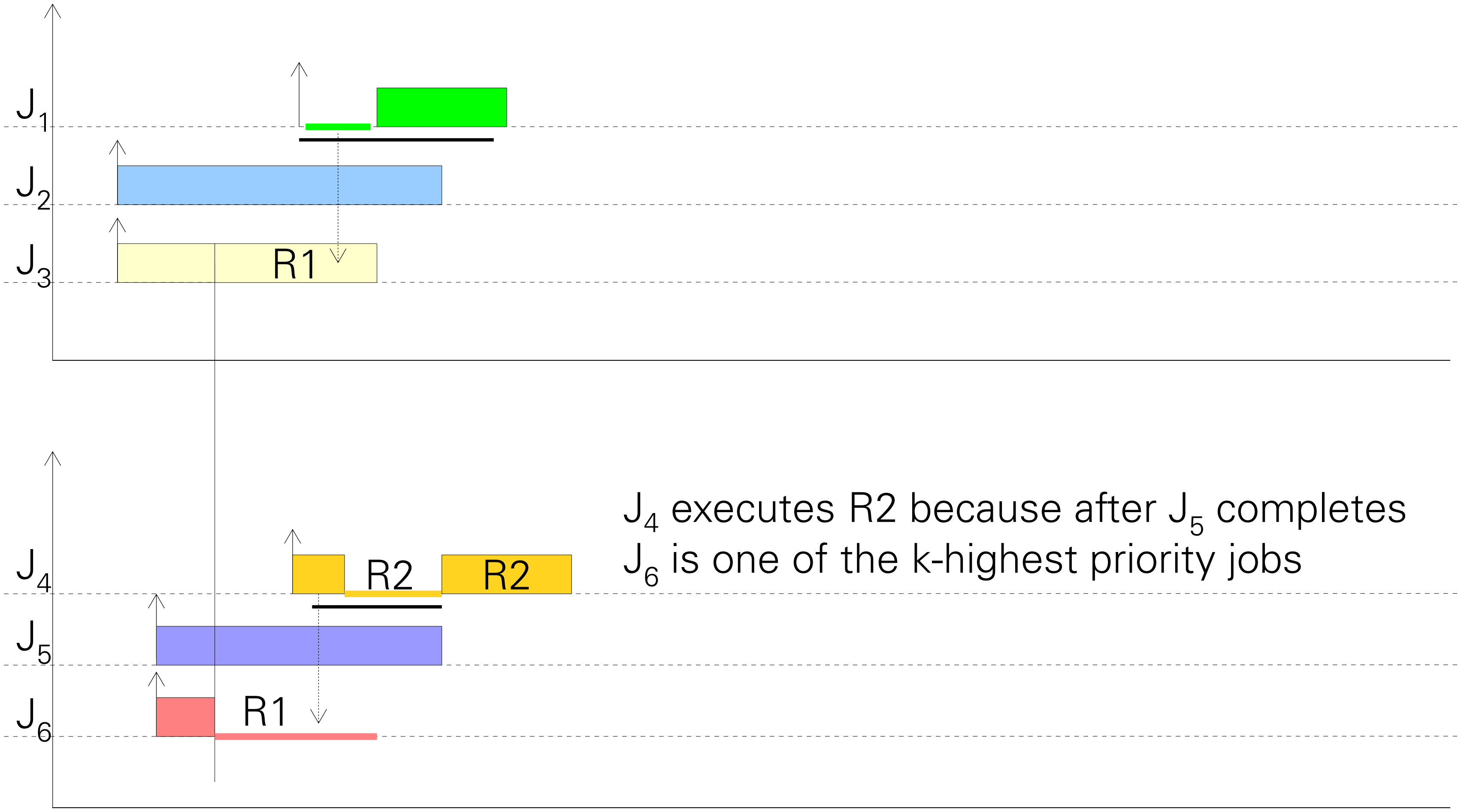

J_4 executes R2 because after J_5 completes J_6 is one of the k-highest priority jobs

Locking for Clustered Scheduling

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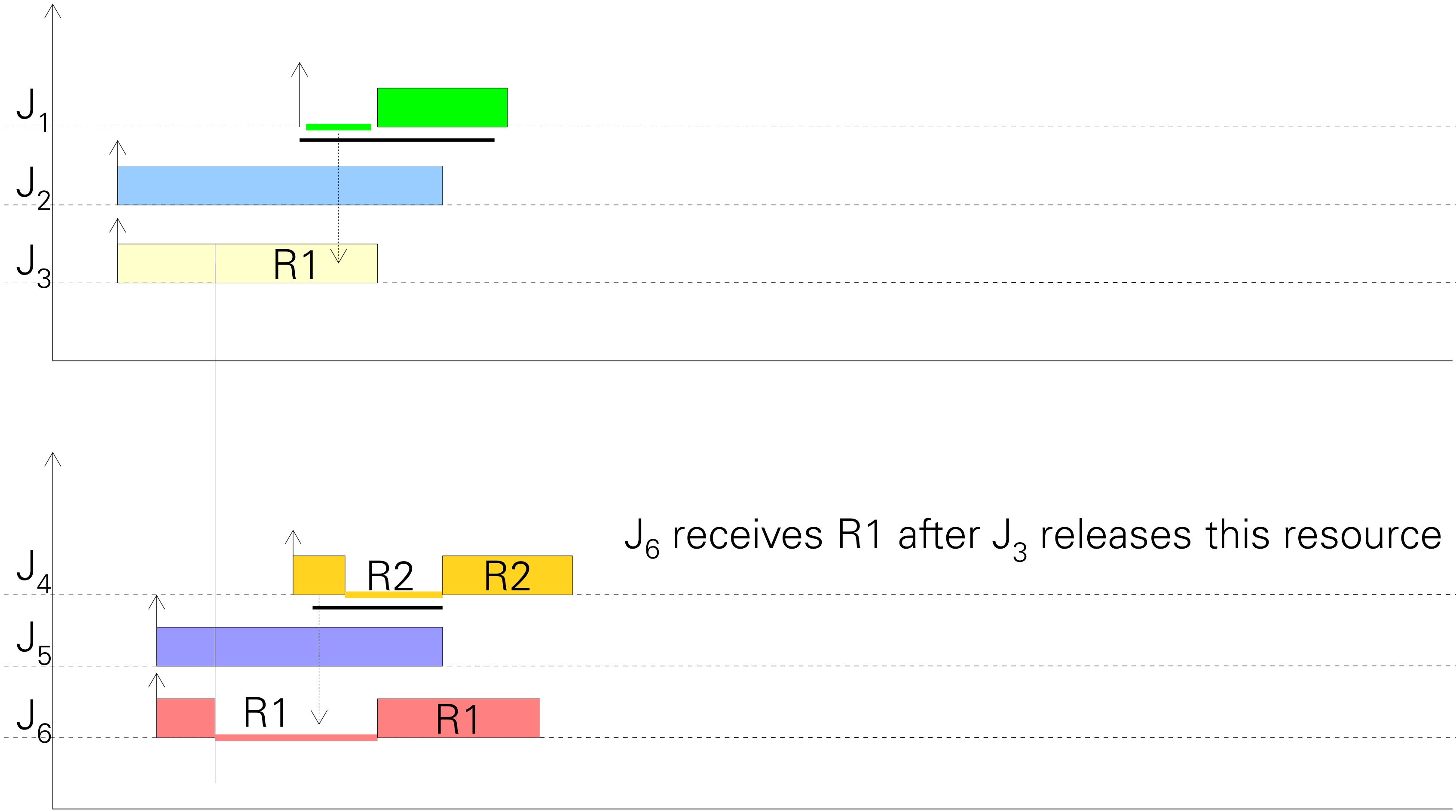

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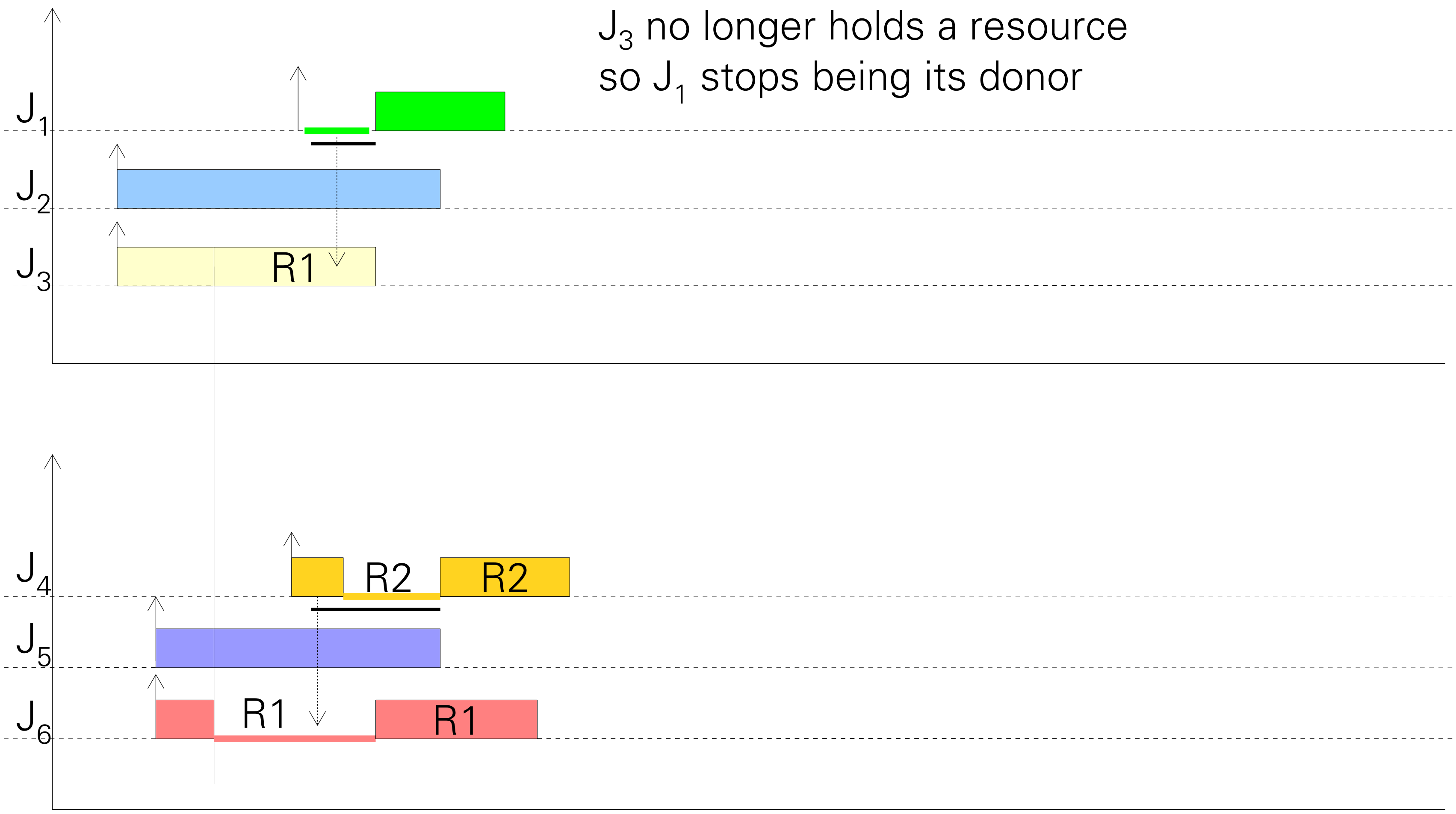

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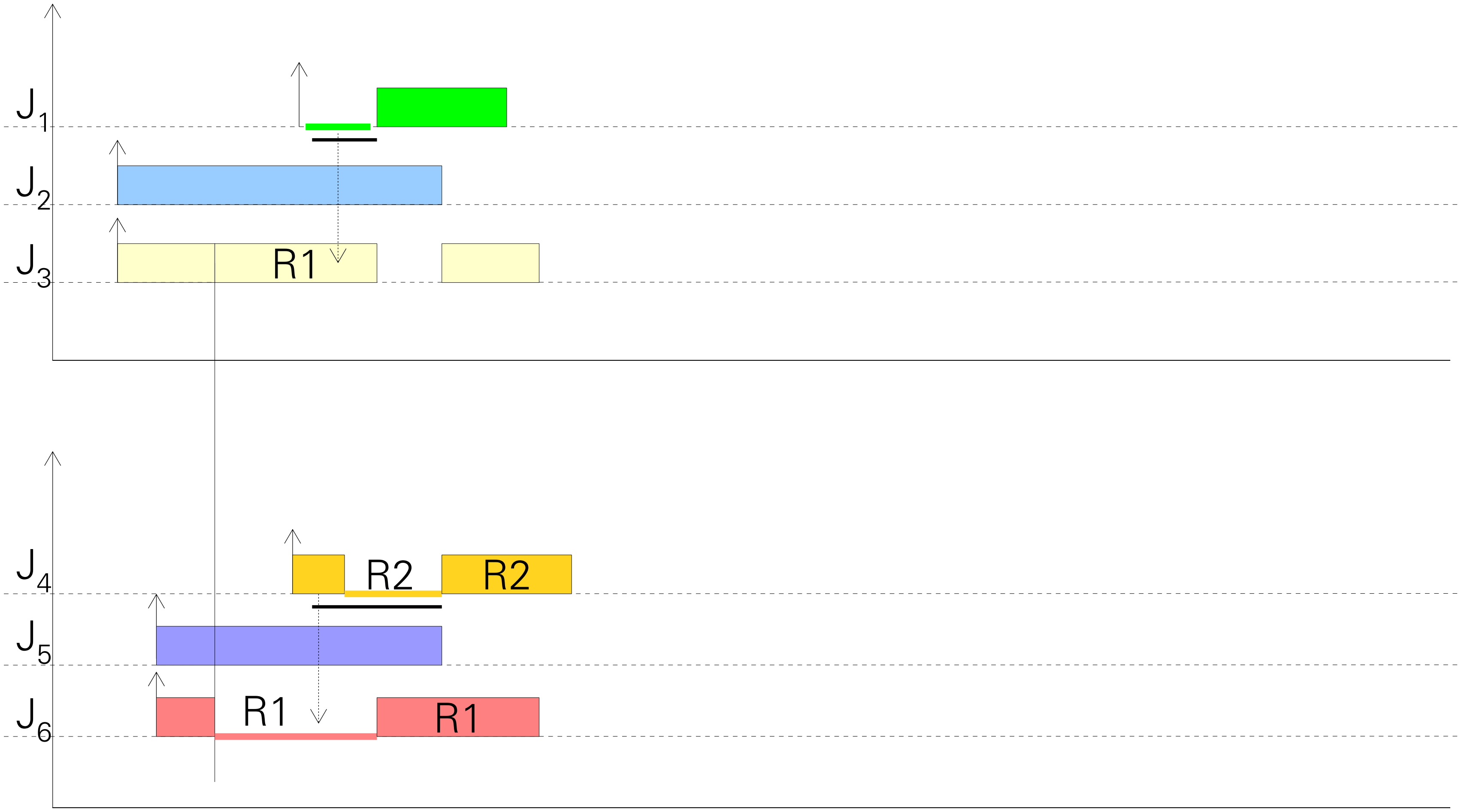

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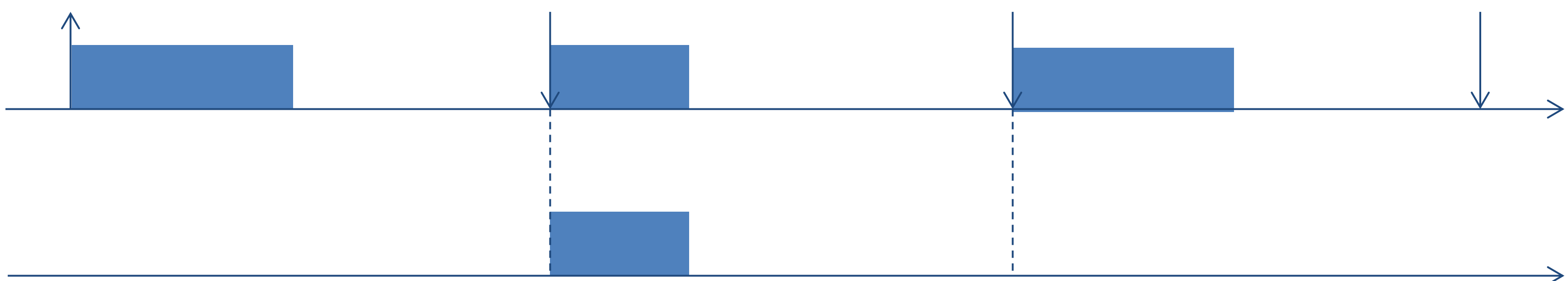
Open Issues [Burns '09]

- Limited processor Utilization
  - minimally dynamic algorithms
  - novel partitioning approaches
    - increase the guaranteed processing capability; overheads
- Ineffective Schedulability Tests (in particular, sporadic workloads)
  - large gap between feasibility / infeasibility tests
  - identify finite collection of worst-case job arrival sequences
- Overheads
  - migration costs; run queue manipulations; context switching
  - algorithms that permit intra-cluster migration; task-level migr.
- **Task Models**
  - [Colette] benefit / overhead oriented task models
  - [Edmons] speedup from extra parallelism

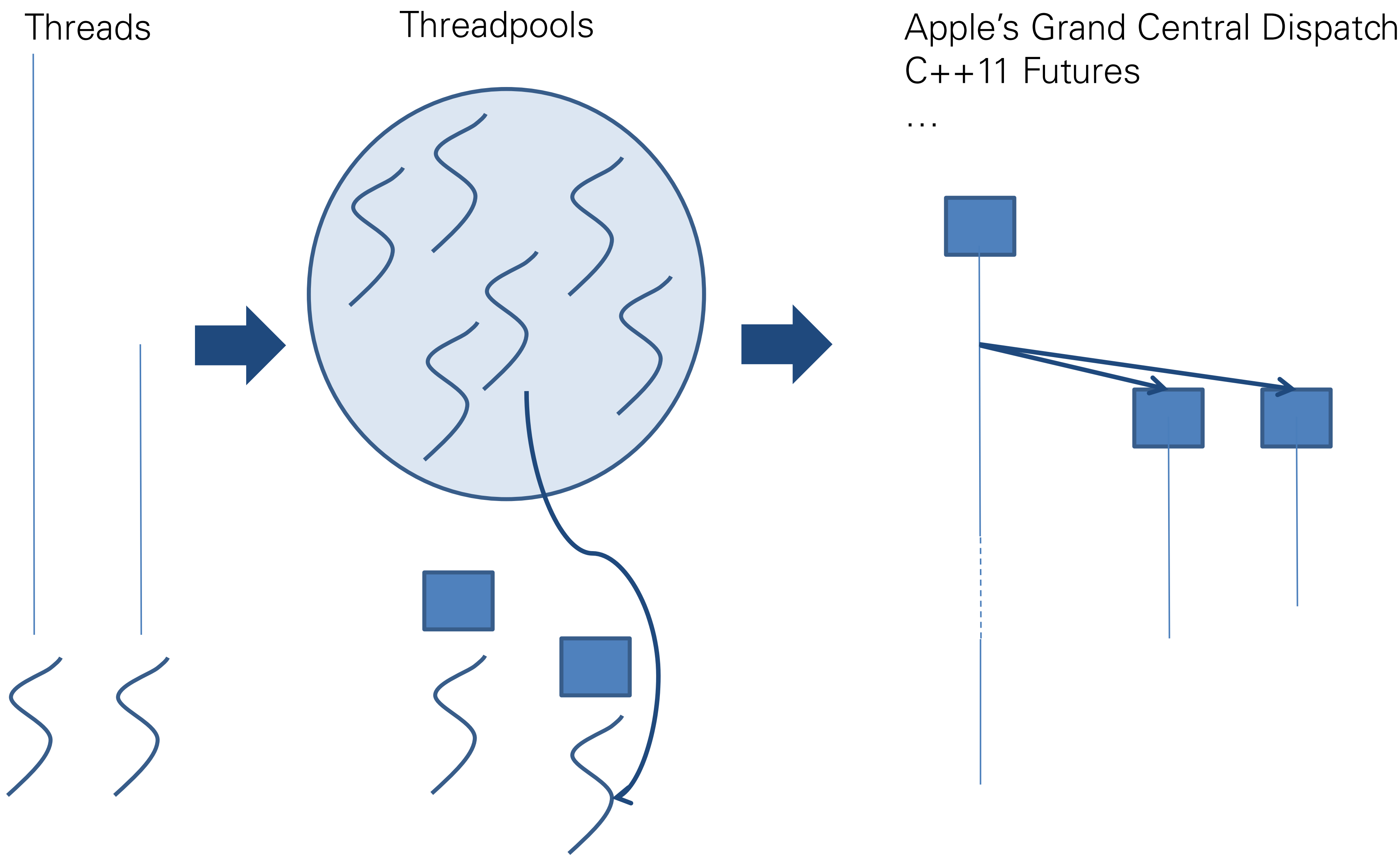
Integrating Job Parallelism [Colette]

Task: $\tau_i \stackrel{\text{def}}{=} (C_i, P_i, \Gamma_i)$ $\Gamma_i \stackrel{\text{def}}{=} (\gamma_{i,1}, \gamma_{i,2}, \ldots, \gamma_{i,m})$

Job with j processors completes $\gamma_{i,j}$ x t units of execution



Runtime Integration



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