Scheduling

Learning Outcomes

- Understand the role of the scheduler, and how its behaviour influences the performance of the system.
- Know the difference between I/O-bound and CPU-bound tasks, and how they relate to scheduling.
- Understand typical interactive and real time scheduling approaches.

What is Scheduling?

- On a multi-programmed system
  - We may have more than one *Ready* process
- On a batch system
  - We may have many jobs waiting to be run
- On a multi-user system
  - We may have many users concurrently using the system

- The ***scheduler*** decides who to run next.
  - The process of choosing is called *scheduling.*

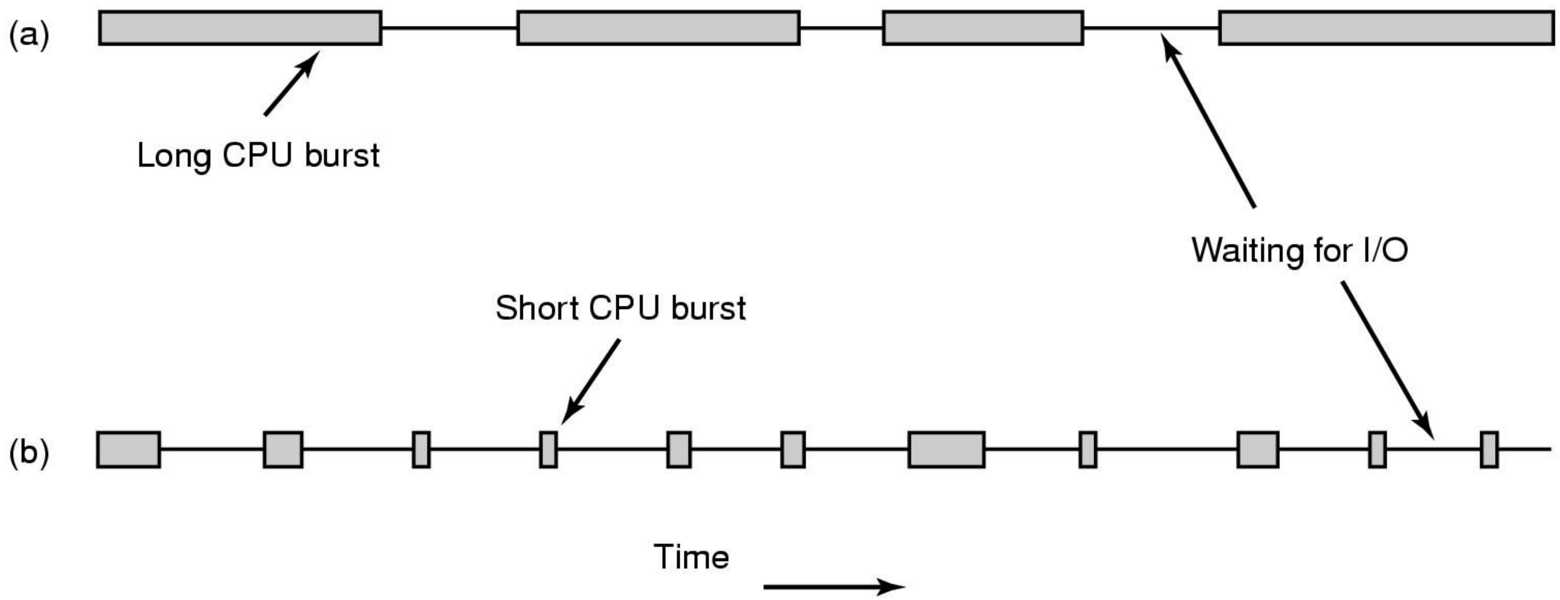
Is scheduling important?

- It is not in certain scenarios
  - If you have no choice
    - Early systems
      - Usually batching
      - Scheduling algorithm simple
        - » Run next on tape or next on punch tape
  - Only one thing to run
    - Simple PCs
      - Only ran a word processor, etc.…
    - Simple Embedded Systems
      - TV remote control, washing machine, etc.…

Is scheduling important?

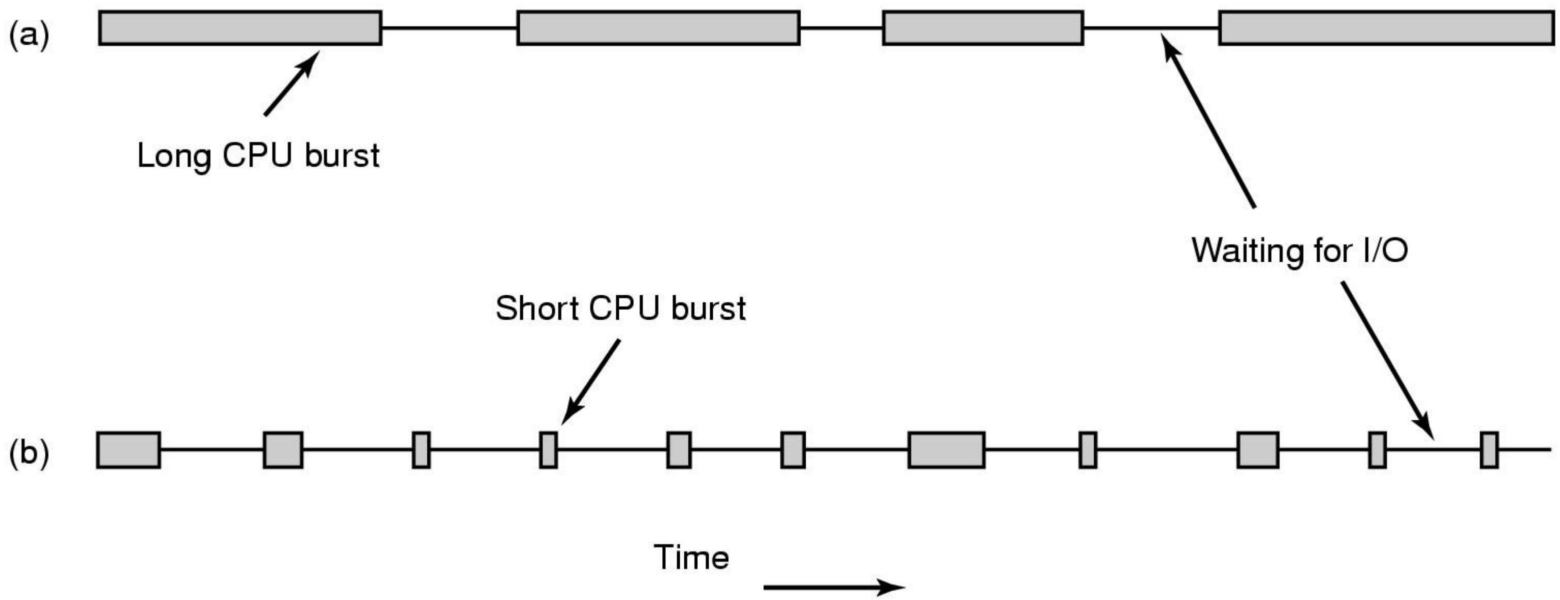
- It is in most realistic scenarios
  - Multitasking/Multi-user System
    - Example
      - Email daemon takes 2 seconds to process an email
      - User clicks button on application.
    - Scenario 1
      - Run daemon, then application
        - » System appears really sluggish to the user
    - Scenario 2
      - Run application, then daemon
        - » Application appears really responsive, small email delay is unnoticed
- Scheduling decisions can have a dramatic effect on the perceived performance of the system
  - Can also affect correctness of a system with deadlines

Application Behaviour



- Bursts of CPU usage alternate with periods of I/O wait

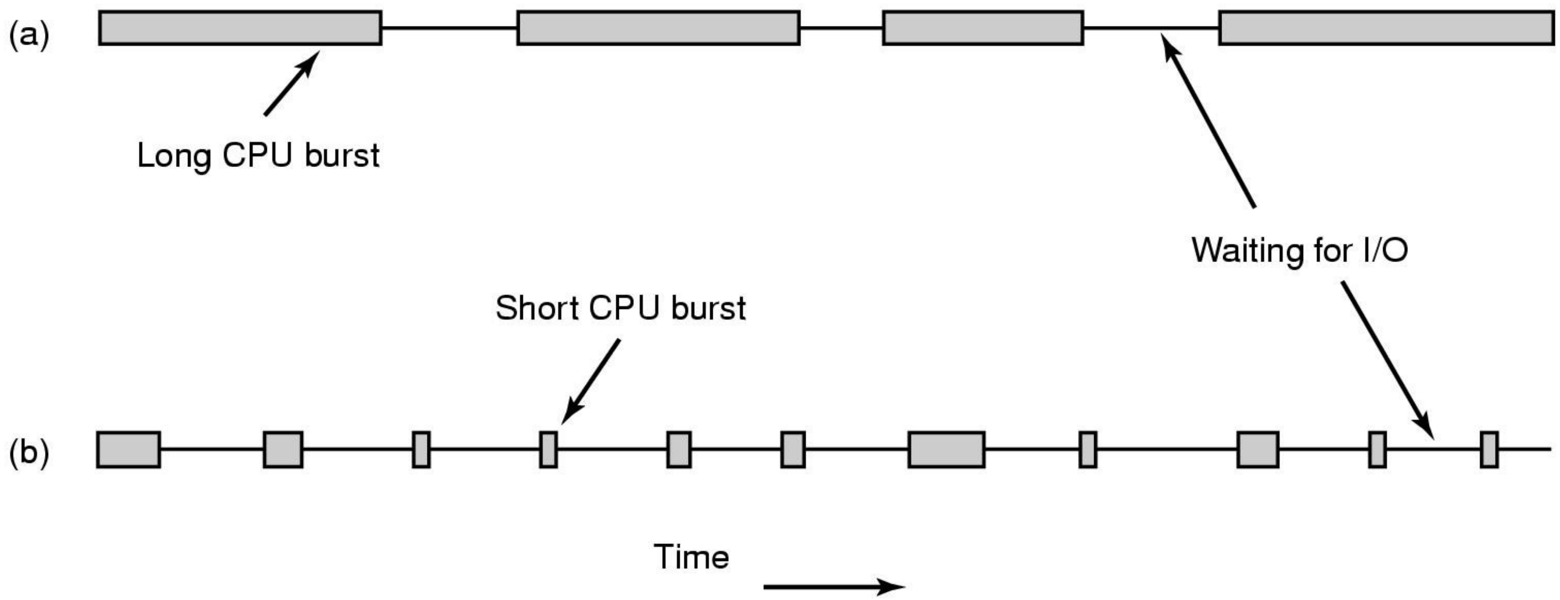
Application Behaviour



a) CPU-Bound process

- Spends most of its computing
- Time to completion largely determined by received CPU time

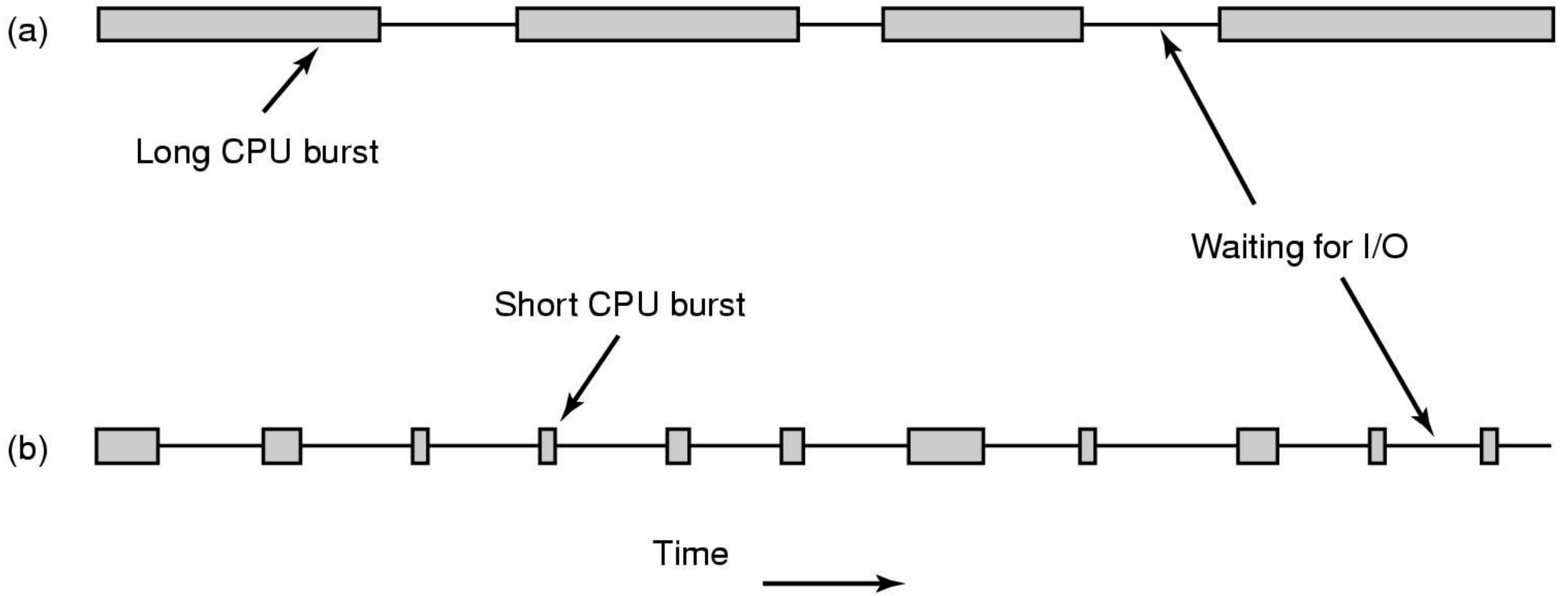
Application Behaviour



b) I/O-Bound process

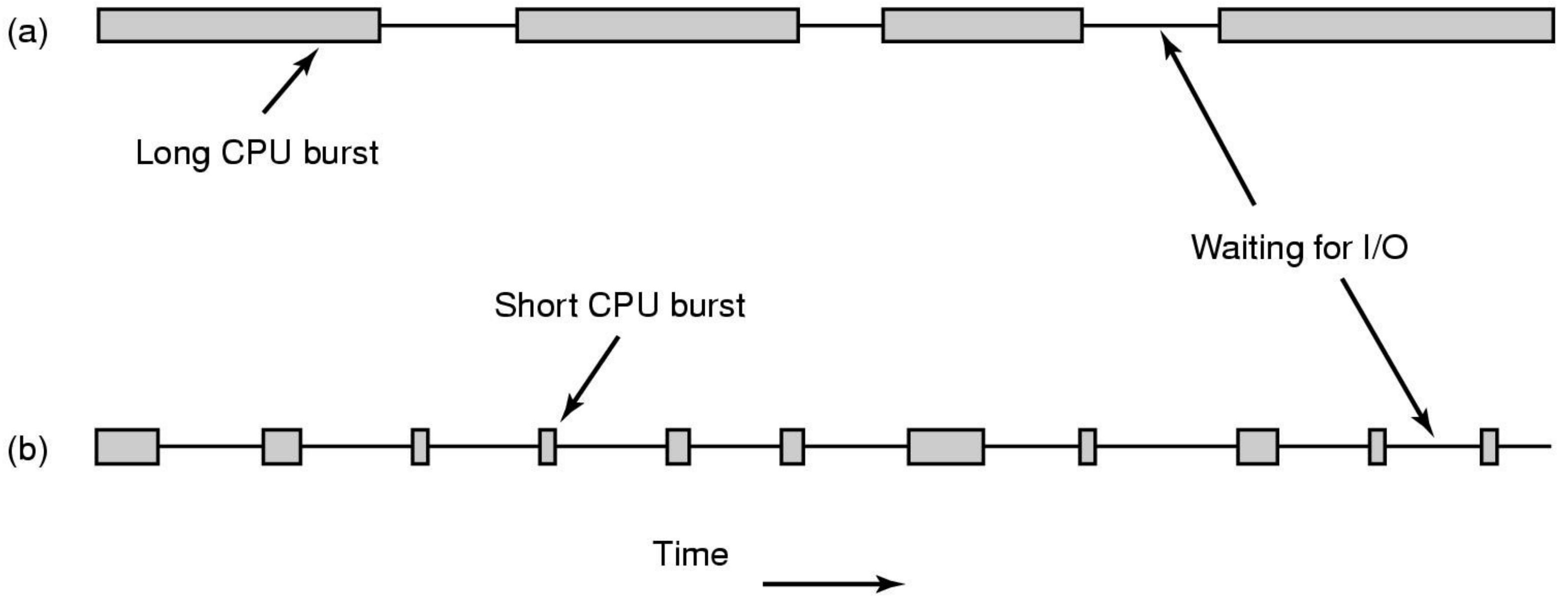
- Spend most of its time waiting for I/O to complete
  - Small bursts of CPU to process I/O and request next I/O
- Time to completion largely determined by I/O request time

Observation



- We need a mix of CPU-bound and I/O-bound processes to keep both CPU and I/O systems busy
- Process can go from CPU- to I/O-bound (or vice versa) in different phases of execution

Key Insight



- Choosing to run an I/O-bound process delays a CPU-bound process by very little
- Choosing to run a CPU-bound process prior to an I/O-bound process delays the next I/O request significantly
  - No overlap of I/O waiting with computation
  - Results in device (disk) not as busy as possible

⇒ Generally, favour I/O-bound processes over CPU-bound processes

When is scheduling performed?

- A new process
  - Run the parent or the child?
- A process exits
  - Who runs next?
- A process waits for I/O
  - Who runs next?
- A process blocks on a lock
  - Who runs next? The lock holder?
- An I/O interrupt occurs
  - Who do we resume, the interrupted process or the process that was waiting?
- On a timer interrupt? (See next slide)

- Generally, a scheduling decision is required when a process (or thread) can no longer continue, or when an activity results in more than one ready process.

Preemptive versus Non-preemptive Scheduling

- Non-preemptive
  - Once a thread is in the *running* state, it continues until it completes, blocks on I/O, or voluntarily yields the CPU
  - A single process can monopolised the entire system
- Preemptive Scheduling
  - Current thread can be interrupted by OS and moved to *ready* state.
  - Usually after a timer interrupt and process has exceeded its maximum run time
    - Can also be as a result of higher priority process that has become *ready* (after I/O interrupt).
  - Ensures fairer service as single thread can't monopolise the system
    - Requires a timer interrupt

Categories of Scheduling Algorithms

- The choice of scheduling algorithm depends on the goals of the application (or the operating system)
  - No one algorithm suits all environments
- We can roughly categorise scheduling algorithms as follows
  - Batch Systems
    - No users directly waiting, can optimise for overall machine performance
  - Interactive Systems
    - Users directly waiting for their results, can optimise for users perceived performance
  - Realtime Systems
    - Jobs have deadlines, must schedule such that all jobs (mostly) meet their deadlines.

Goals of Scheduling Algorithms

- All Algorithms
  - Fairness
    - Give each process a *fair* share of the CPU
  - Policy Enforcement
    - What ever policy chosen, the scheduler should ensure it is carried out
  - Balance/Efficiency
    - Try to keep all parts of the system busy

Goals of Scheduling Algorithms

- Interactive Algorithms
  - Minimise *response time*
    - Response time is the time difference between issuing a command and getting the result
      - E.g selecting a menu, and getting the result of that selection
    - Response time is important to the user's perception of the performance of the system.
  - Provide *Proportionality*
    - Proportionality is the user expectation that short jobs will have a short response time, and long jobs can have a long response time.
    - Generally, favour short jobs

Goals of Scheduling Algorithms

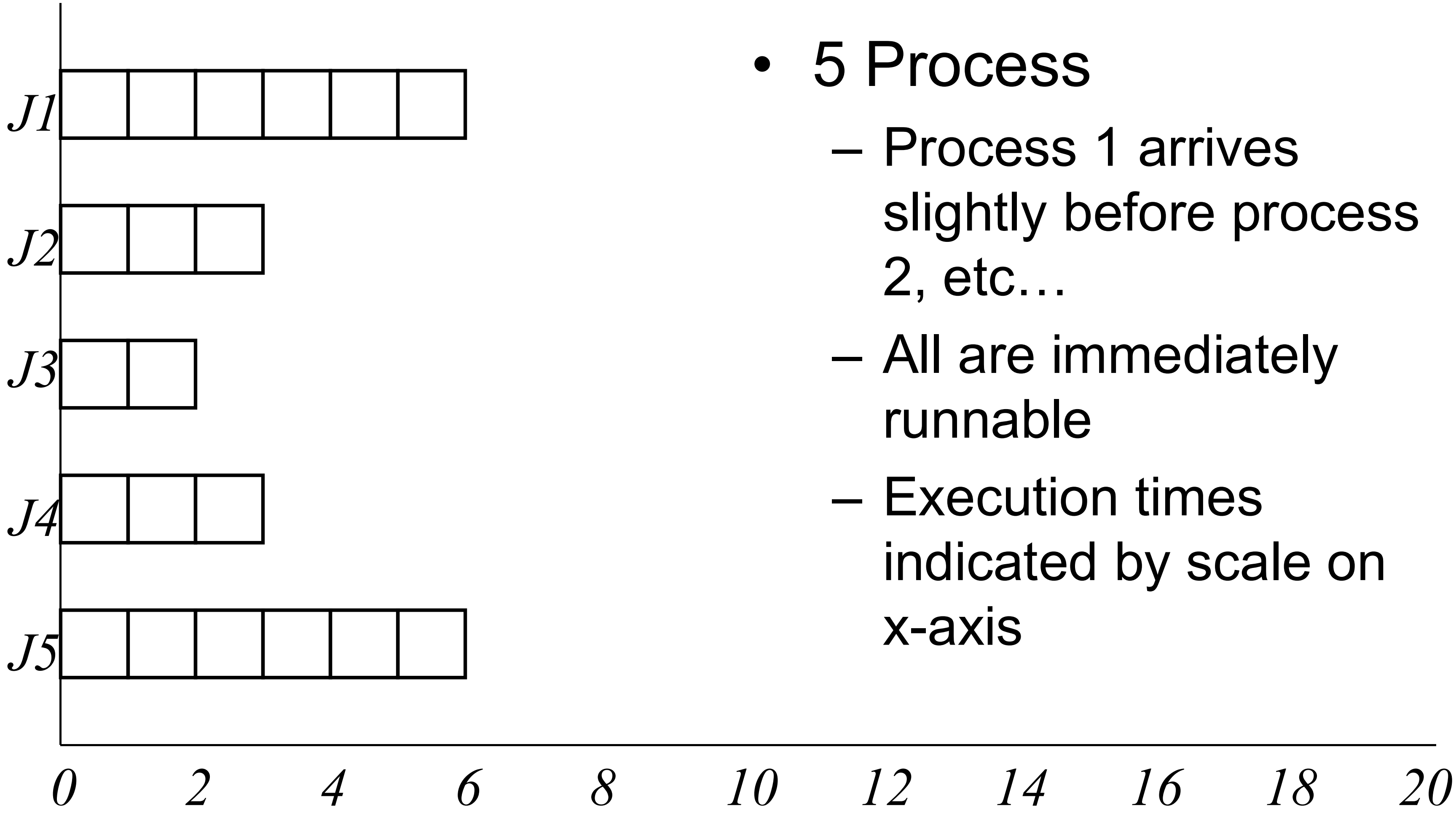
- Real-time Algorithms
  - Must meet deadlines
    - Each job/task has a deadline.
    - A missed deadline can result in data loss or catastrophic failure
      - Aircraft control system missed deadline to apply brakes
  - Provide Predictability
    - For some apps, an occasional missed deadline is okay
      - E.g. DVD decoder
    - Predictable behaviour allows smooth DVD decoding with only rare skips

Interactive Scheduling

Round Robin Scheduling

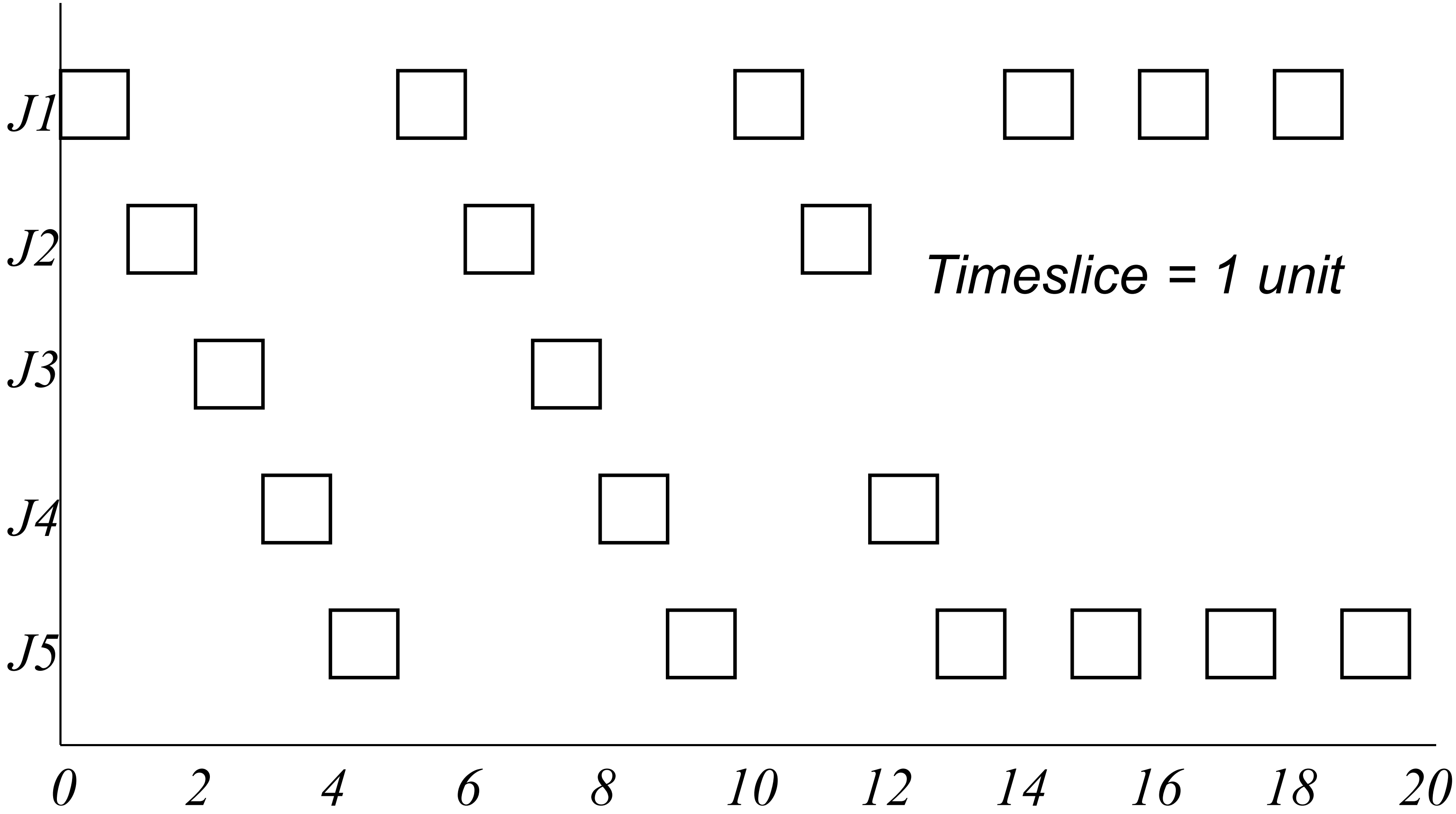
- Each process is given a *timeslice* to run in
- When the timeslice expires, the next process preempts the current process, and runs for its timeslice, and so on
  - The preempted process is placed at the end of the queue
- Implemented with
  - A ready queue
  - A regular timer interrupt

Example

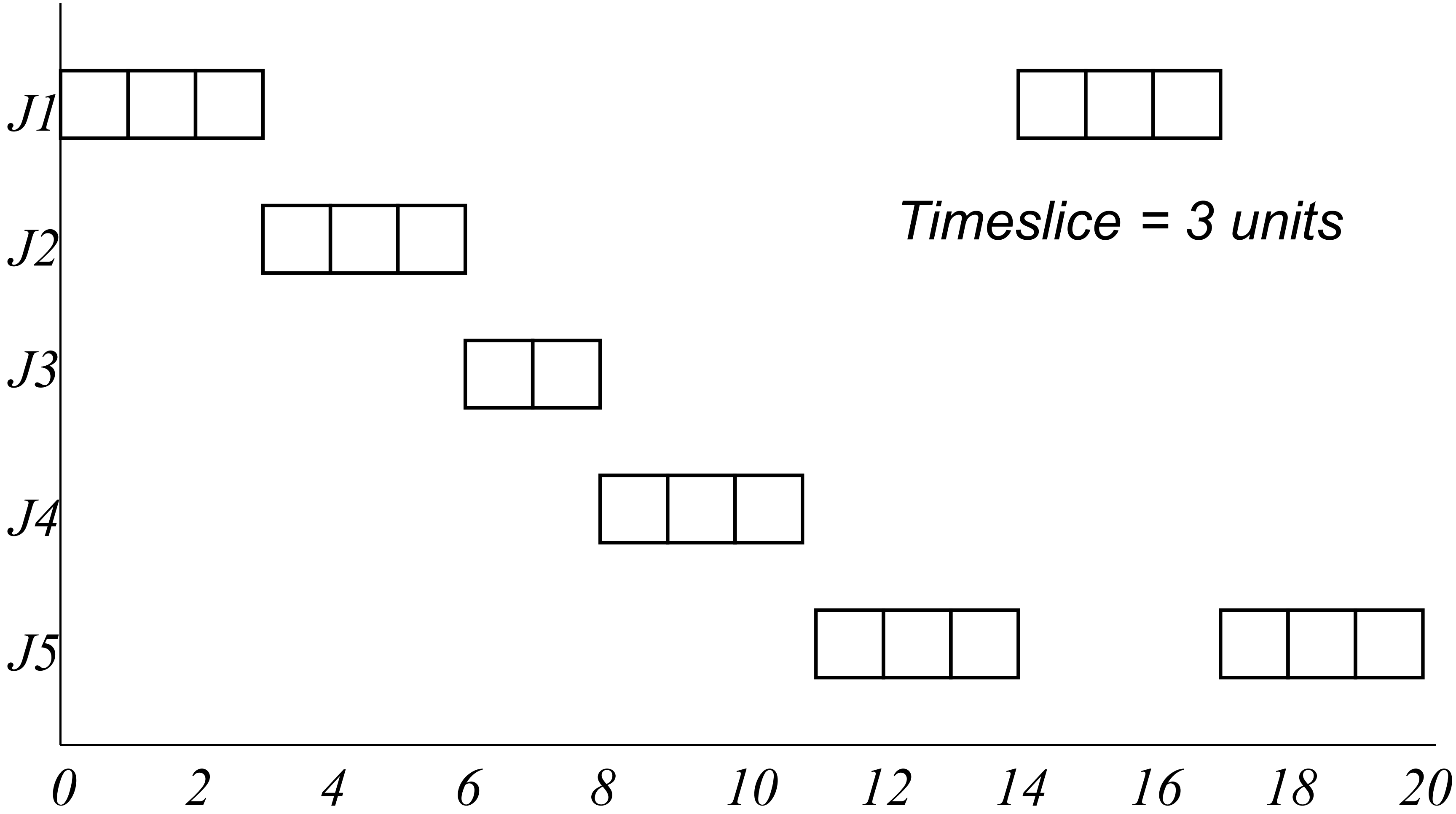


- 5 Process
  - Process 1 arrives slightly before process 2, etc…
  - All are immediately runnable
  - Execution times indicated by scale on x-axis

Round Robin Schedule



Round Robin Schedule



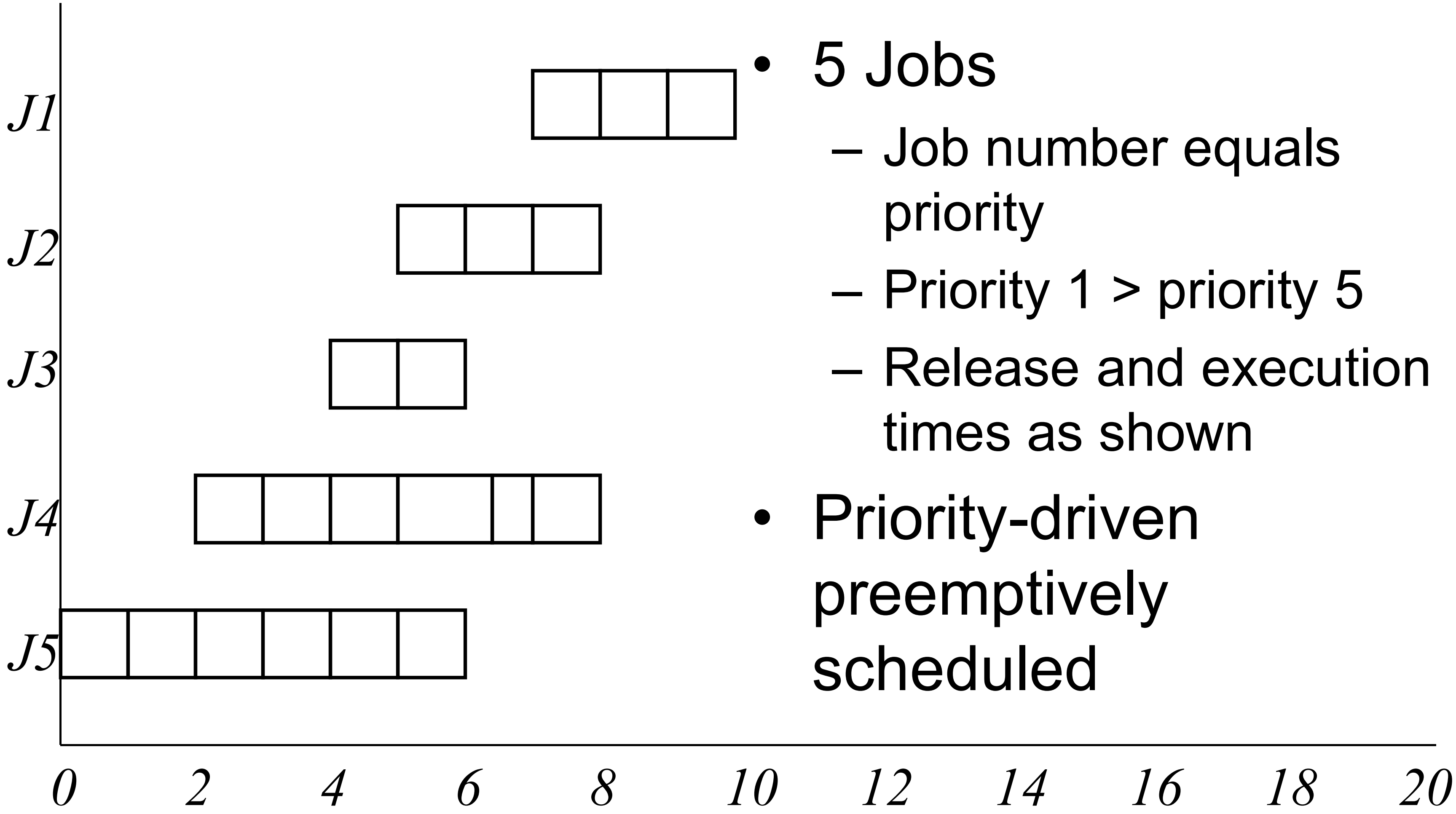
Round Robin

- Pros
  - Fair, easy to implement
- Con
  - Assumes everybody is equal
- Issue: What should the timeslice be?
  - Too short
    - Waste a lot of time switching between processes
    - Example: timeslice of 4ms with 1 ms context switch = 20% round robin overhead
  - Too long
    - System is not responsive
    - Example: timeslice of 100ms
      - If 10 people hit "enter" key simultaneously, the last guy to run will only see progress after 1 second.
    - Degenerates into FCFS if timeslice longer than burst length

Priorities

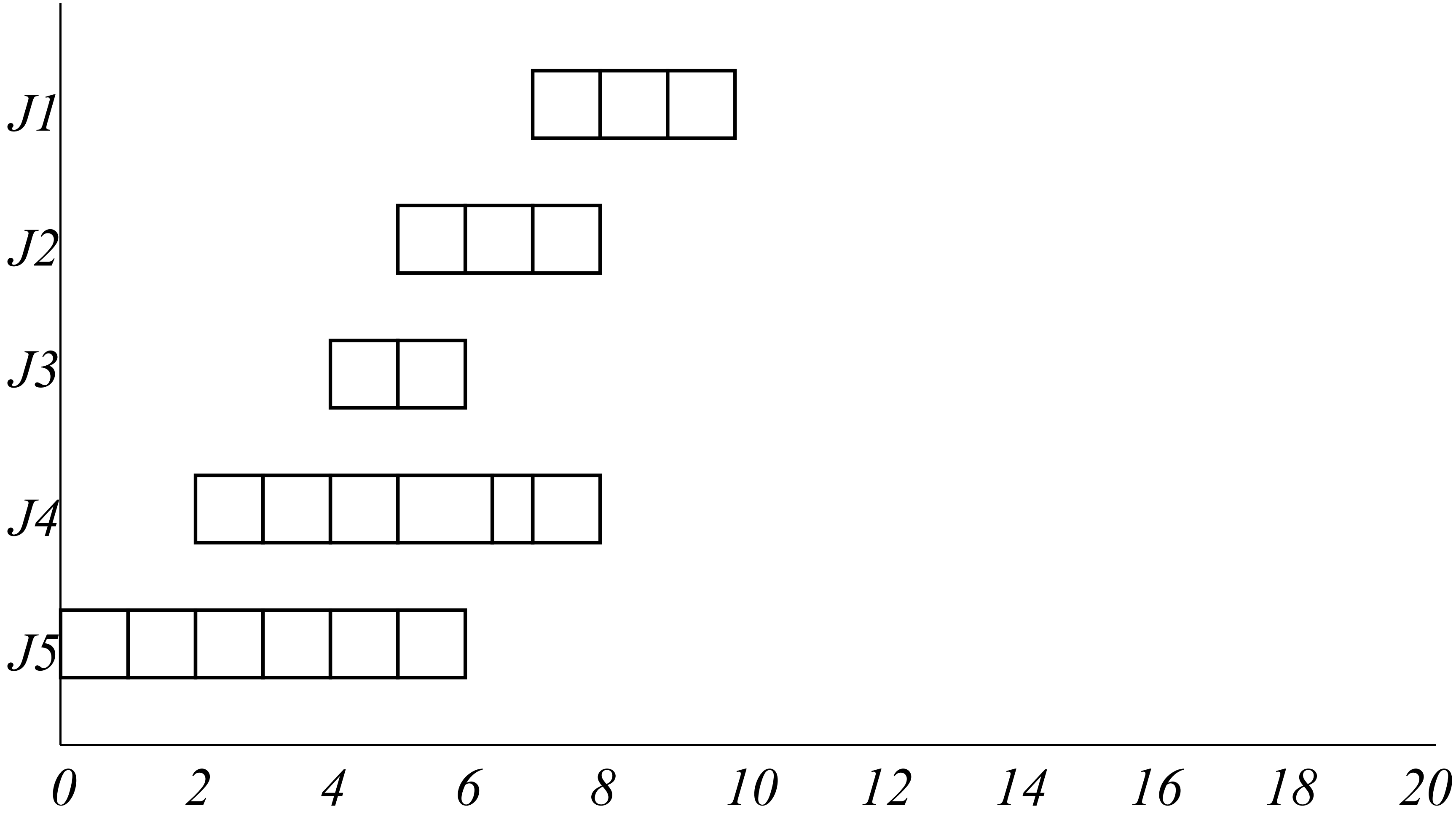
- Each Process (or thread) is associated with a priority
- Provides basic mechanism to influence a scheduler decision:
  - Scheduler will always chooses a thread of higher priority over lower priority
- Priorities can be defined internally or externally
  - Internal: e.g. I/O bound or CPU bound
  - External: e.g. based on importance to the user

Example



- 5 Jobs
  - Job number equals priority
  - Priority 1 > priority 5
  - Release and execution times as shown
- Priority-driven preemptively scheduled

Example



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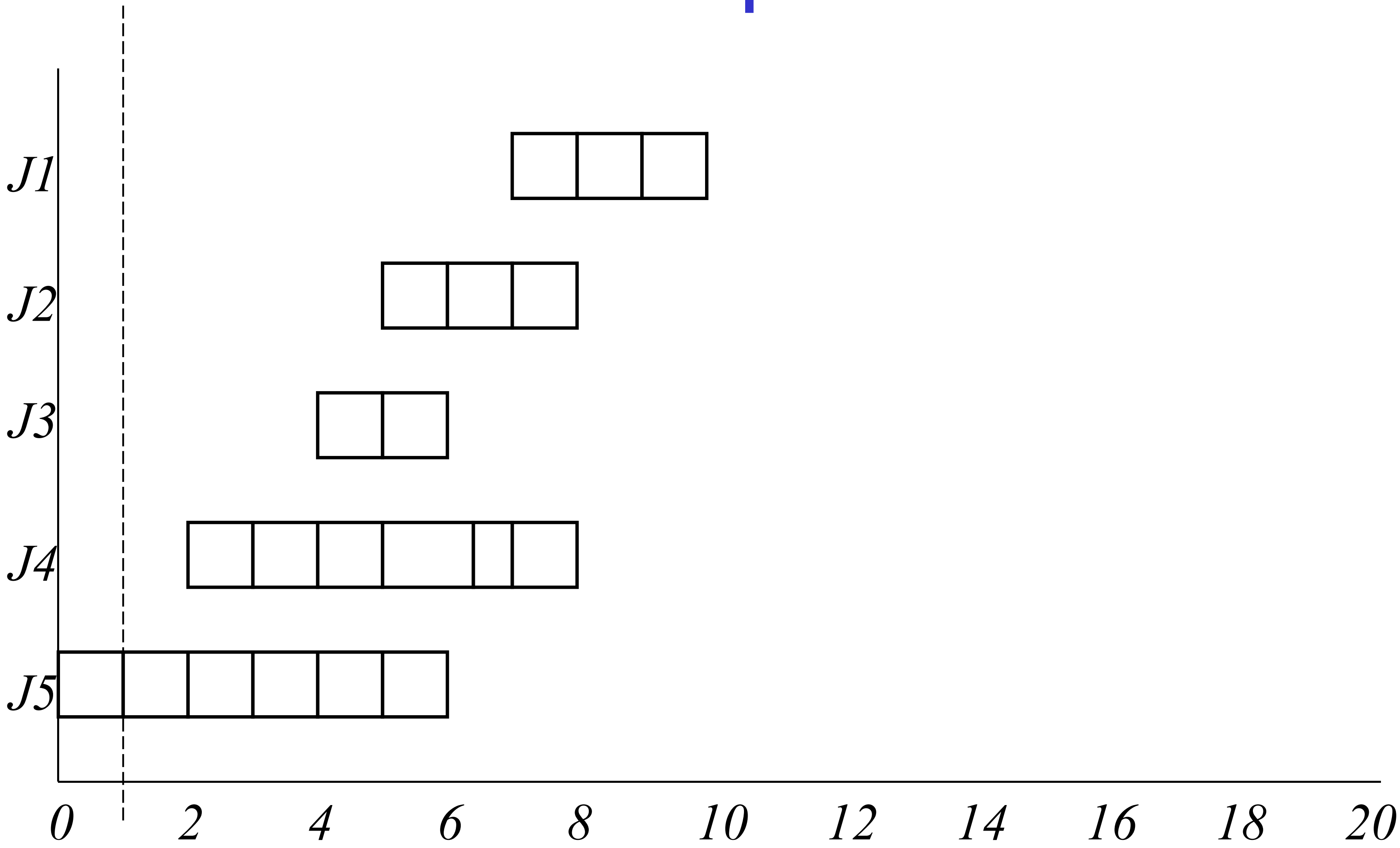

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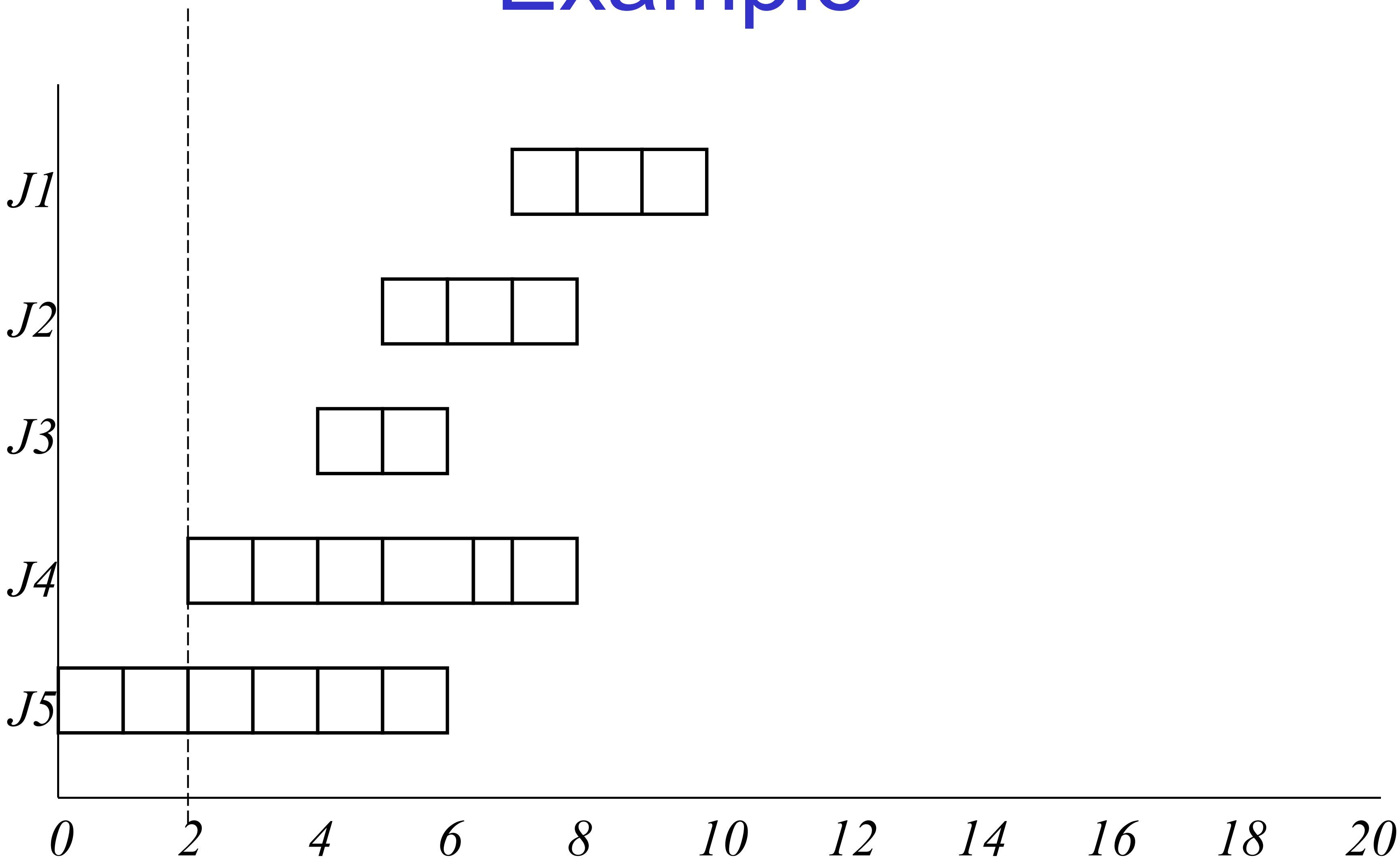

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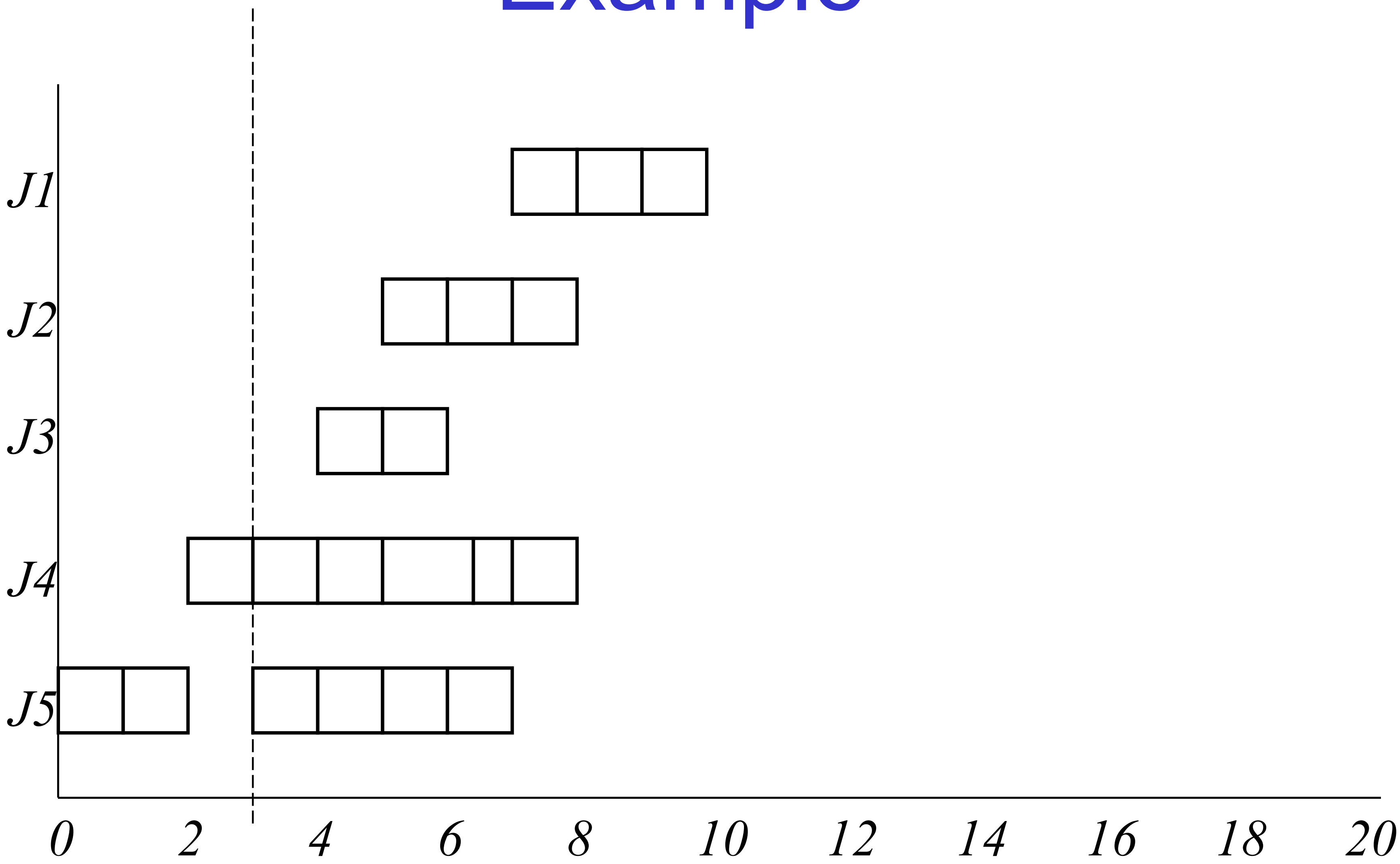

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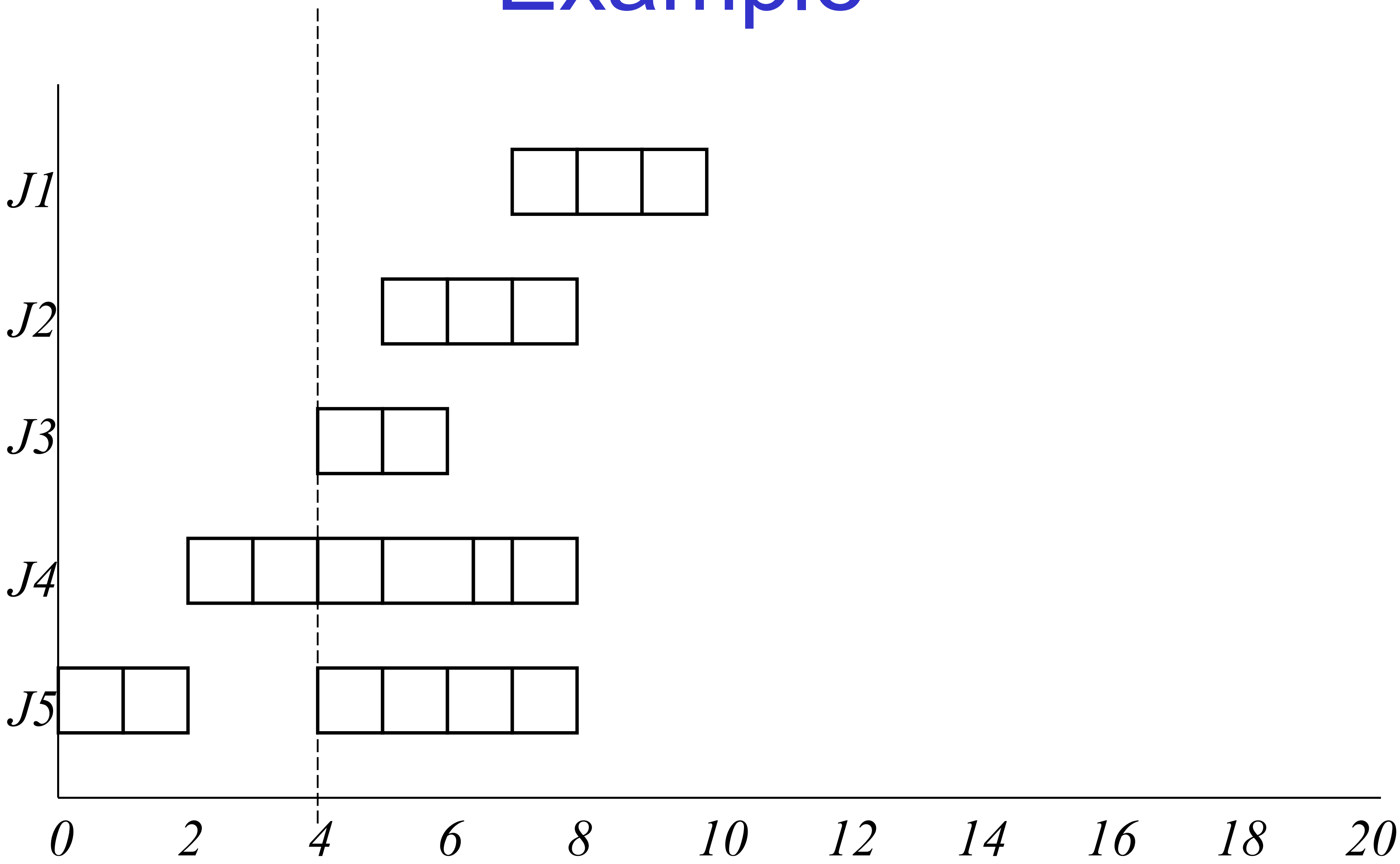

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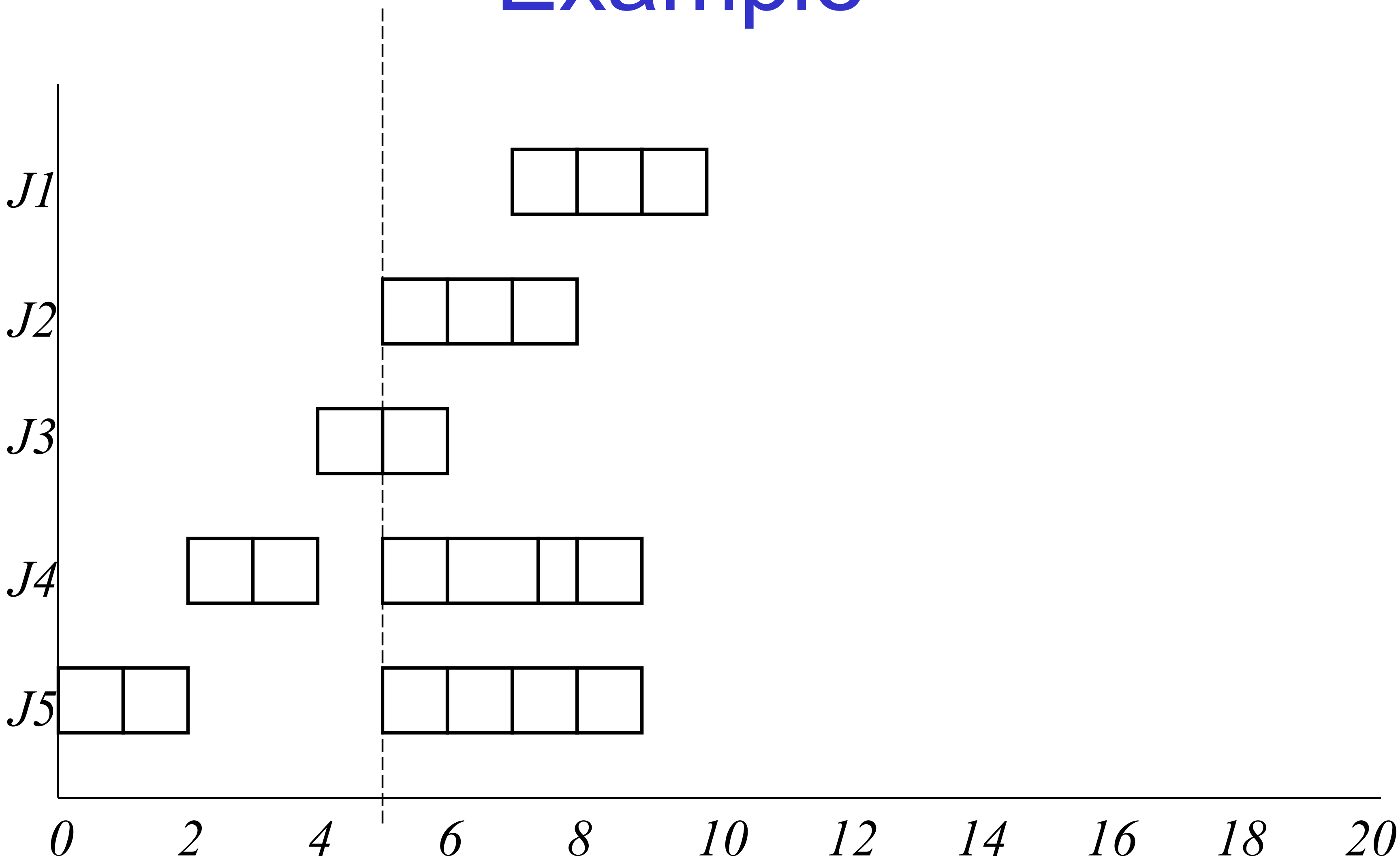

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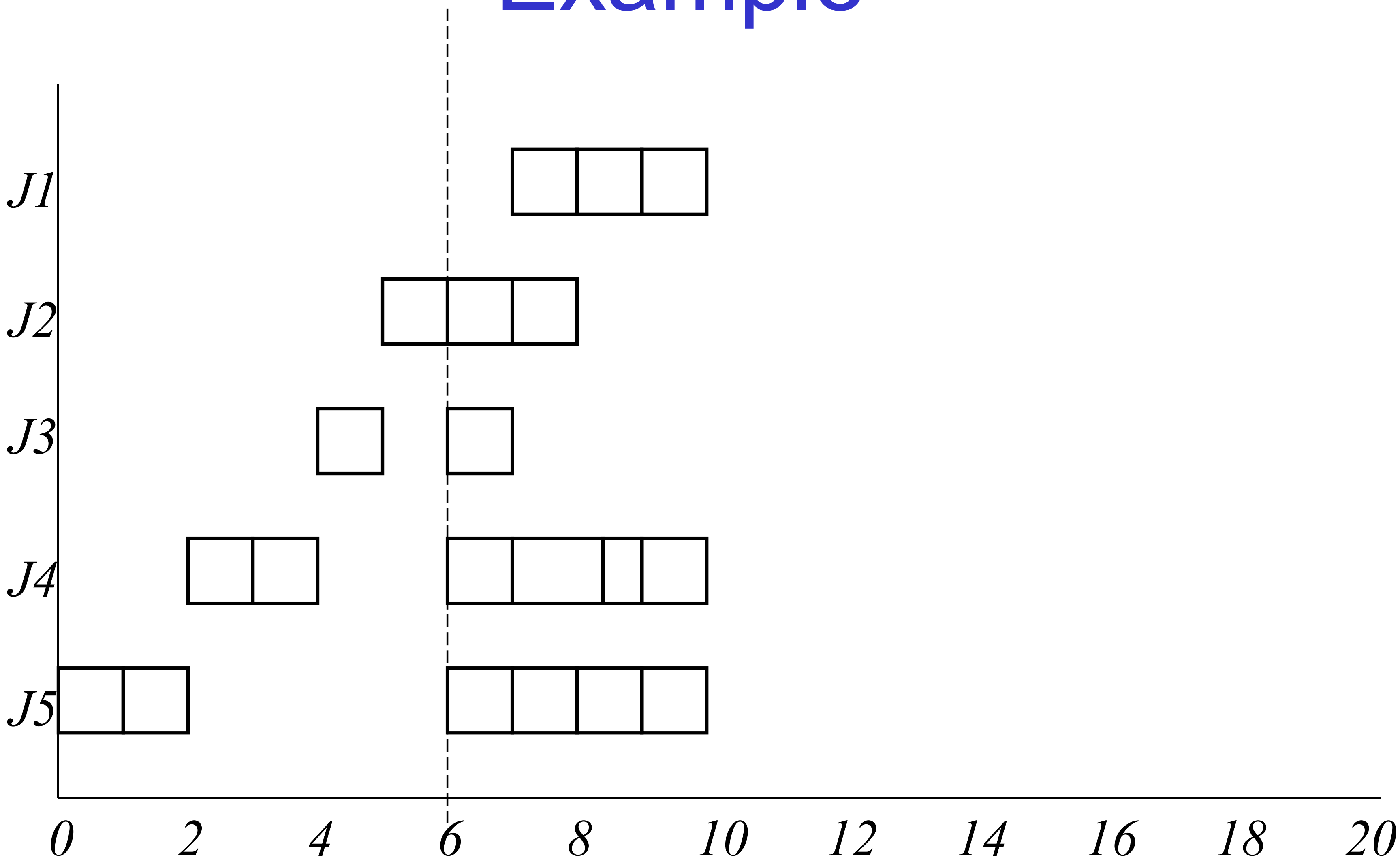

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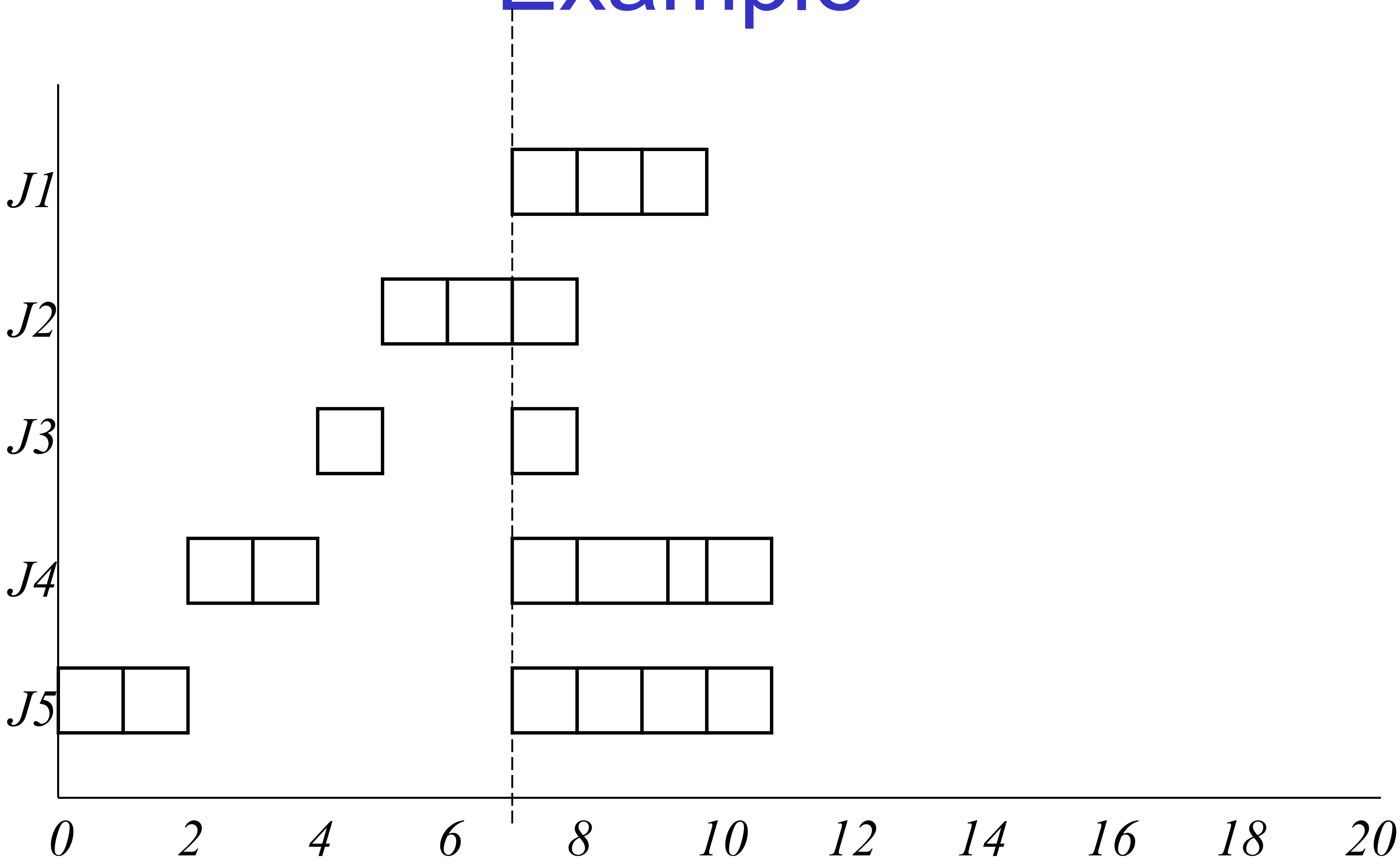

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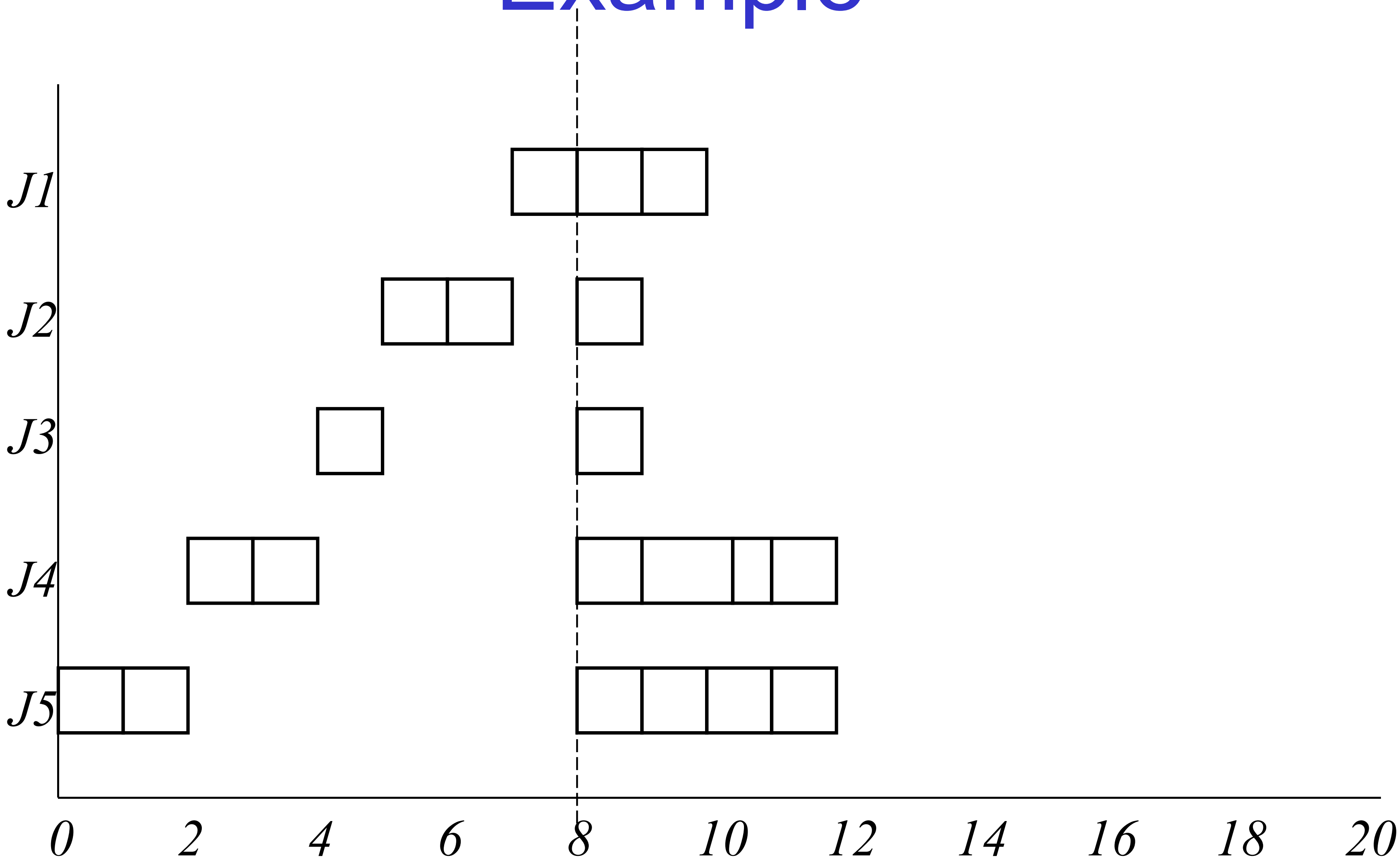

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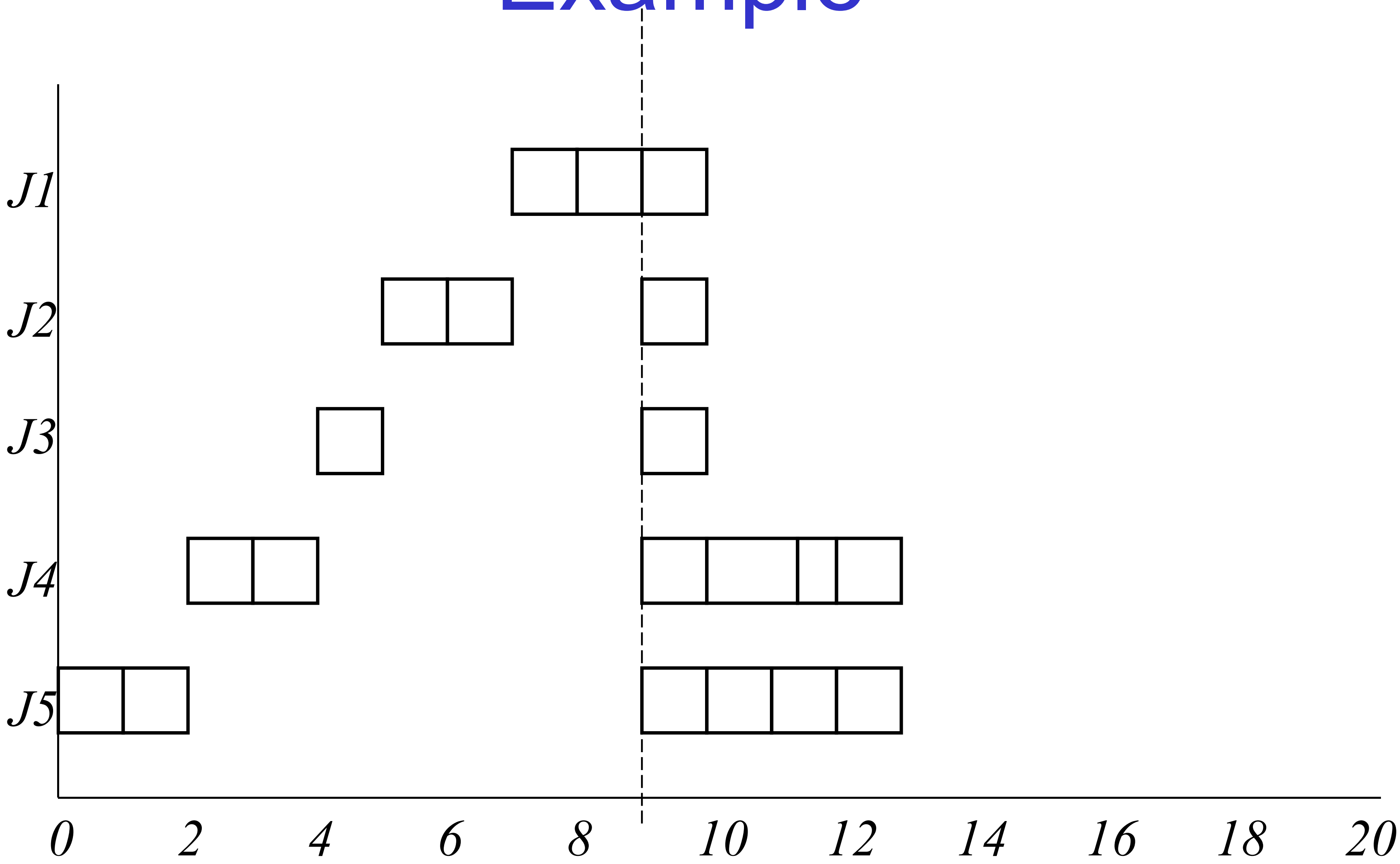

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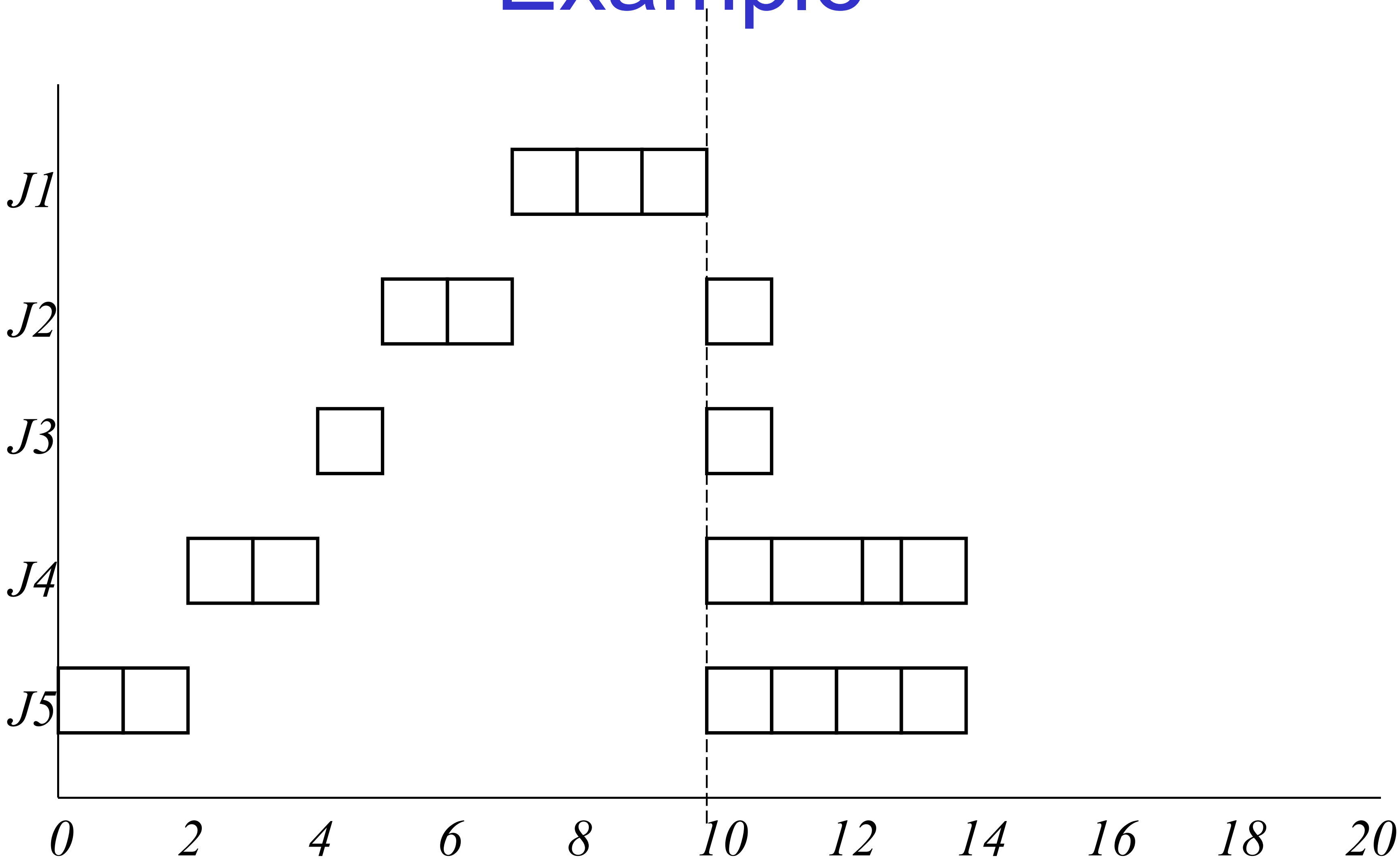

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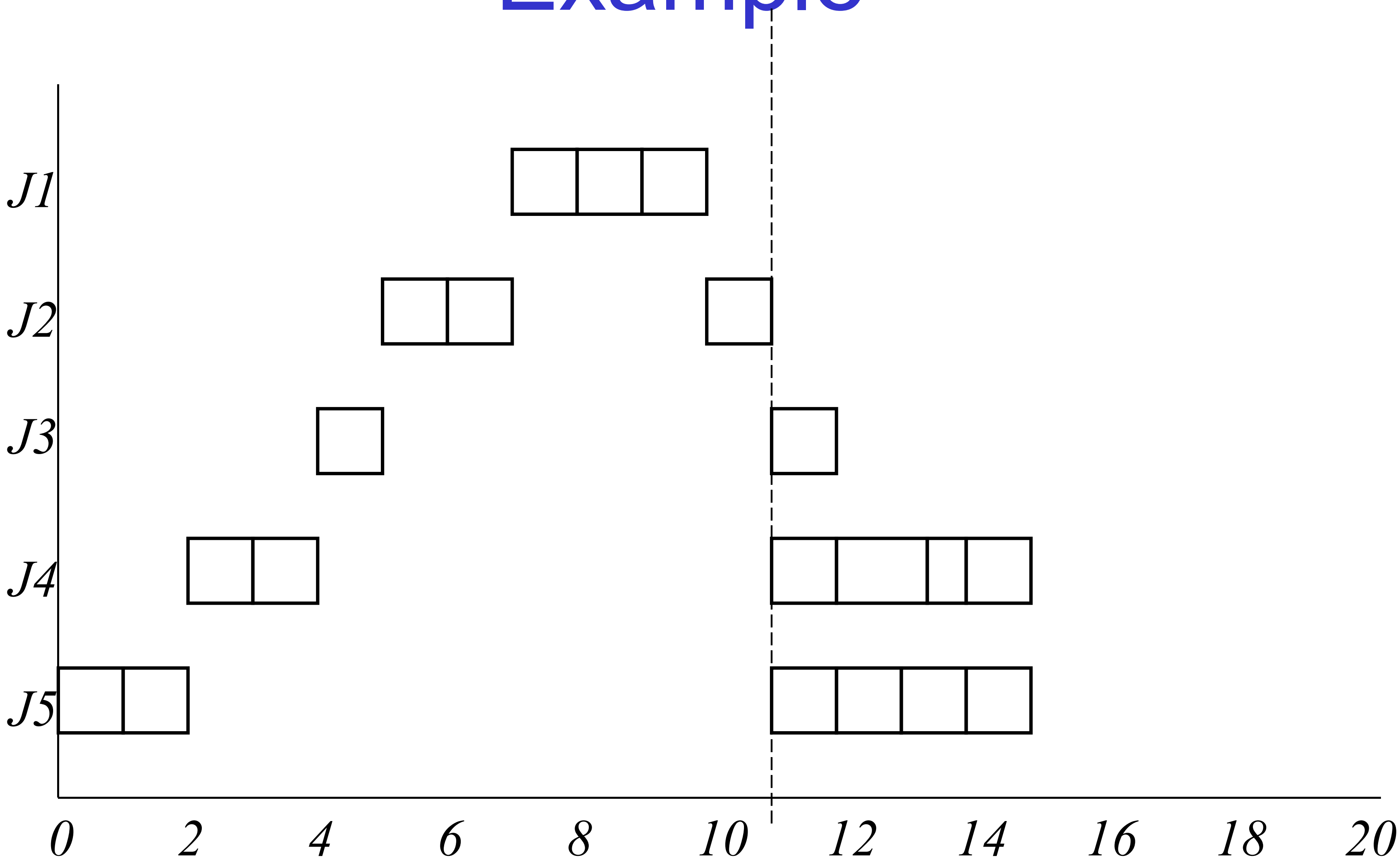

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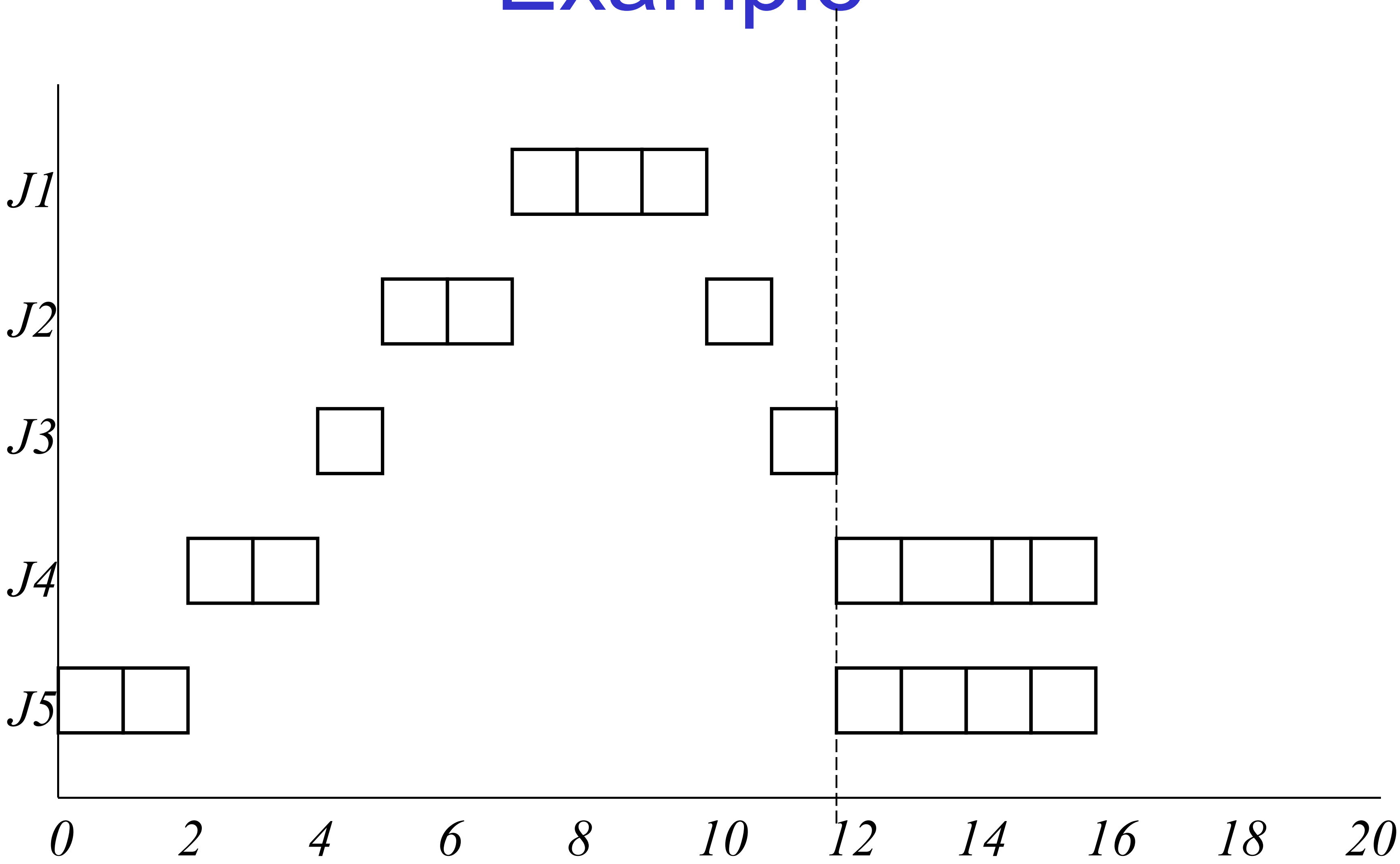

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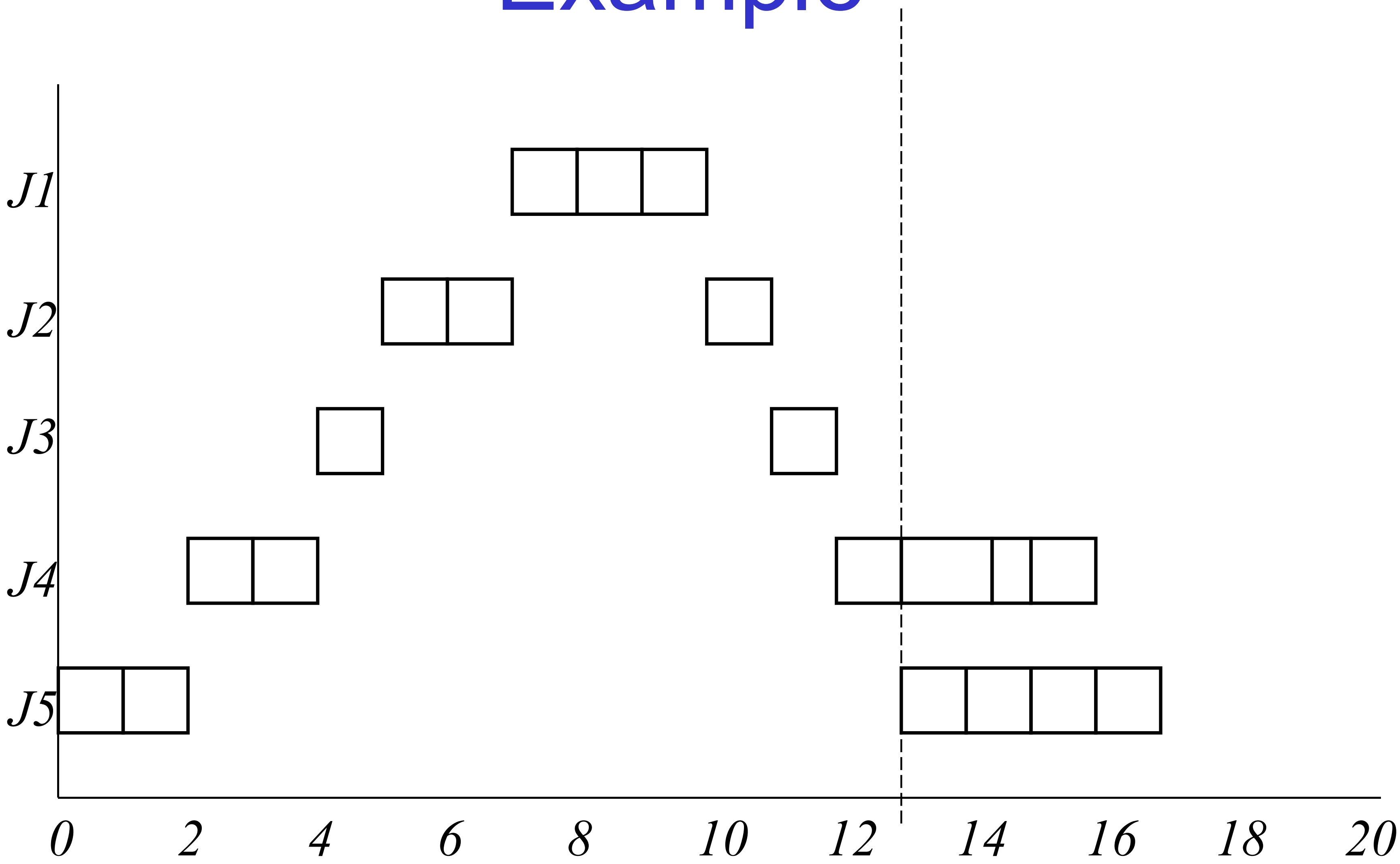

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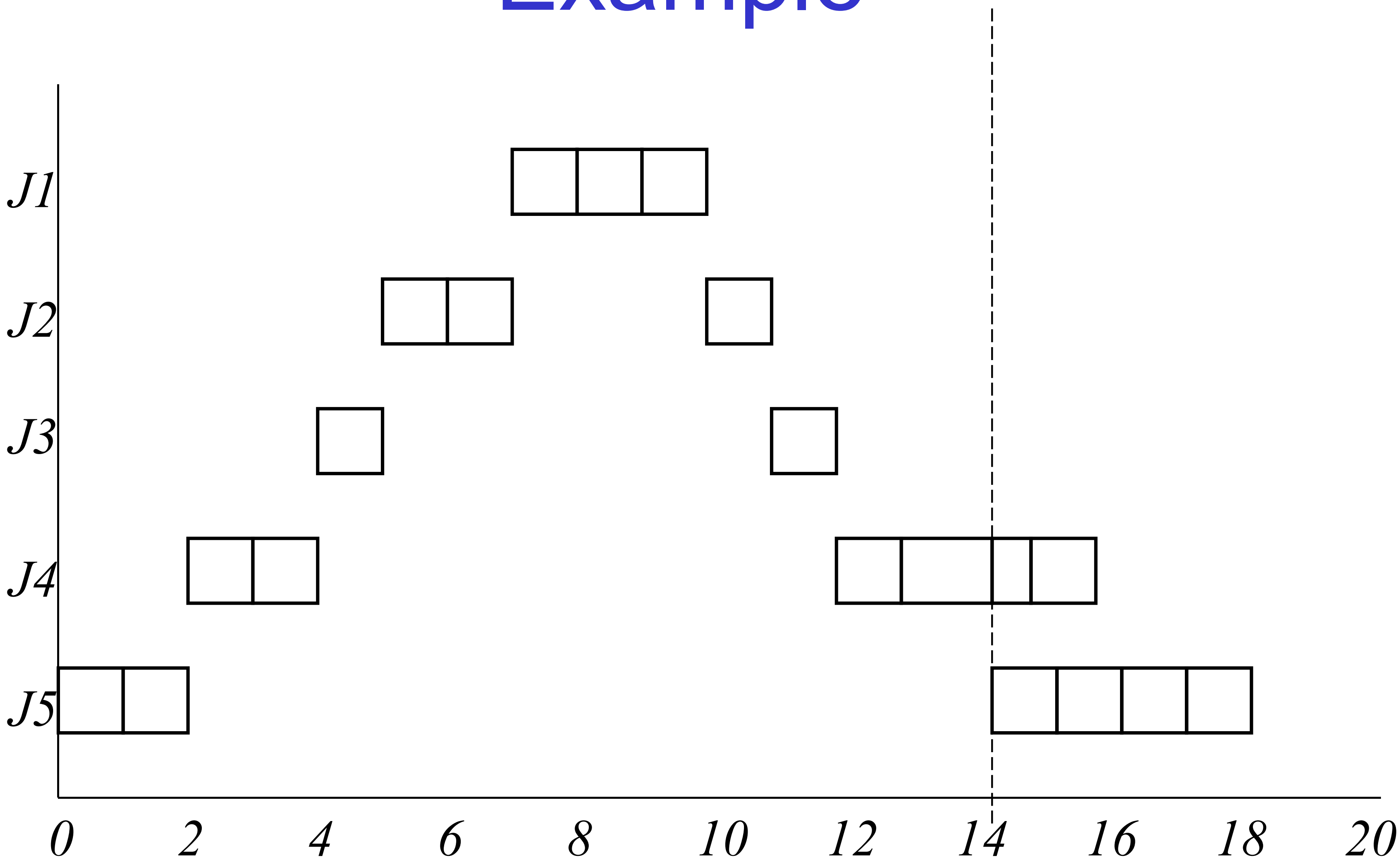

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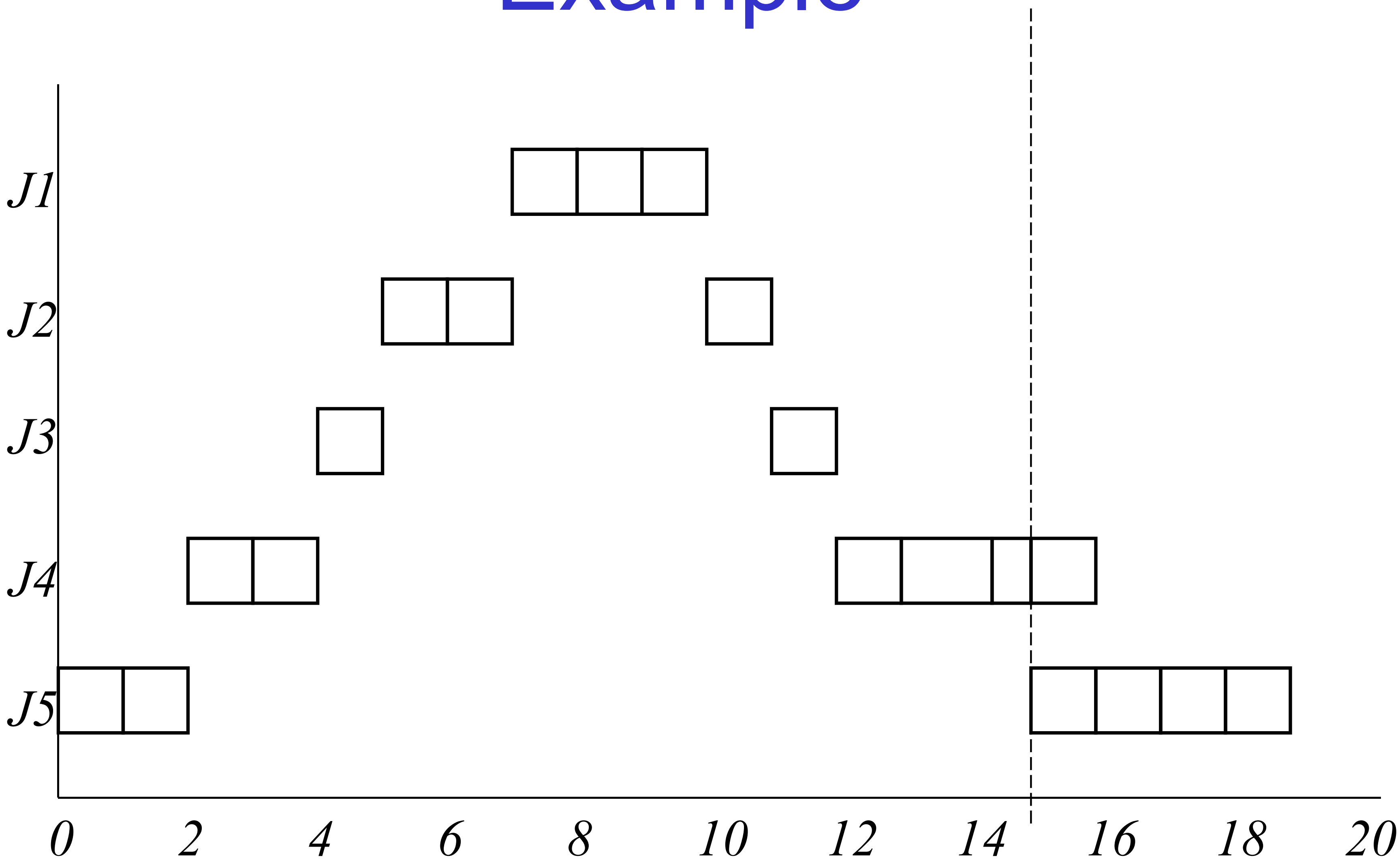

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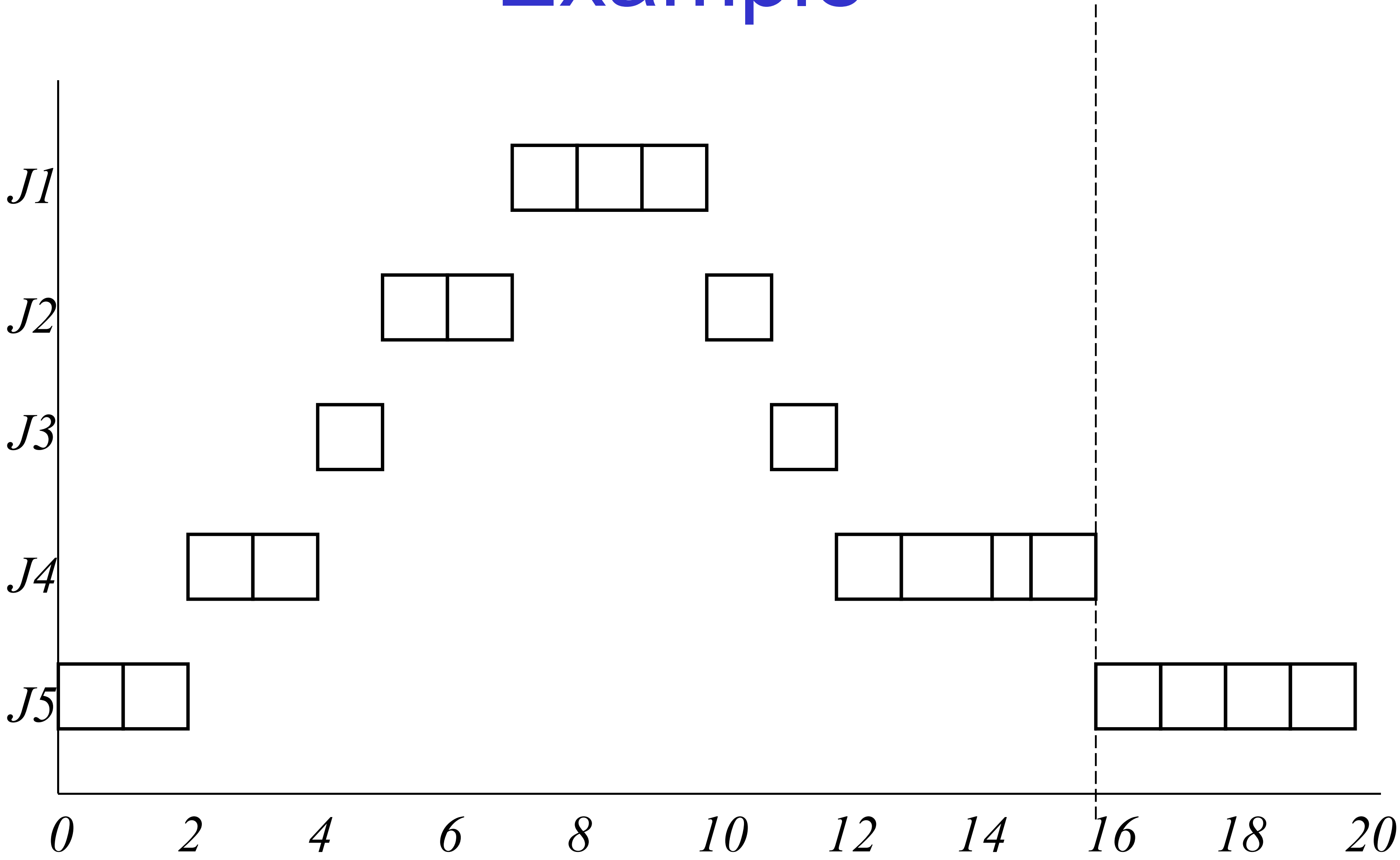

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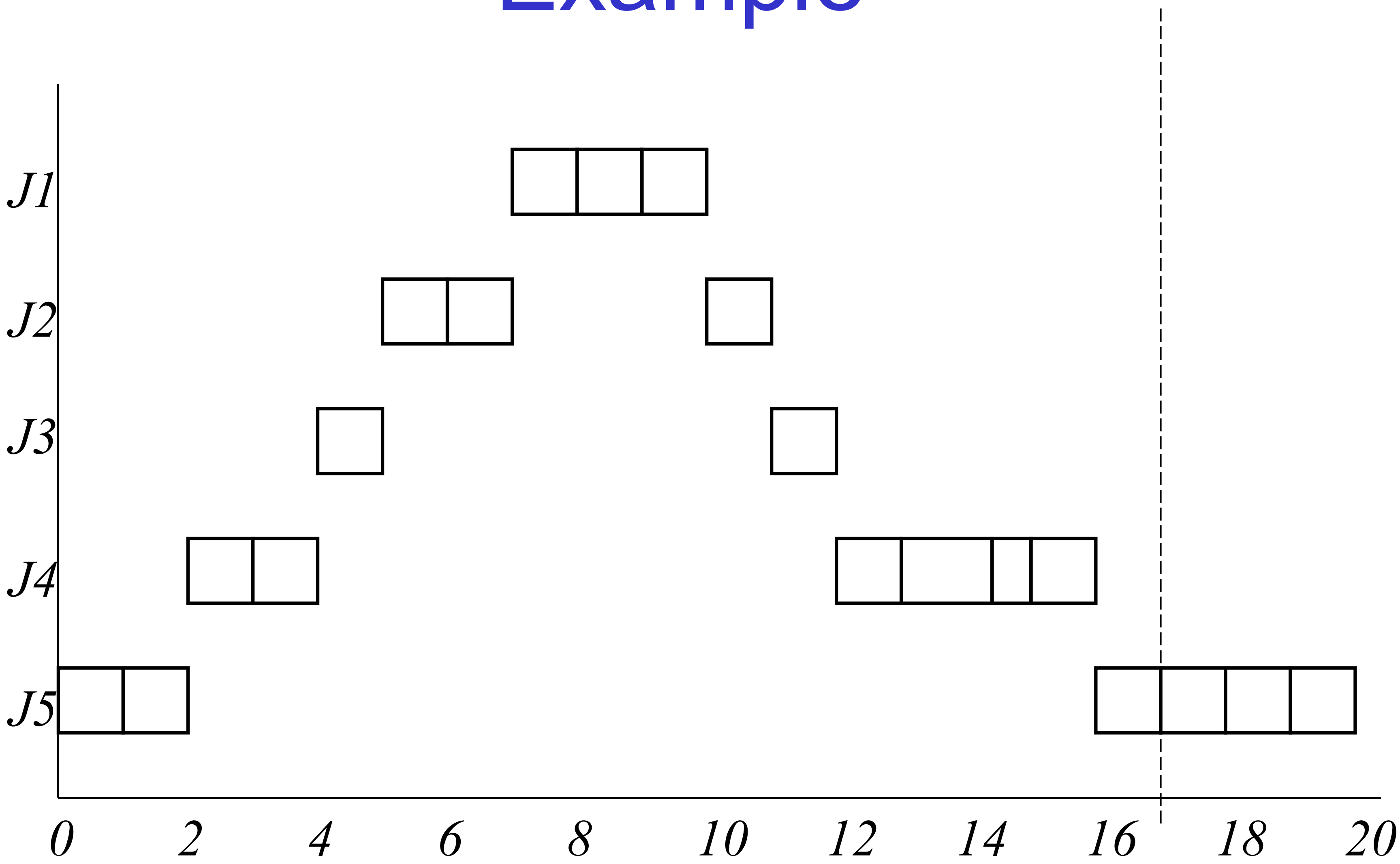

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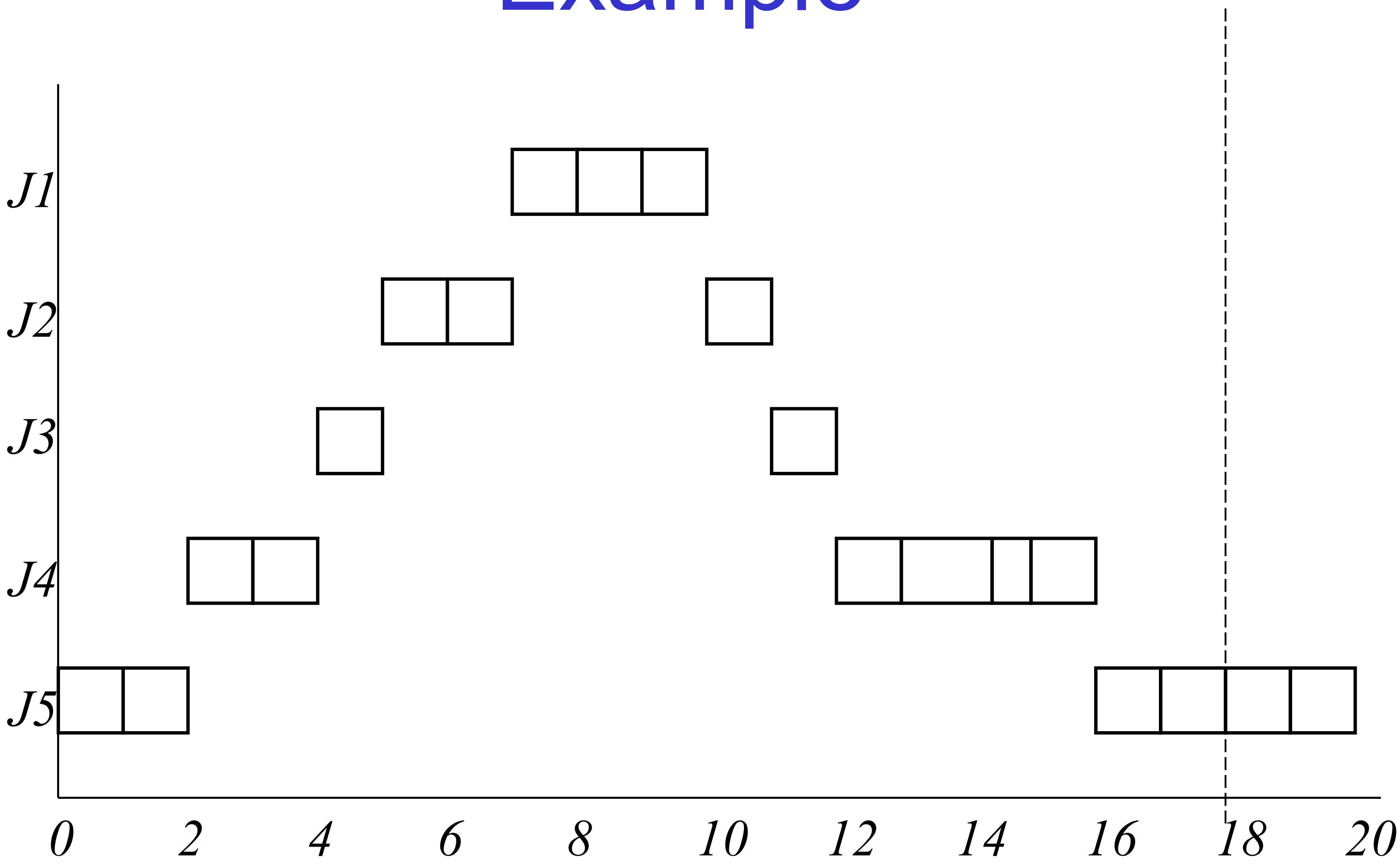

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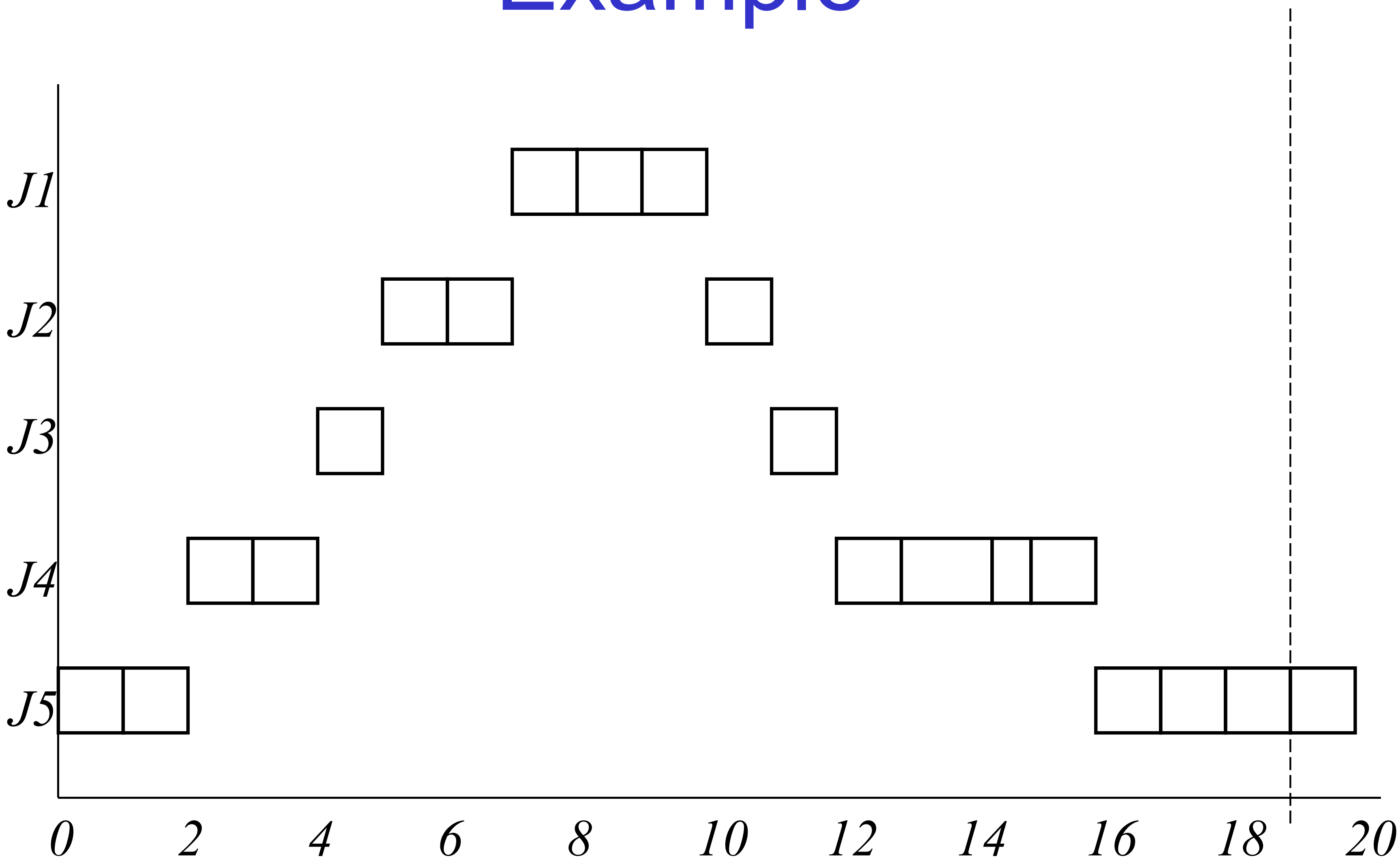

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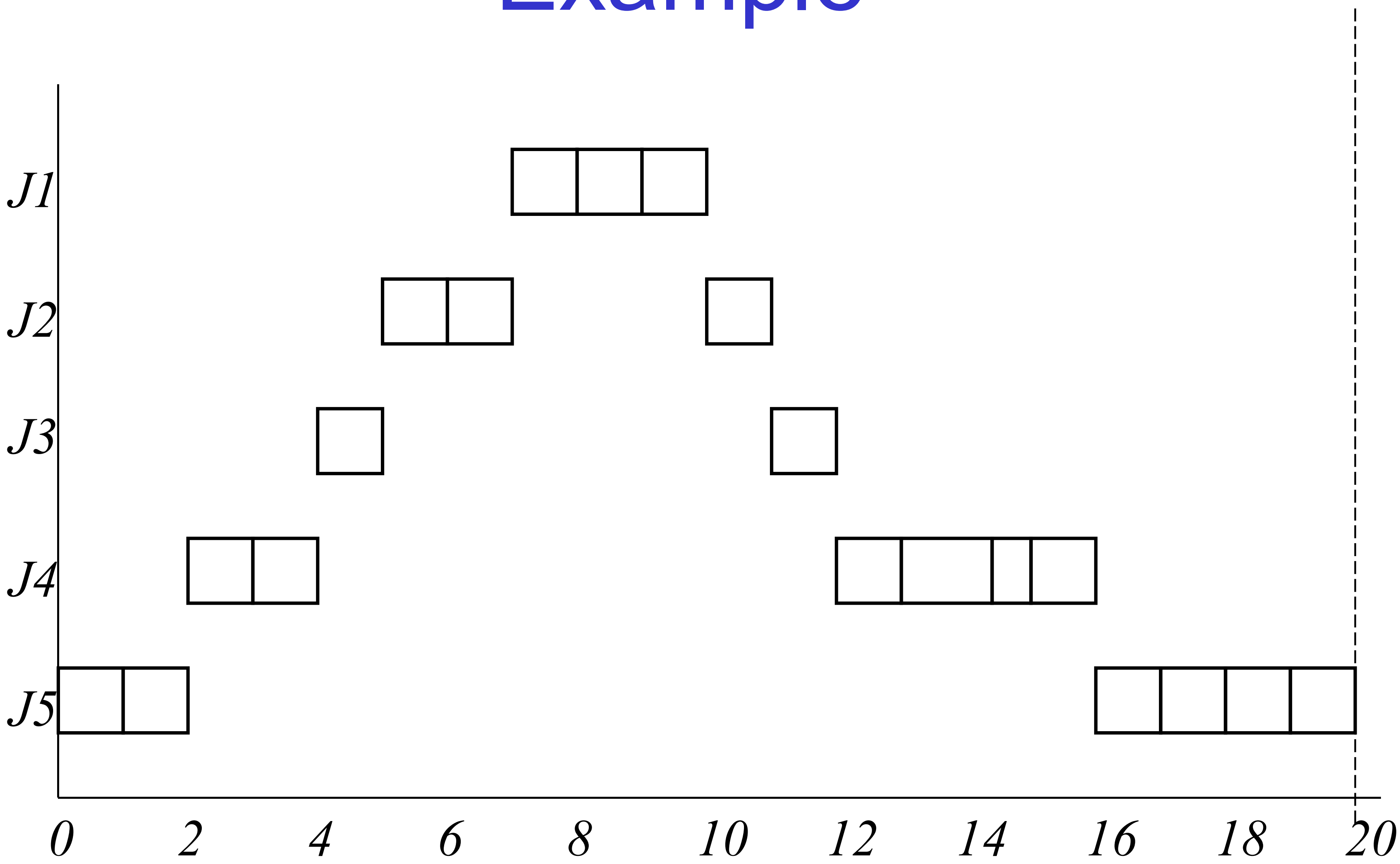
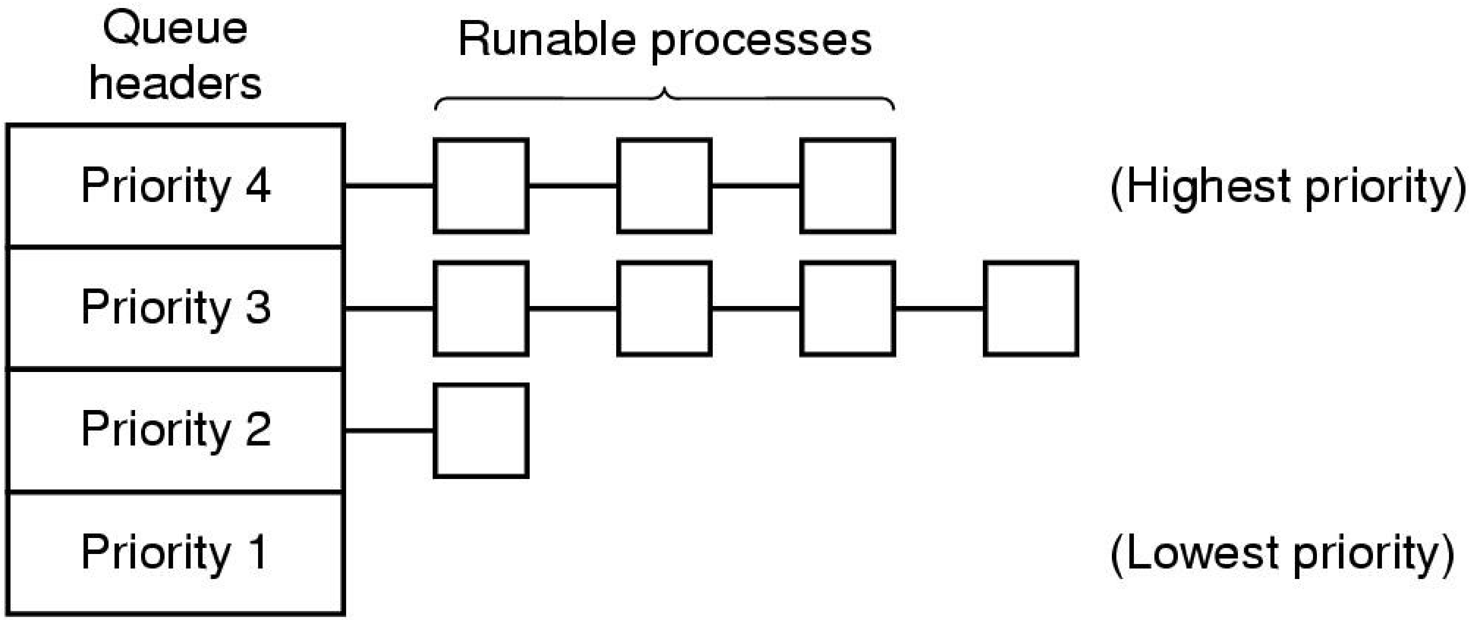


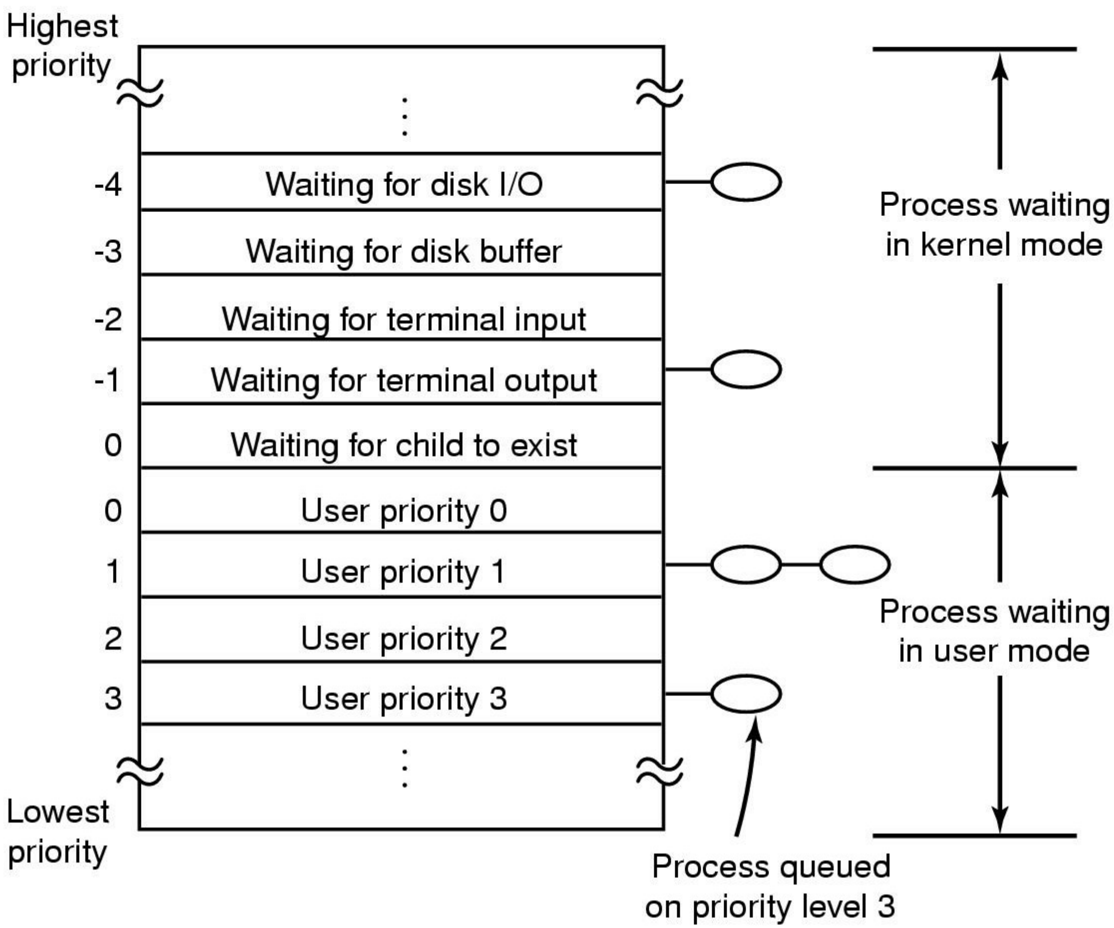
Priorities



- Usually implemented by multiple priority queues, with round robin on each queue
- Con
  - Low priorities can starve
    - Need to adapt priorities periodically
      - Based on ageing or execution history

Traditional UNIX Scheduler

- Two-level scheduler
  - High-level scheduler schedules processes between memory and disk
  - Low-level scheduler is CPU scheduler
    - Based on a multi-level queue structure with round robin at each level



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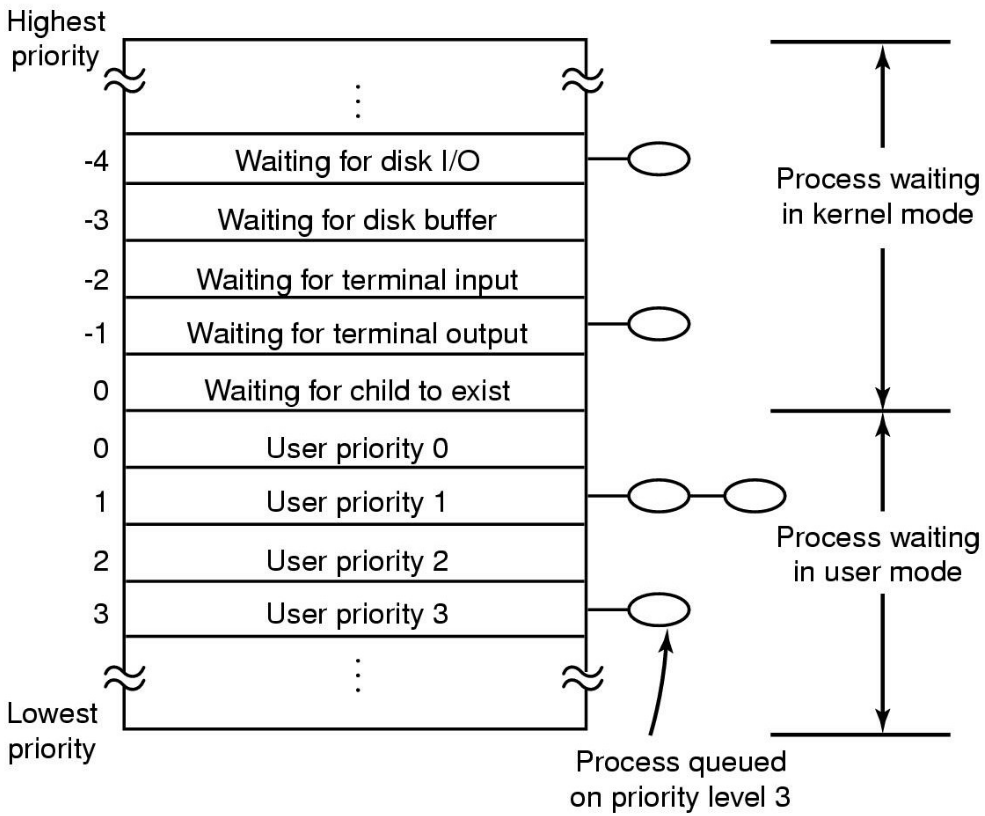
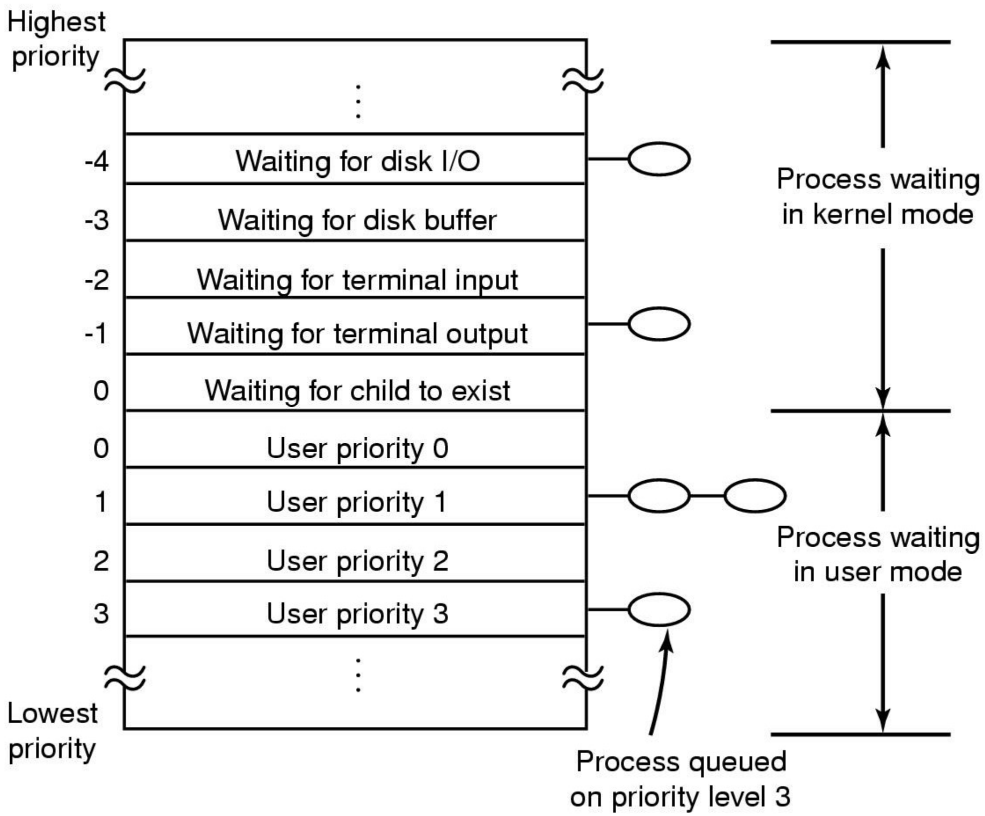
Traditional UNIX Scheduler

- The highest priority (lower number) is scheduled
- Priorities are re-calculated once per second, and re-inserted in appropriate queue
  - Avoid starvation of low priority threads
  - Penalise CPU-bound threads



Traditional UNIX Scheduler

- *Priority = CPU_usage +nice +base*
  - *CPU_usage* = number of clock ticks
    - Decays over time to avoid permanently penalising the process
  - *Nice* is a value given to the process by a user to permanently boost or reduce its priority
    - Reduce priority of background jobs
  - *Base* is a set of hardwired, negative values used to boost priority of I/O bound system activities
    - Swapper, disk I/O, Character I/O

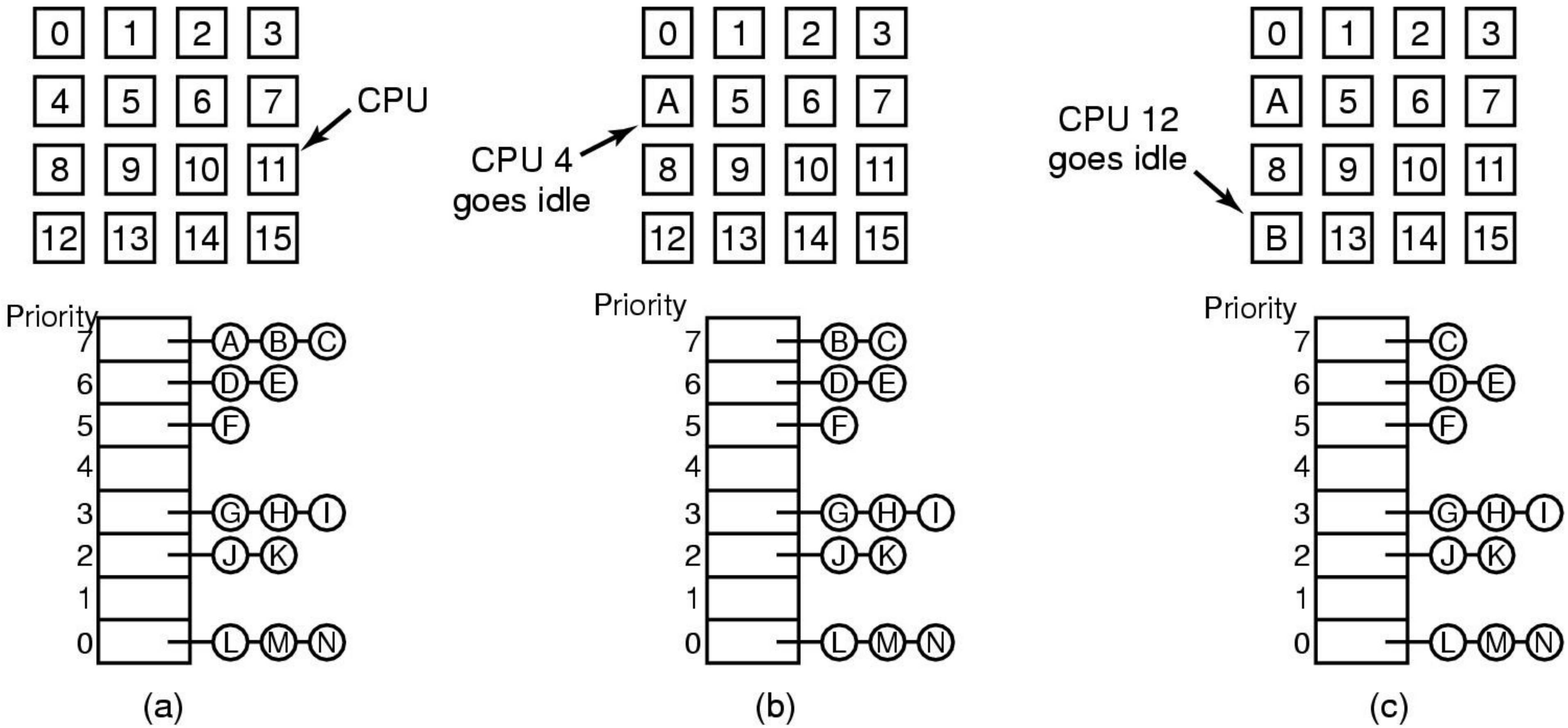


Multiprocessor Scheduling

- Given *X* processes (or threads) and *Y* CPUs,
  - how do we allocate them to the CPUs

A Single Shared Ready Queue

- When a CPU goes idle, it take the highest priority process from the shared ready queue



Single Shared Ready Queue

- Pros
  - Simple
  - Automatic load balancing
- Cons
  - Lock contention on the ready queue can be a major bottleneck
    - Due to frequent scheduling or many CPUs or both
  - Not all CPUs are equal
    - The last CPU a process ran on is likely to have more related entries in the cache.

Affinity Scheduling

- Basic Idea
  - Try hard to run a process on the CPU it ran on last time

- One approach: *Multiple Queue Multiprocessor Scheduling*

Multiple Queue SMP Scheduling

- Each CPU has its own ready queue
- Coarse-grained algorithm assigns processes to CPUs
  - Defines their affinity, and roughly balances the load
- The bottom-level fine-grained scheduler:
  - Is the frequently invoked scheduler (e.g. on blocking on I/O, a lock, or exhausting a timeslice)
  - Runs on each CPU and selects from its own ready queue
    - Ensures affinity
  - If nothing is available from the local ready queue, it runs a process from another CPUs ready queue rather than go idle
    - Termed “Work stealing”

Multiple Queue SMP Scheduling

- Pros
  - No lock contention on per-CPU ready queues in the (hopefully) common case
  - Load balancing to avoid idle queues
  - Automatic affinity to a single CPU for more cache friendly behaviour

Real-time Scheduling

Real Time Scheduling

- Correctness of the system may depend not only on the logical result of the computation but also ***on the time when*** these results are produced, e.g.
  - Tasks attempt to control events or to react to events that take place in the outside world
  - These external events occur in *real time* and processing must be able to keep up
  - Processing must happen in a timely fashion,
    - neither too late, nor too early

Real Time System (RTS)

- RTS accepts an activity *A* and guarantees its requested (timely) behaviour *B* if and only if
  - RTS finds a *schedule*
    - that includes all already accepted activities *Ai* and the new activity *A*,
    - that guarantees all requested timely behaviour *Bi* and *B*, and
    - that can be enforced by the RTS.
- Otherwise, RT system rejects the new activity *A.*

Typical Real Time Systems

- Control of laboratory experiments
- Robotics
- (Air) Traffic control
- Controlling Cars / Trains/ Planes
- Telecommunications
- Medical support (Remote Surgery, Emergency room)
- Multi-Media

• Remark: Some applications may have only **soft-real time** requirements, but some have really **hard real-time** requirements

Hard-Real Time Systems

- Requirements:
  - **Must *always* meet all deadlines** (time guarantees)
  - You have to guarantee that in any situation these applications are done in time, otherwise dangerous things may happen

Examples:

1. If the landing of a fly-by-wire jet cannot react to sudden side-winds within some milliseconds, an accident might occur.
2. An airbag system or the ABS has to react within milliseconds

Soft-Real Time Systems

Requirements:

Must *mostly* meet all deadlines, e.g. 99.9% of cases

Examples:

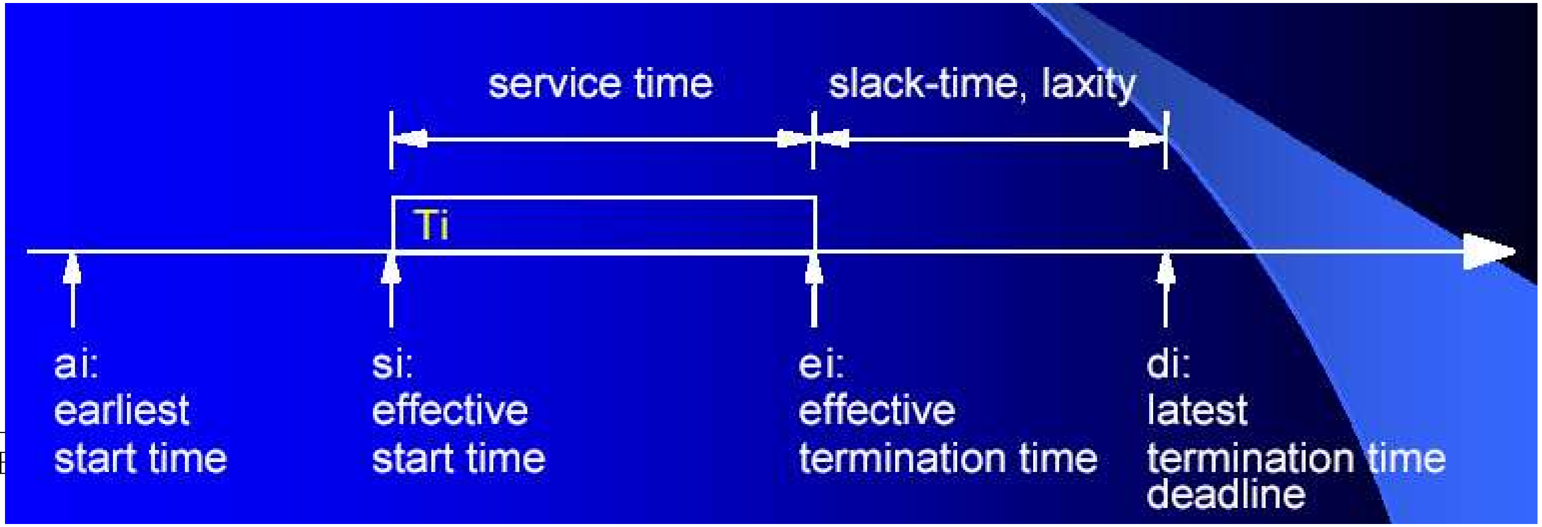
1. Multi-media: 100 frames per day might be dropped (late)
2. Car navigation: 5 late announcements per week are acceptable
3. Washing machine: washing 10 sec over time might occur once in 10 runs, 50 sec once in 100 runs.

Predictability, not Speed

- Real time systems are NOT necessarily fast
- Real time systems can be slow, as long as they are predictably so.
  - It does not matter how fast they are, as long as they meet their deadlines.

Properties of Real-Time Tasks

- To schedule a real time task, its properties must be known *a priori*
- The most relevant properties are
  - Arrival time (or release time) a_i
  - Maximum execution time (service time)
  - Deadline d_i



Categories of Real time tasks

- Periodic
  - Each task is repeated at a regular interval
  - Max execution time is the same each period
  - Arrival time is usually the start of the period
  - Deadline is usually the end
- Aperiodic (and sporadic)
  - Each task can arrive at any time (may have minimum inter-arrival time)

Real-time scheduling approaches

- Static table-driven scheduling
  - Given a set of tasks and their properties, a schedule (table) is precomputed offline.
    - Used for periodic task set
    - Requires entire schedule to be recomputed if we need to change the task set
- Static priority-driven scheduling
  - Given a set of tasks and their properties, each task is assigned a fixed priority
  - A preemptive priority-driven scheduler used in conjunction with the assigned priorities
    - Used for periodic task sets

Real-time scheduling approaches

- Dynamic scheduling
  - Task arrives prior to execution
  - The scheduler determines whether the new task can be *admitted*
    - Can all other admitted tasks and the new task meet their deadlines?
      - If no, reject the new task
  - Can handle both *periodic* and *aperiodic* tasks

Scheduling in Real-Time Systems

- We will only consider periodic systems

Schedulable real-time system

- Given
  - *m* periodic events
  - event *i* occurs within period P_i and requires C_i seconds
- Then the load can only be handled if

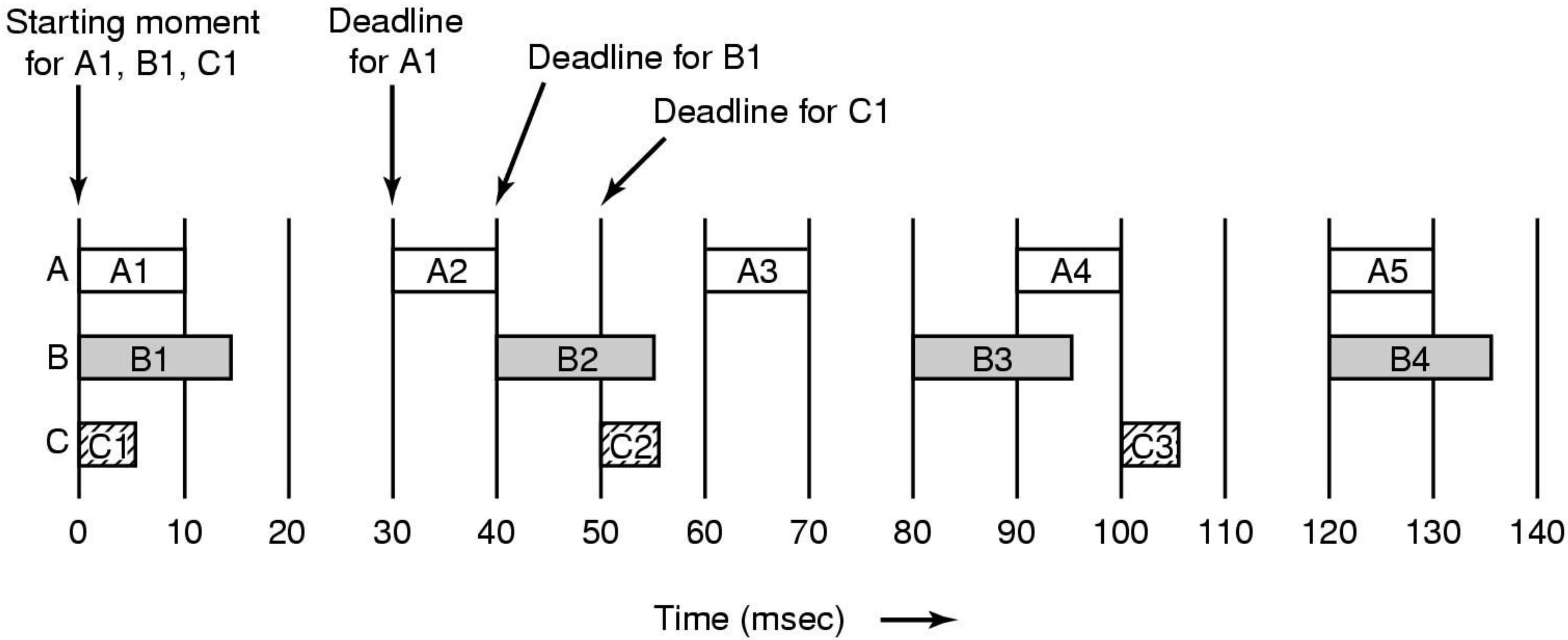
$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

Two Typical Real-time Scheduling Algorithms

- Rate Monotonic Scheduling
  - Static Priority priority-driven scheduling
  - Priorities are assigned based on the period of each task
    - The shorter the period, the higher the priority
- Earliest Deadline First Scheduling
  - The task with the earliest deadline is chosen next

A Scheduling Example

- Three periodic Tasks



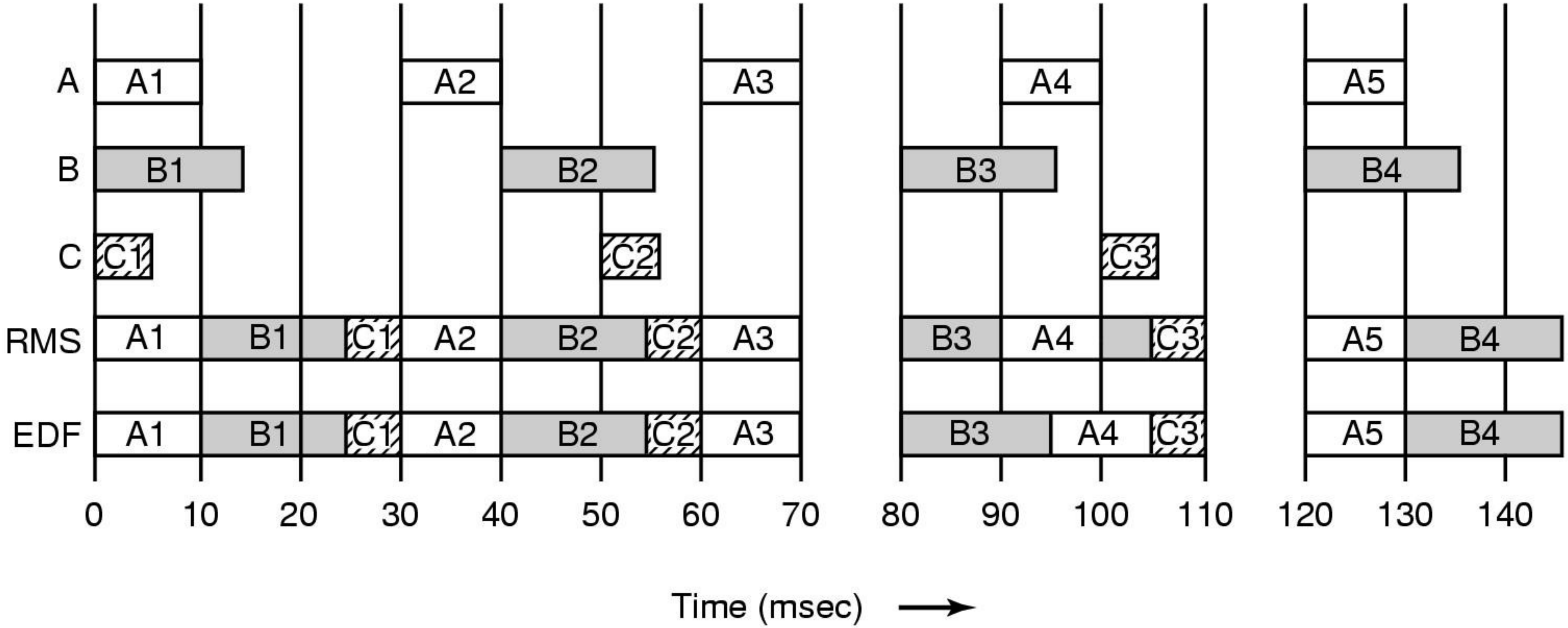
Is the Example Schedulable

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

$$\frac{10}{30} + \frac{15}{40} + \frac{5}{50} = 0.808$$

- YES

Two Schedules: RMS and EDF



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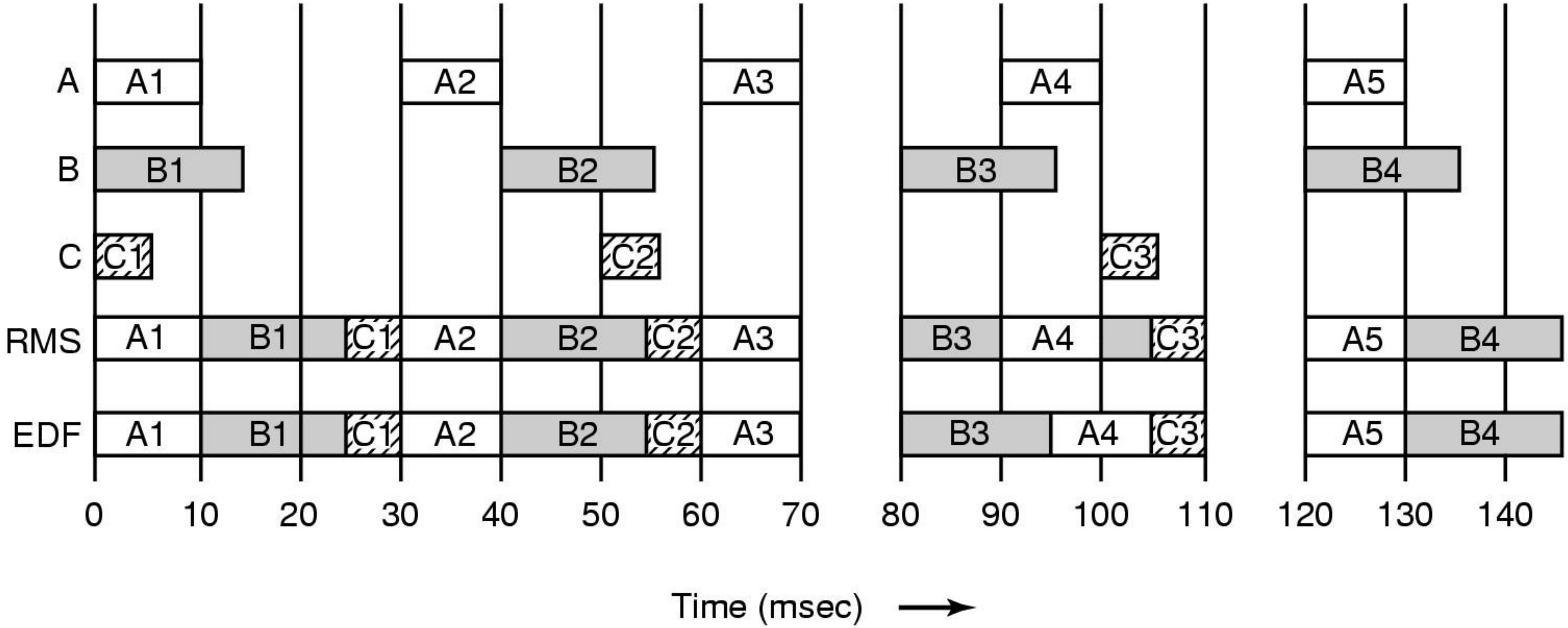
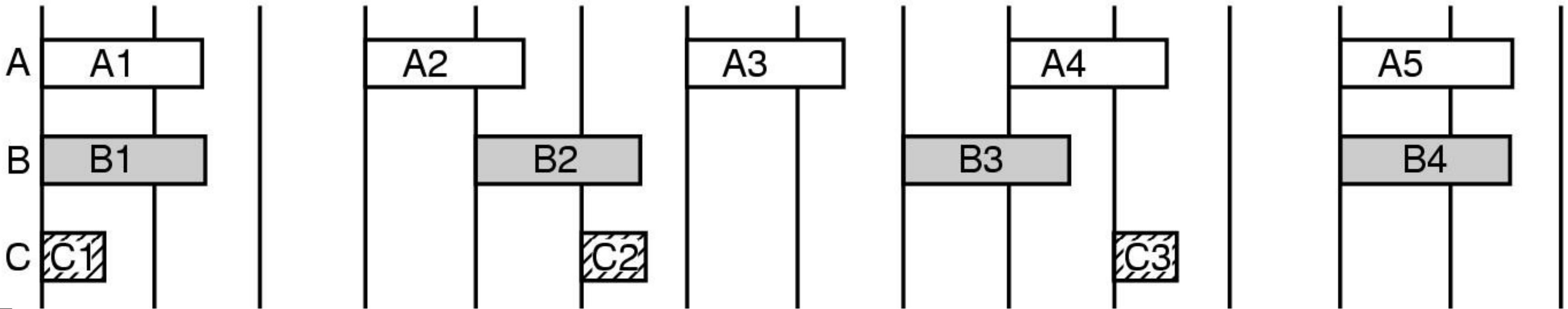
Two Schedules: RMS and EDF



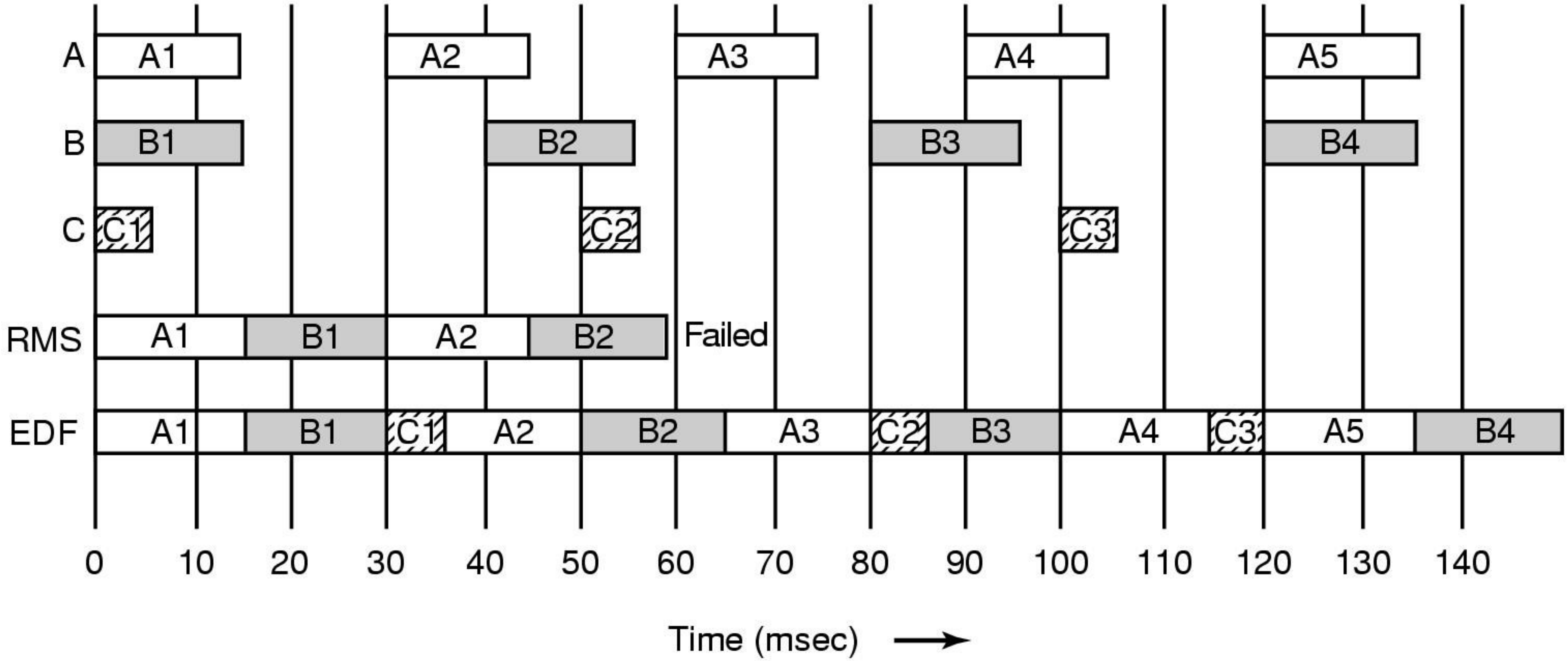
Let's Modify the Example Slightly

- Increase A's CPU requirement to 15 msec
- The system is still schedulable

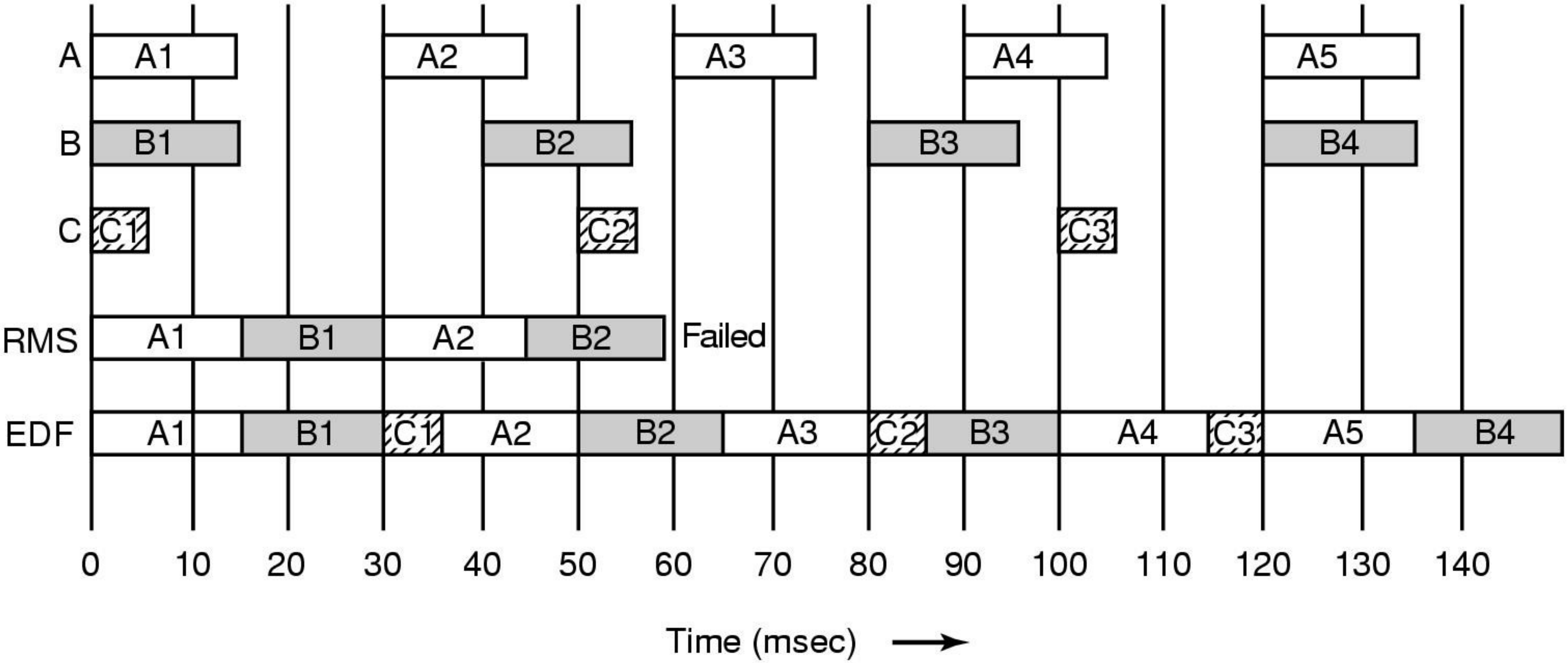
$$\frac{15}{30} + \frac{15}{40} + \frac{5}{50} = 0.975$$



RMS and EDF


A
B
C
A1
A2
A3
A4
A5
B1
B2
B3
B4
C1
C2
C3
RMS
A1
B1
A2
B2
Failed
EDF
A1
B1
C1
A2
B2
A3
C2
B3
A4
C3
A5
B4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (msec)

RMS and EDF


A
A1
A2
A3
A4
A5
B
B1
B2
B3
B4
C
C1
C2
C3
RMS
A1
B1
A2
B2
Failed
EDF
A1
B1
C1
A2
B2
A3
C2
B3
A4
C3
A5
B4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (msec)

RMS failed, why?

- It has been proven that RMS is only guaranteed to work if the CPU utilisation is not too high
  - For three tasks, CPU utilisation must be less than 0.780
    - We were lucky with our original example

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq m(2^{1/m} - 1)$$

EDF

- EDF always works for any schedulable set of tasks, i.e. up to 100% CPU utilisation

- Summary
  - If CPU utilisation is low (usual case, due to safety factor in estimating execution times)
    - Can use RMS which is simple and easy to implement
  - If CPU utilisation is high
    - Must use EDF