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.*

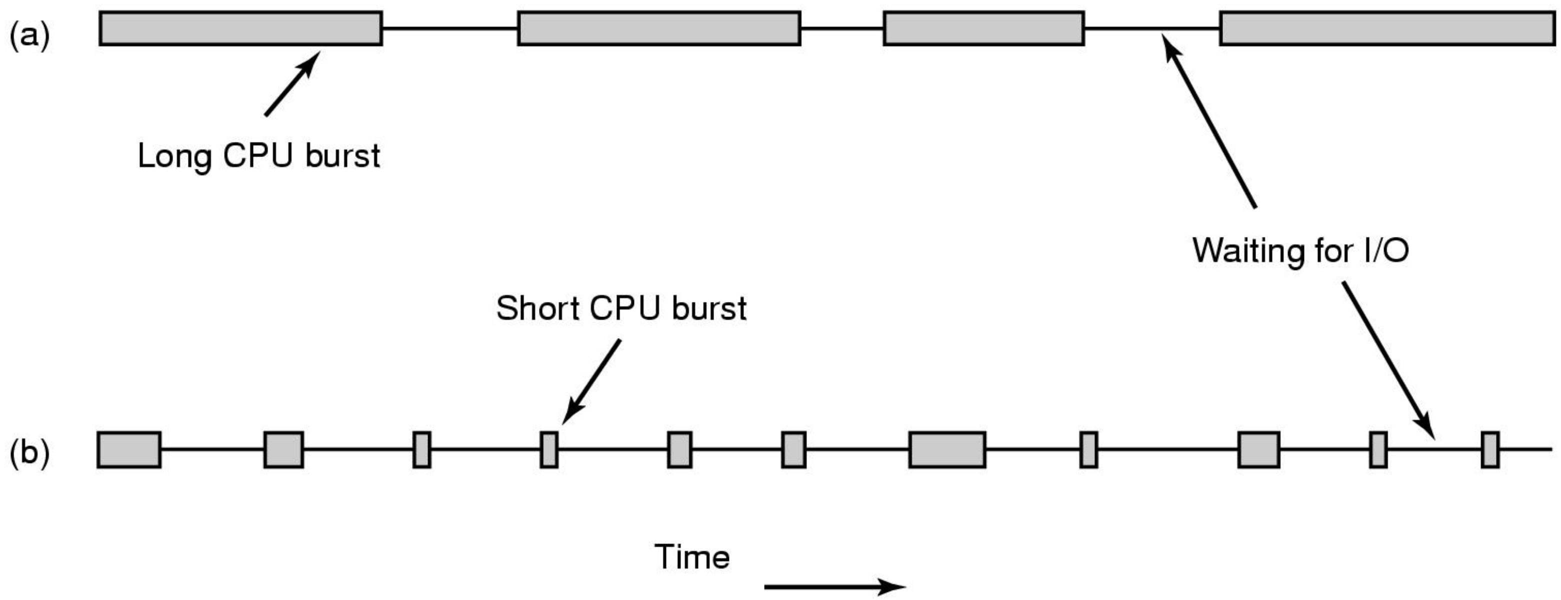
Is scheduling important?

- 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?

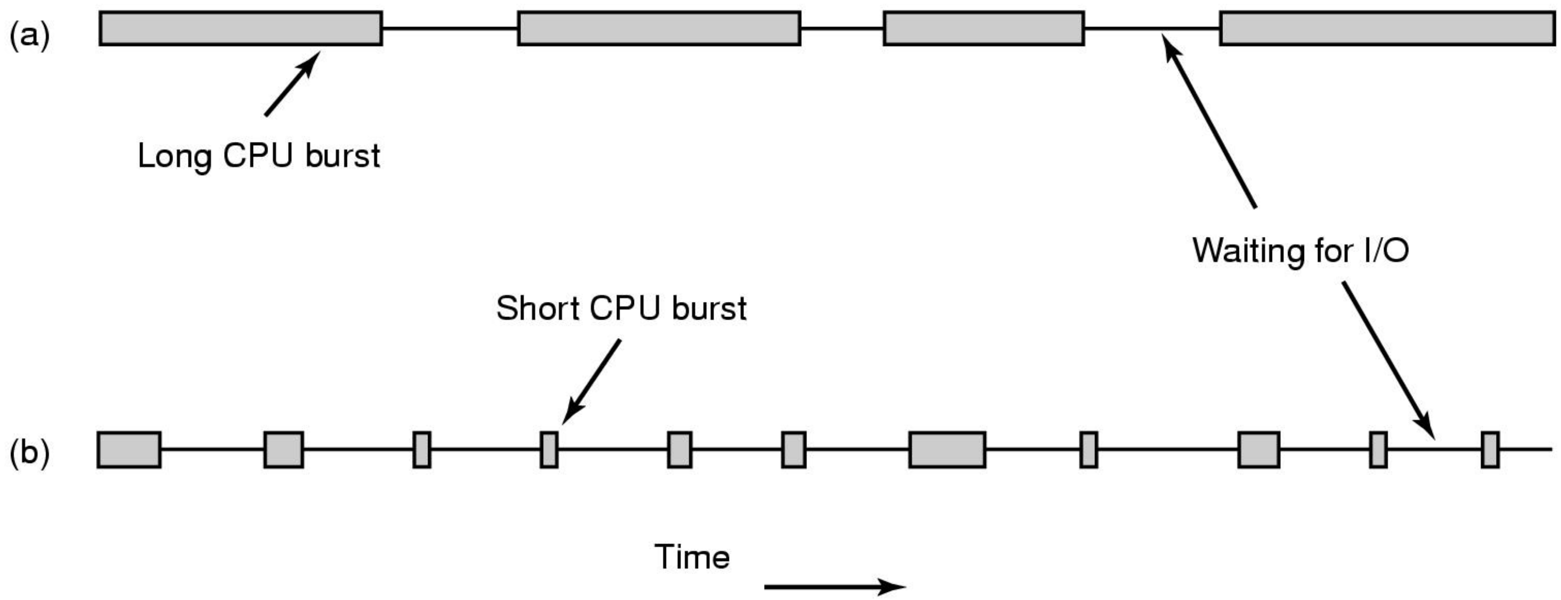
- It is in most realistic scenarios
  - Multitasking/Multi-user System
    - Example
      - Email daemon takes 2 seconds to process an email
      - User clicks button on application.
    - Scenario 1
      - Run daemon, then application
        - » System appears really sluggish to the user
    - Scenario 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

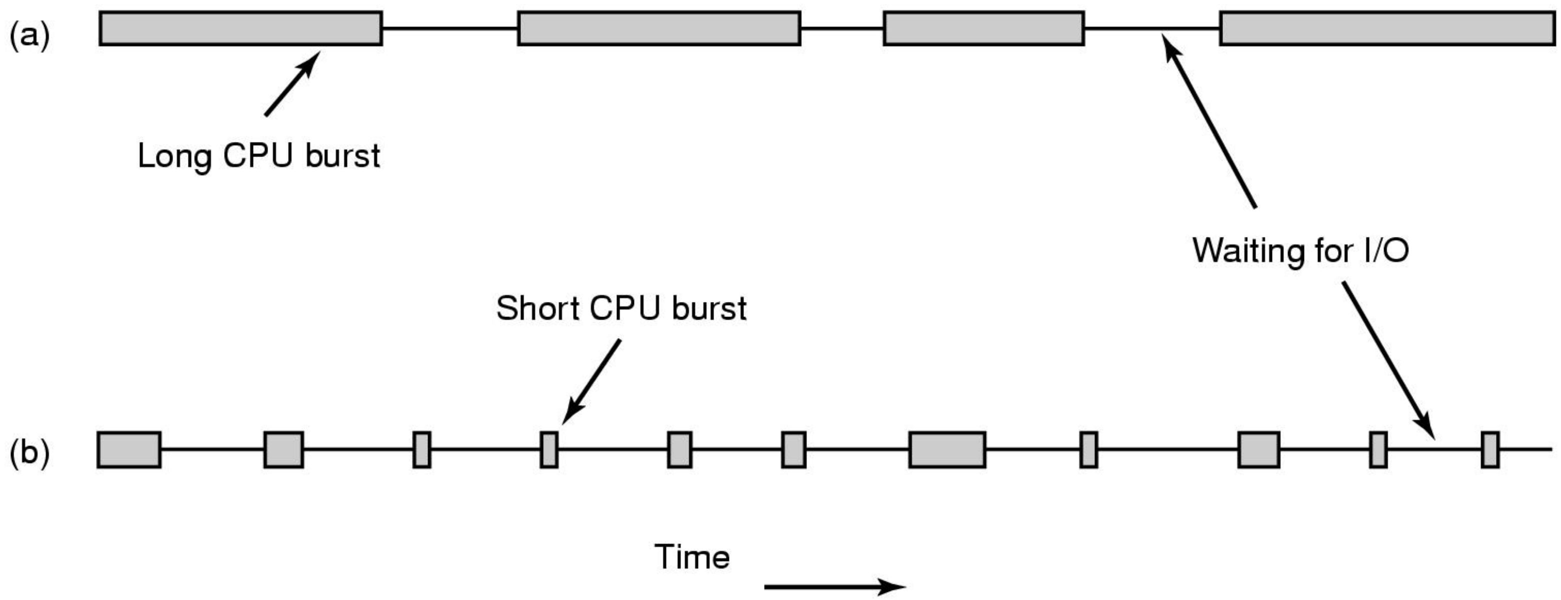
Application Behaviour



a) CPU-Bound process

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

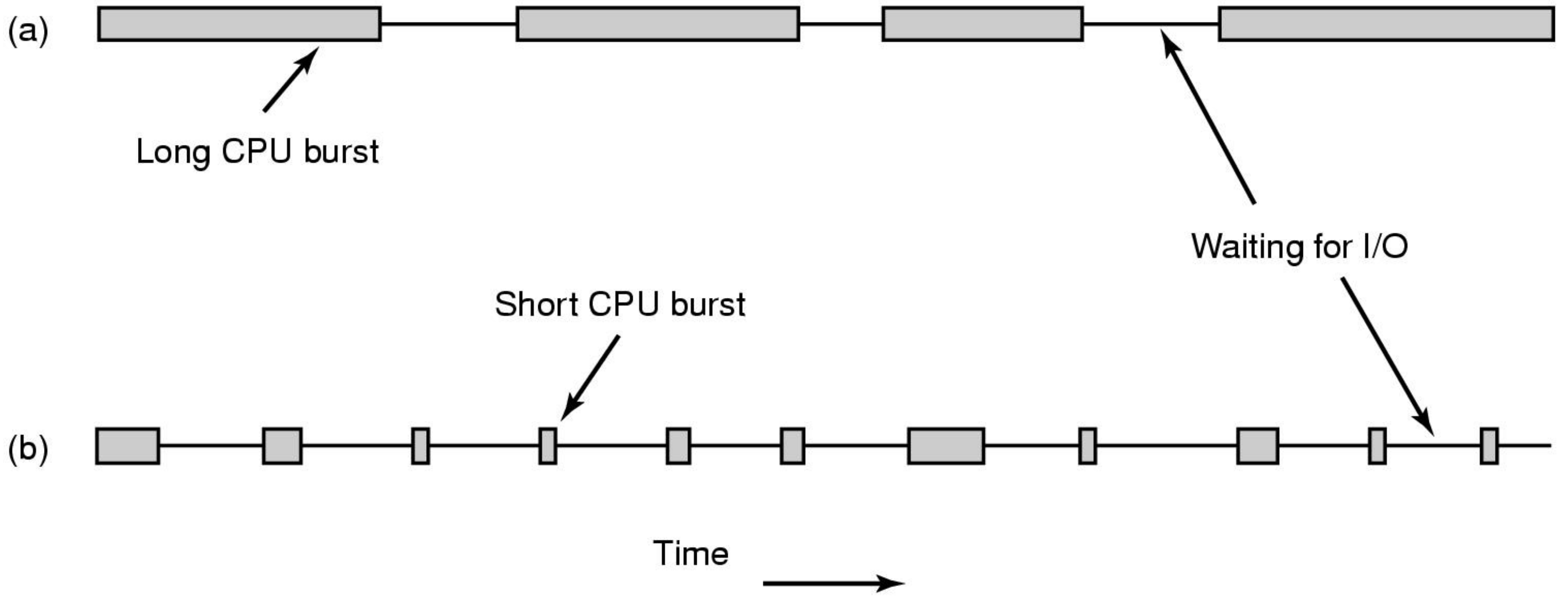
Application Behaviour



b) I/O-Bound process

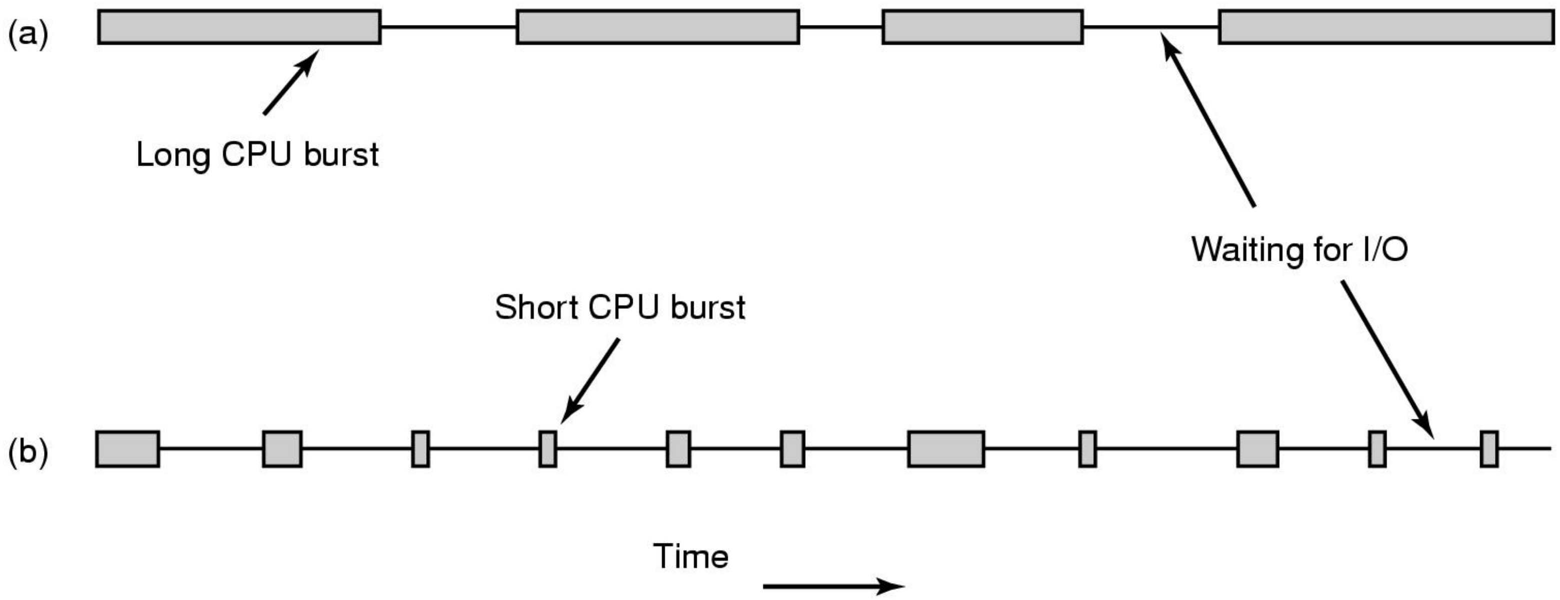
- Spend most of its time waiting for I/O to complete
  - Small bursts of CPU to process I/O and request next I/O
- Time to completion largely determined by I/O request time

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

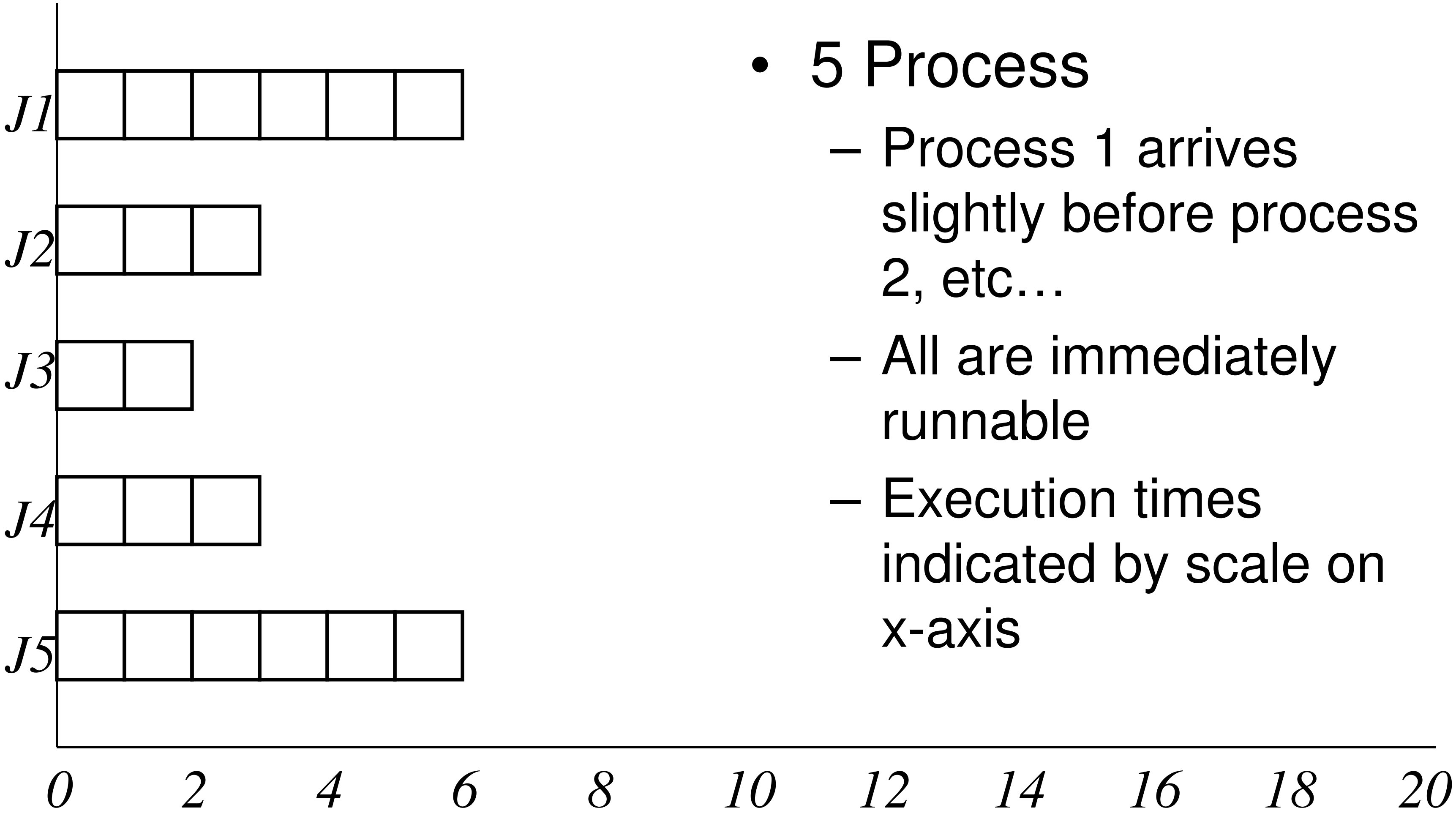
- Real-time Algorithms
  - Must meet deadlines
    - Each job/task has a deadline.
    - A missed deadline can result in data loss or catastrophic failure
      - Aircraft control system missed deadline to apply brakes
  - Provide Predictability
    - For some apps, an occasional missed deadline is okay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

Interactive Scheduling

Round Robin Scheduling

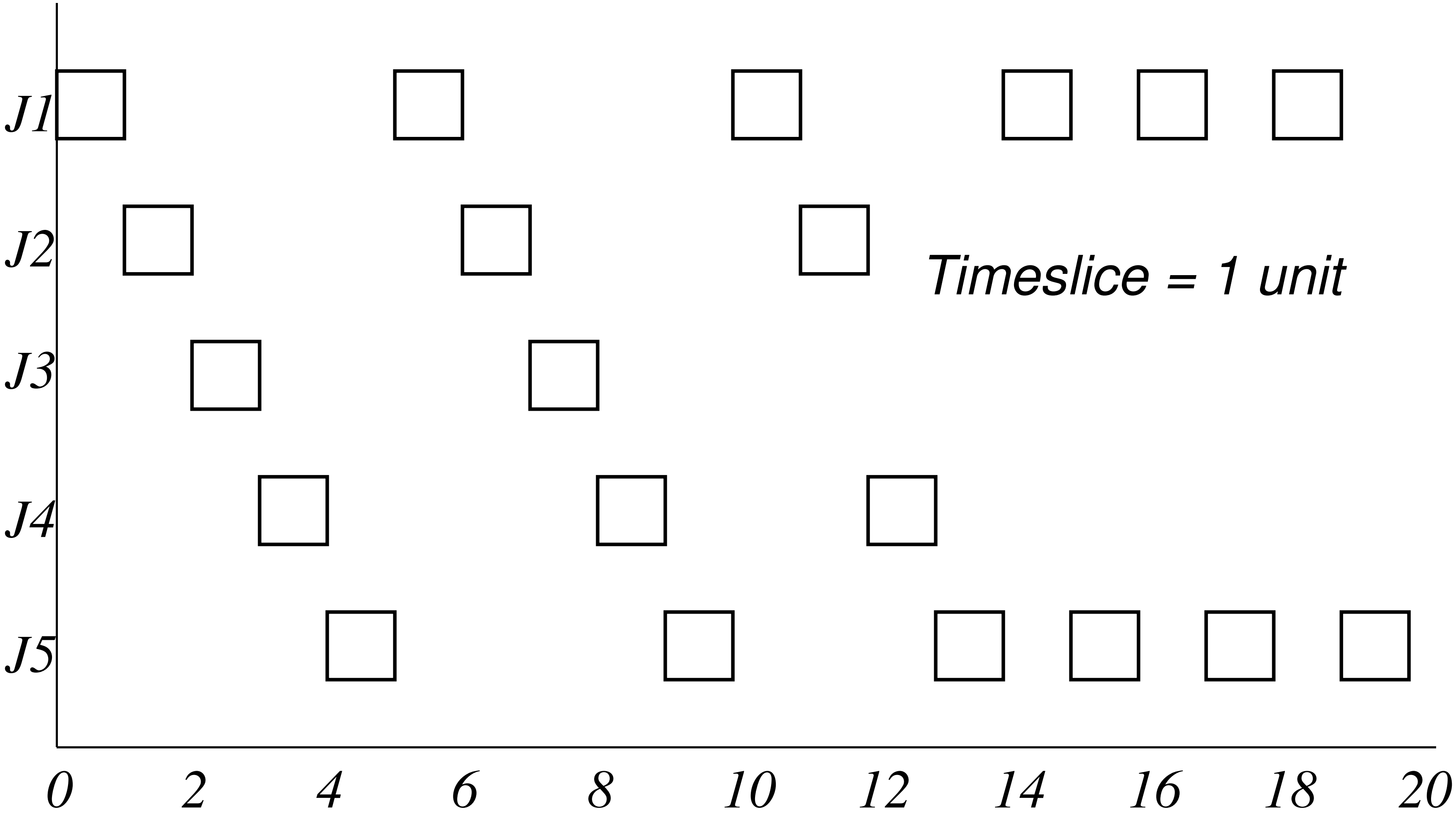
- Each process is given a *timeslice* to run in
- When the timeslice expires, the next process preempts the current process, and runs for its timeslice, and so on
  - The preempted process is placed at the end of the queue
- Implemented with
  - A ready queue
  - A regular timer interrupt

Example

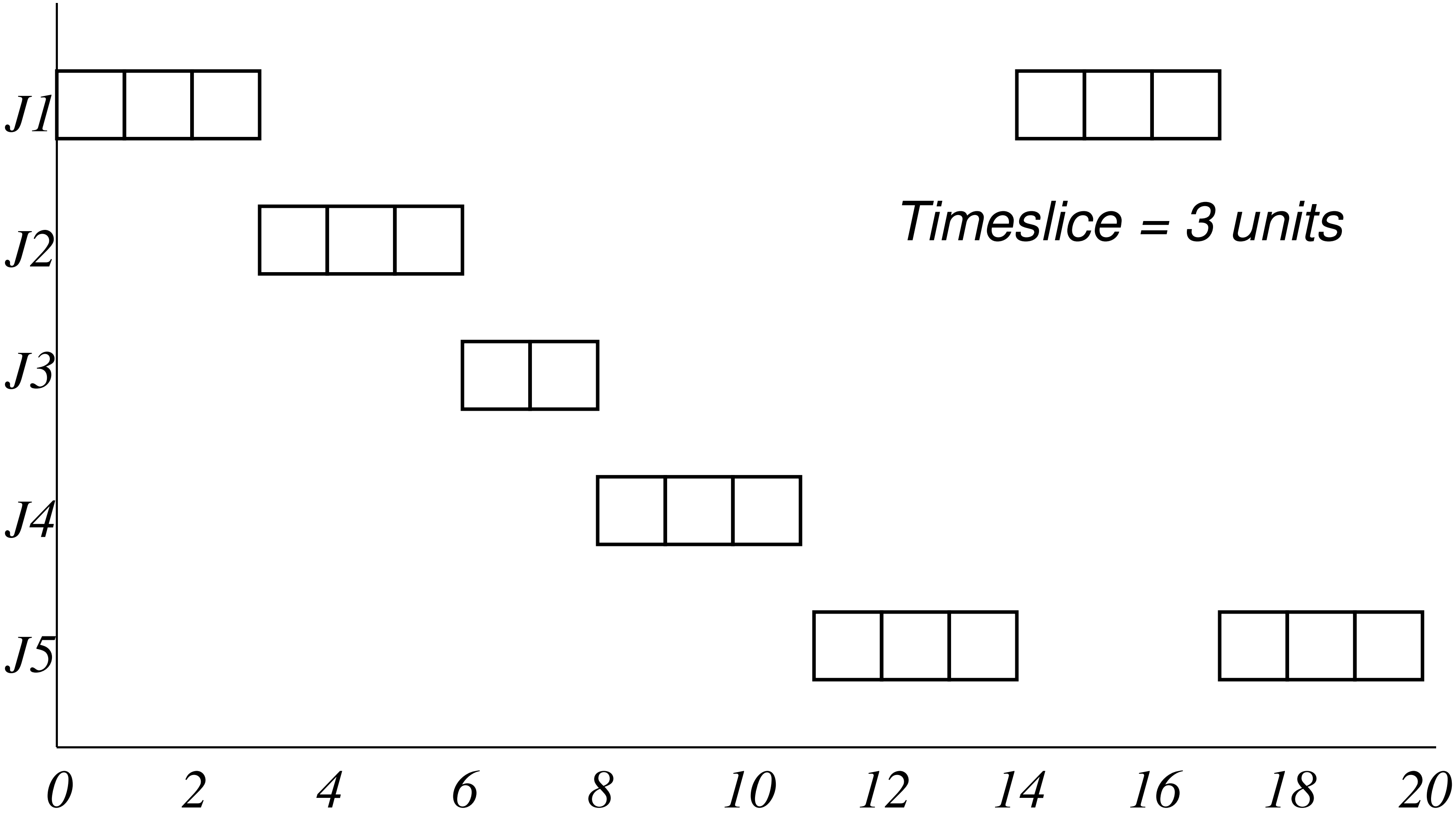


- 5 Process
  - Process 1 arrives slightly before process 2, etc…
  - All are immediately runnable
  - Execution times indicated by scale on x-axis

Round Robin Schedule



Round Robin Schedule



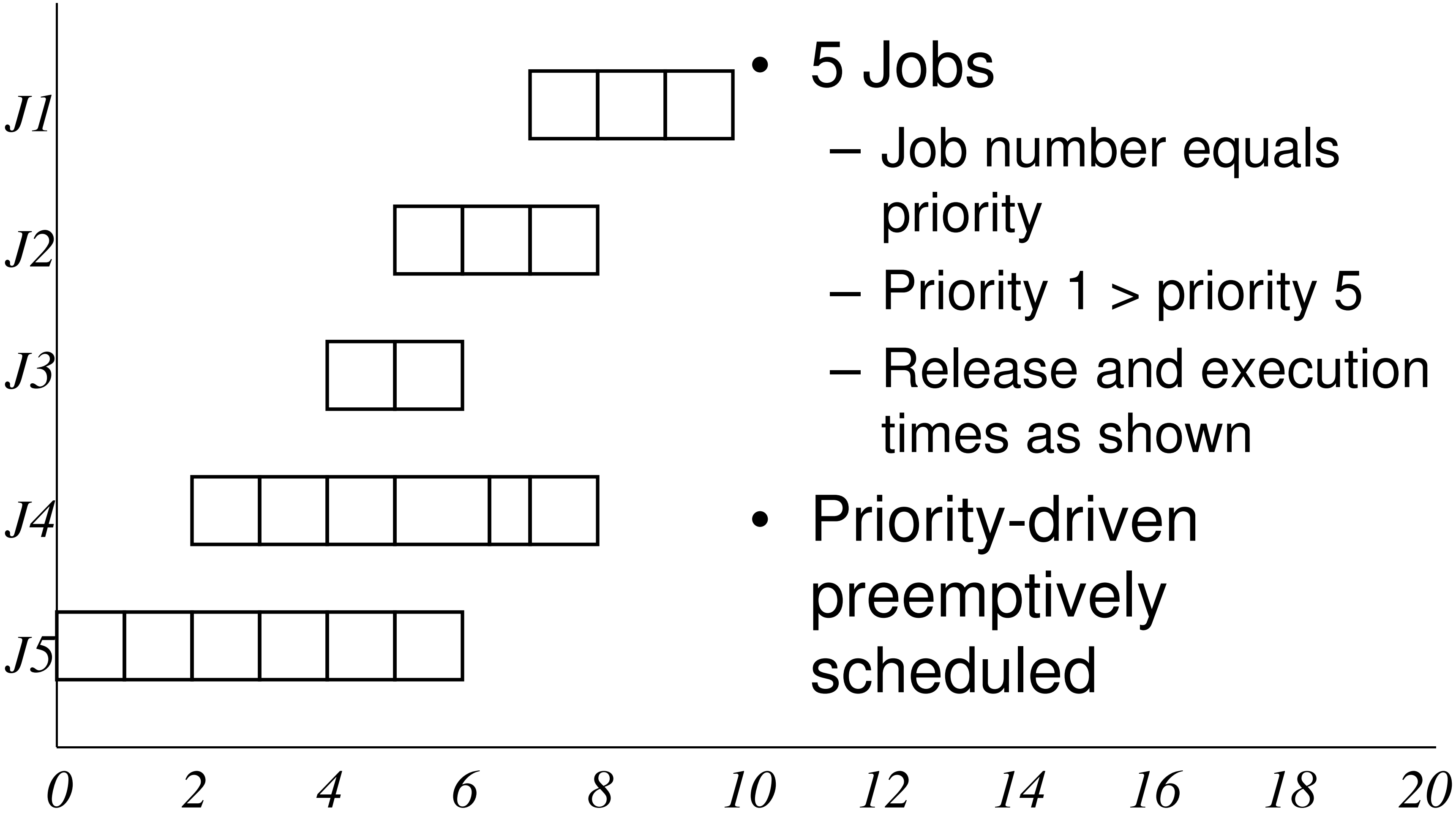
Round Robin

- 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

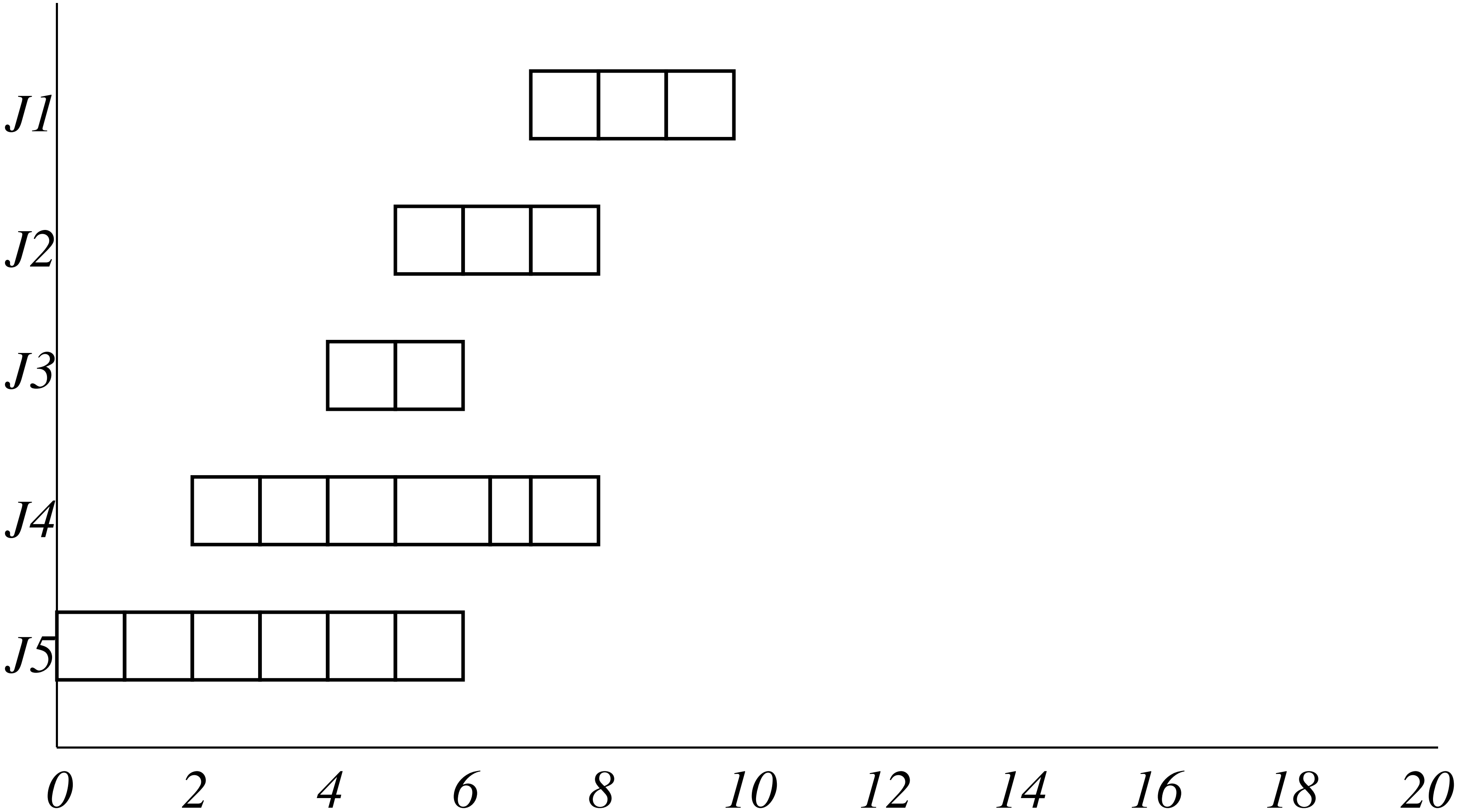
- Each Process (or thread) is associated with a priority
- Provides basic mechanism to influence a scheduler decision:
  - Scheduler will always chooses a thread of higher priority over lower priority
- Priorities can be defined internally or externally
  - Internal: e.g. I/O bound or CPU bound
  - External: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

Example



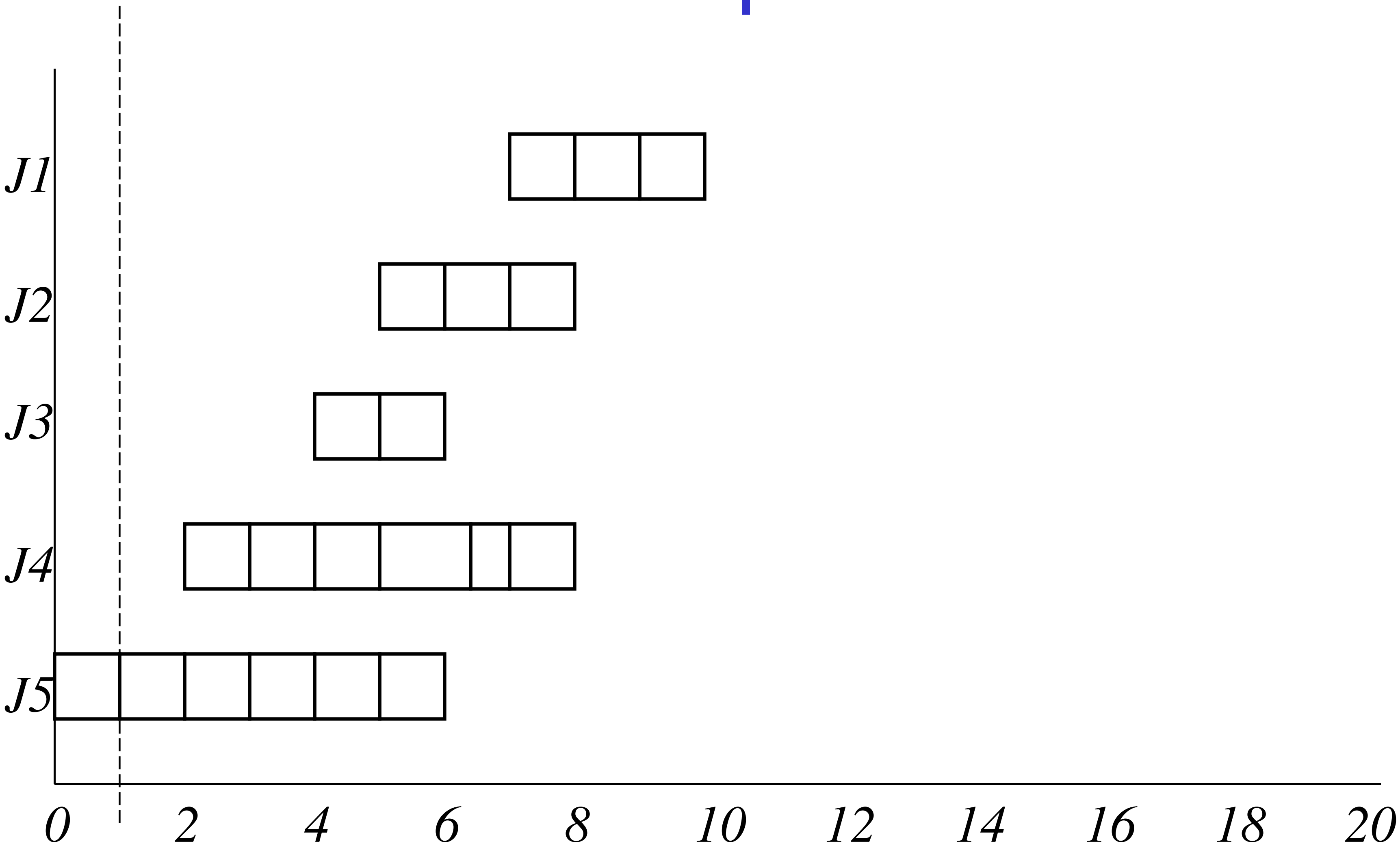
- 5 Jobs
  - Job number equals priority
  - Priority 1 > priority 5
  - Release and execution times as shown
- Priority-driven preemptively scheduled

Example

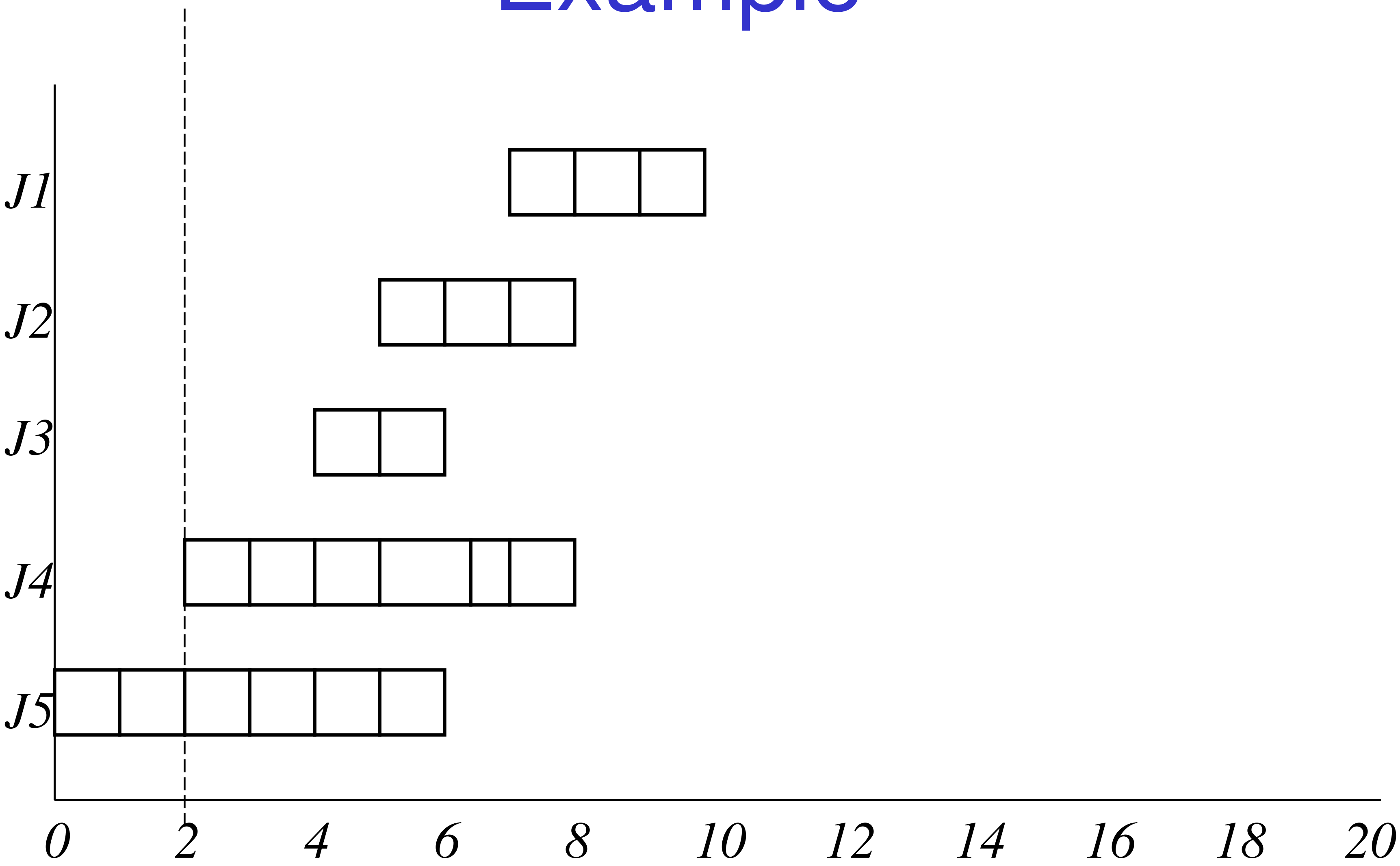


THE UNIVERSITY OF
NEW SOUTH WALES

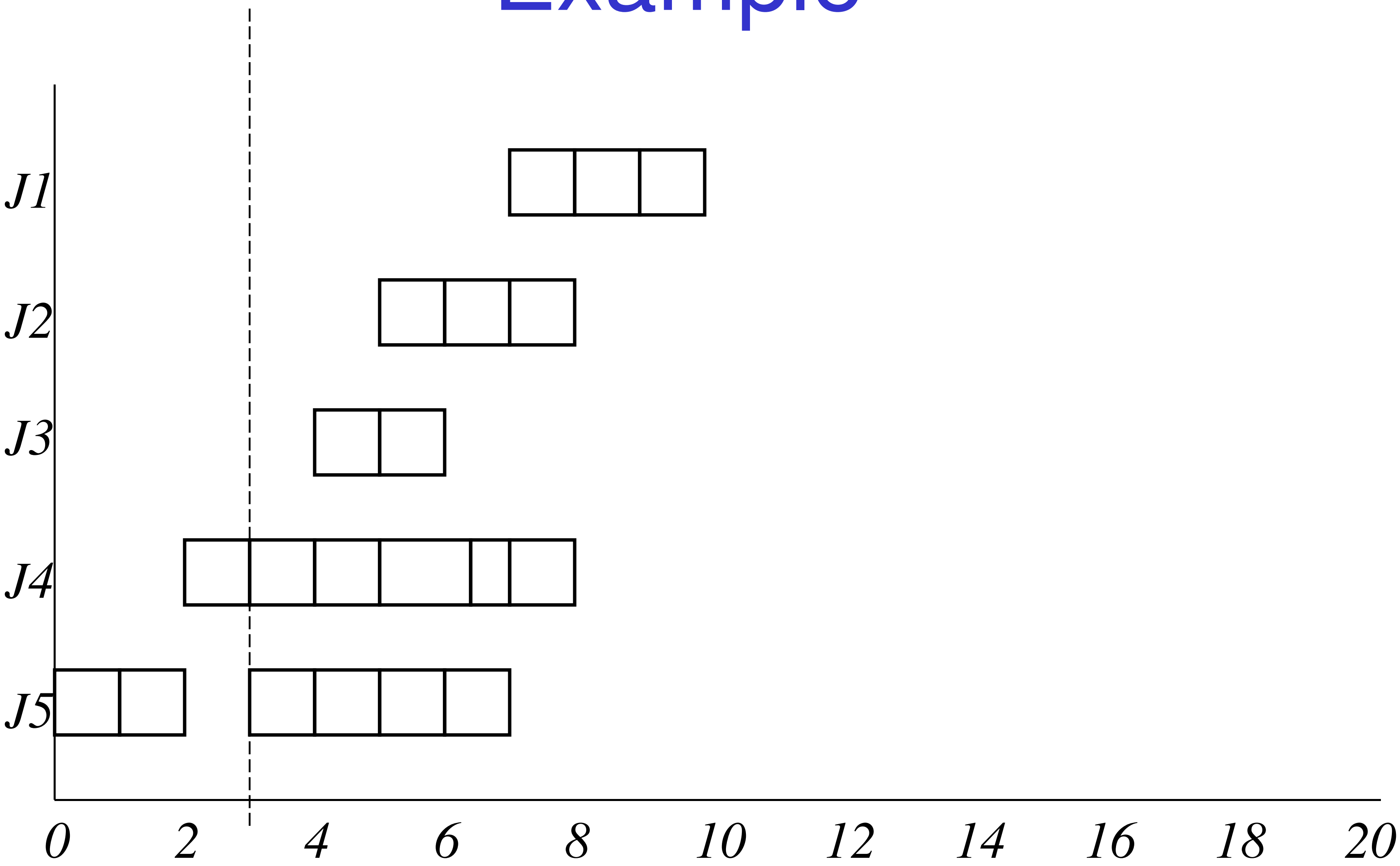
Example



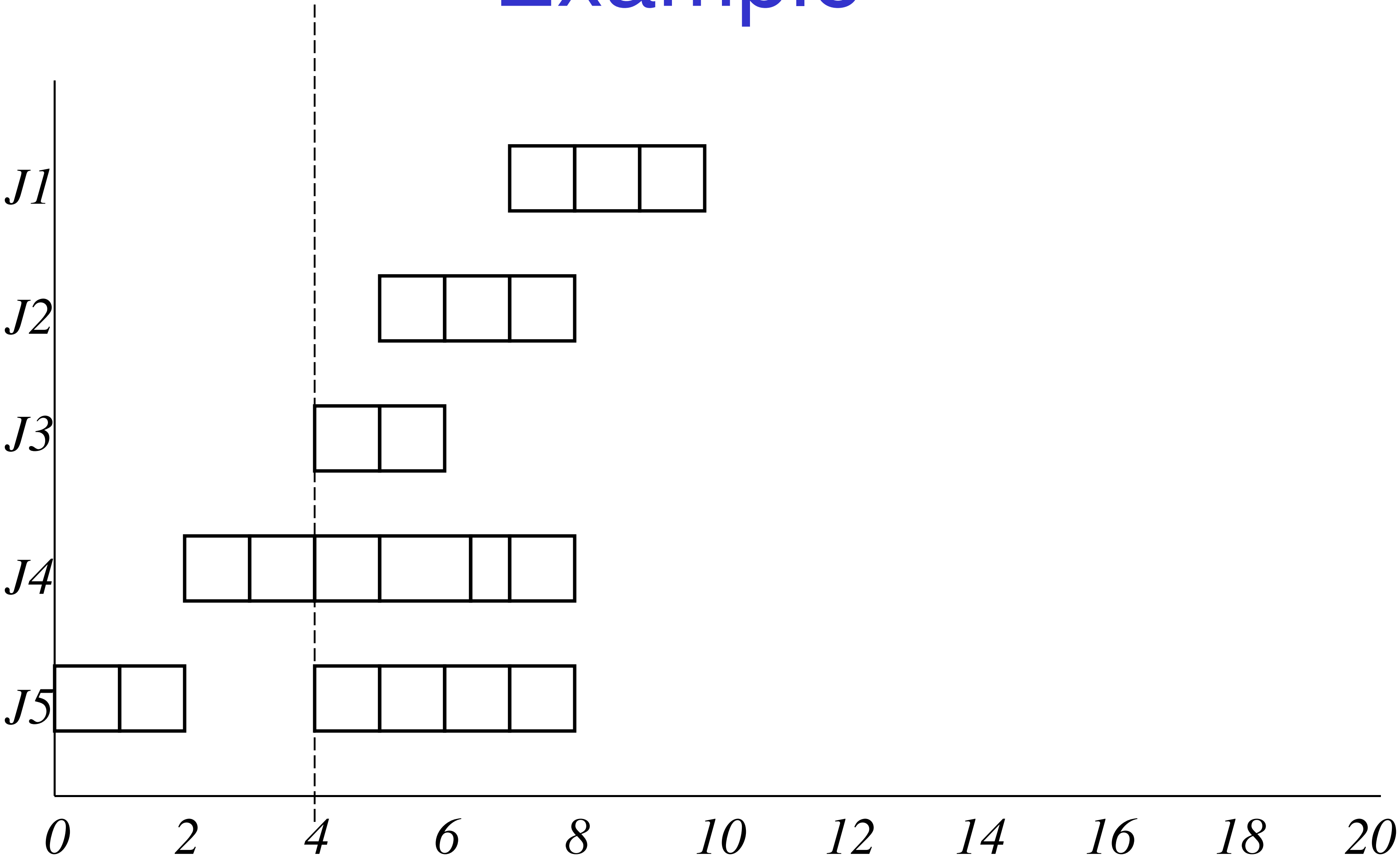
Example



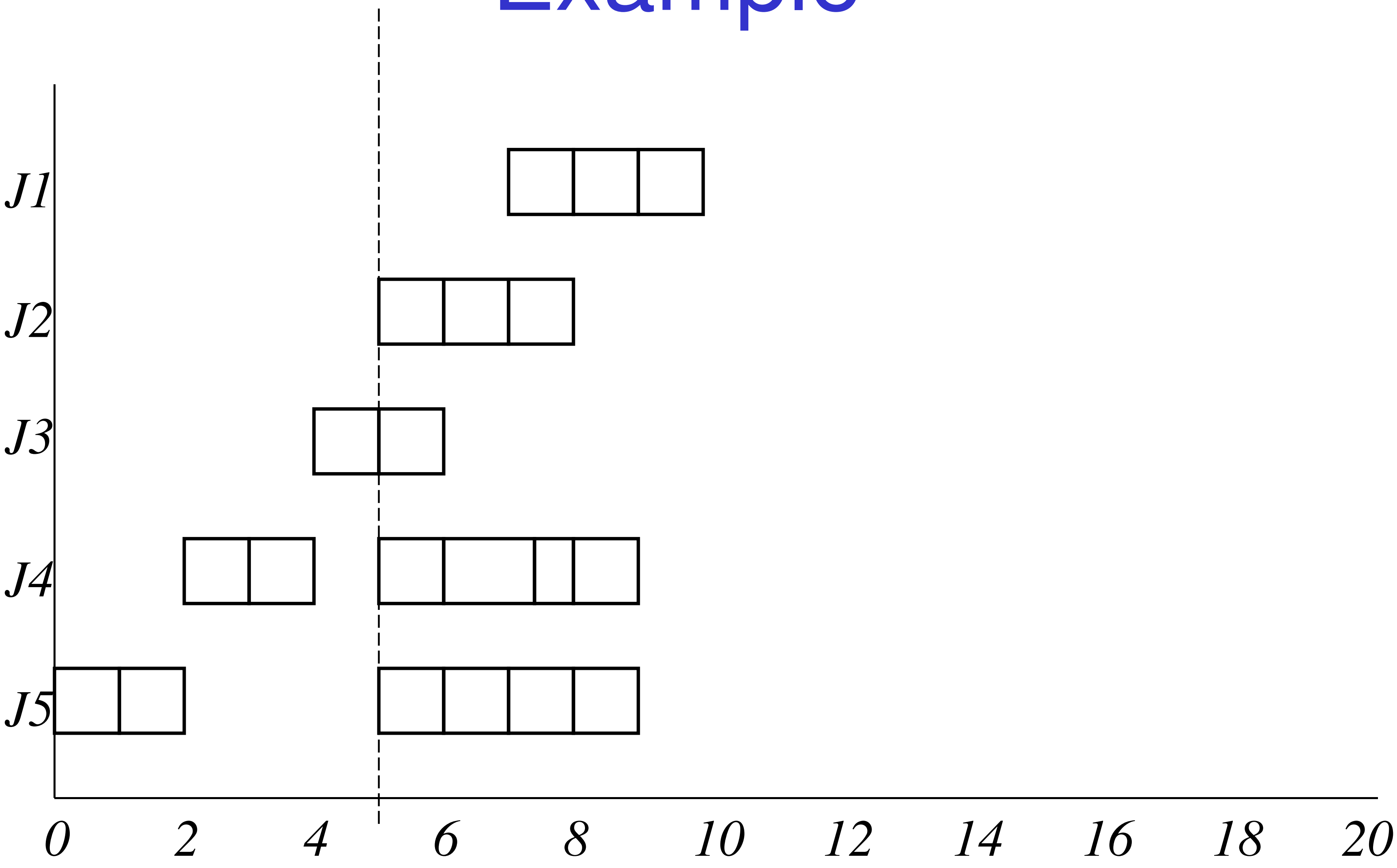
Example



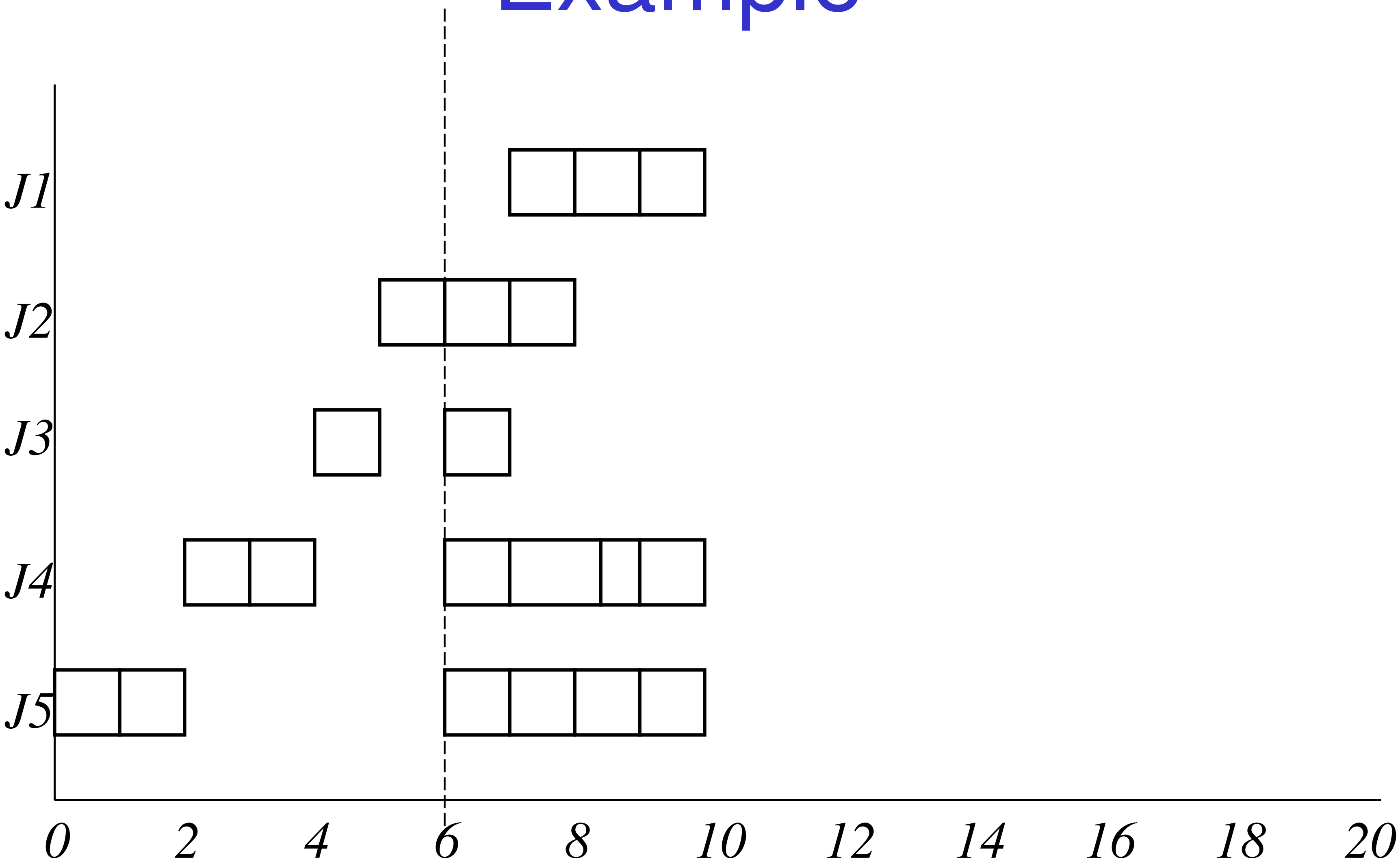
Example



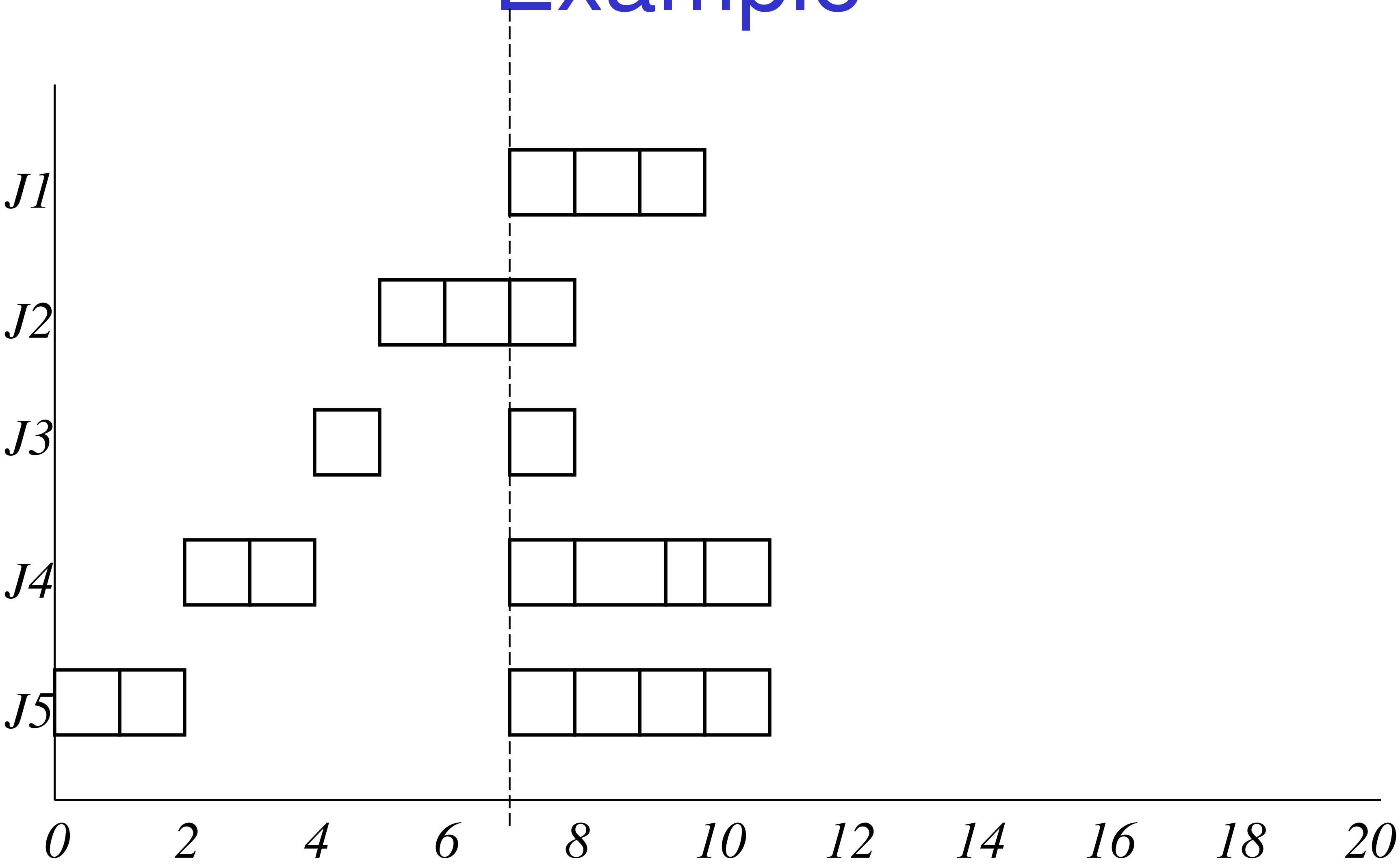
Example



Example

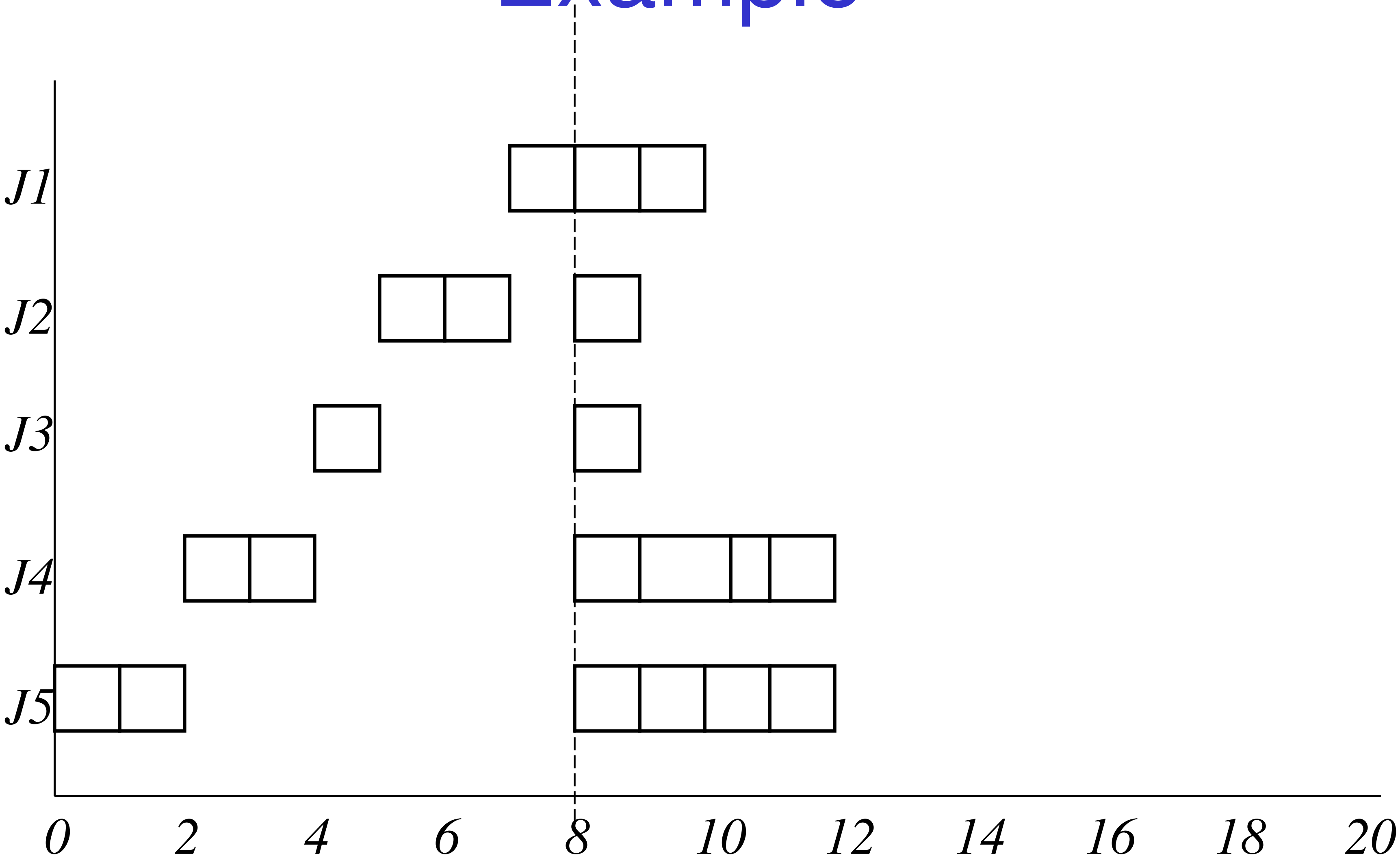


Example



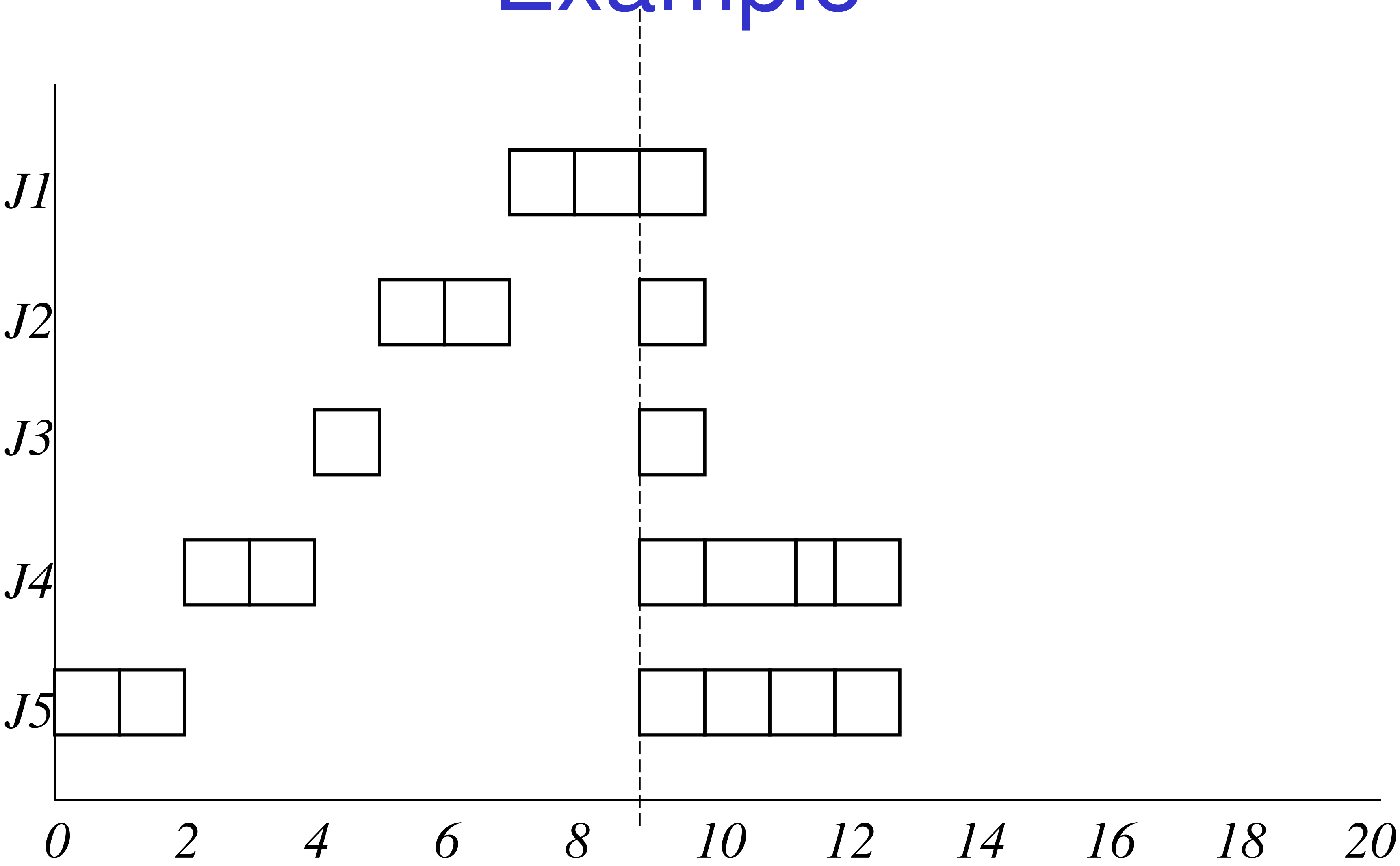
THE UNIVERSITY OF
NEW SOUTH WALES

Example

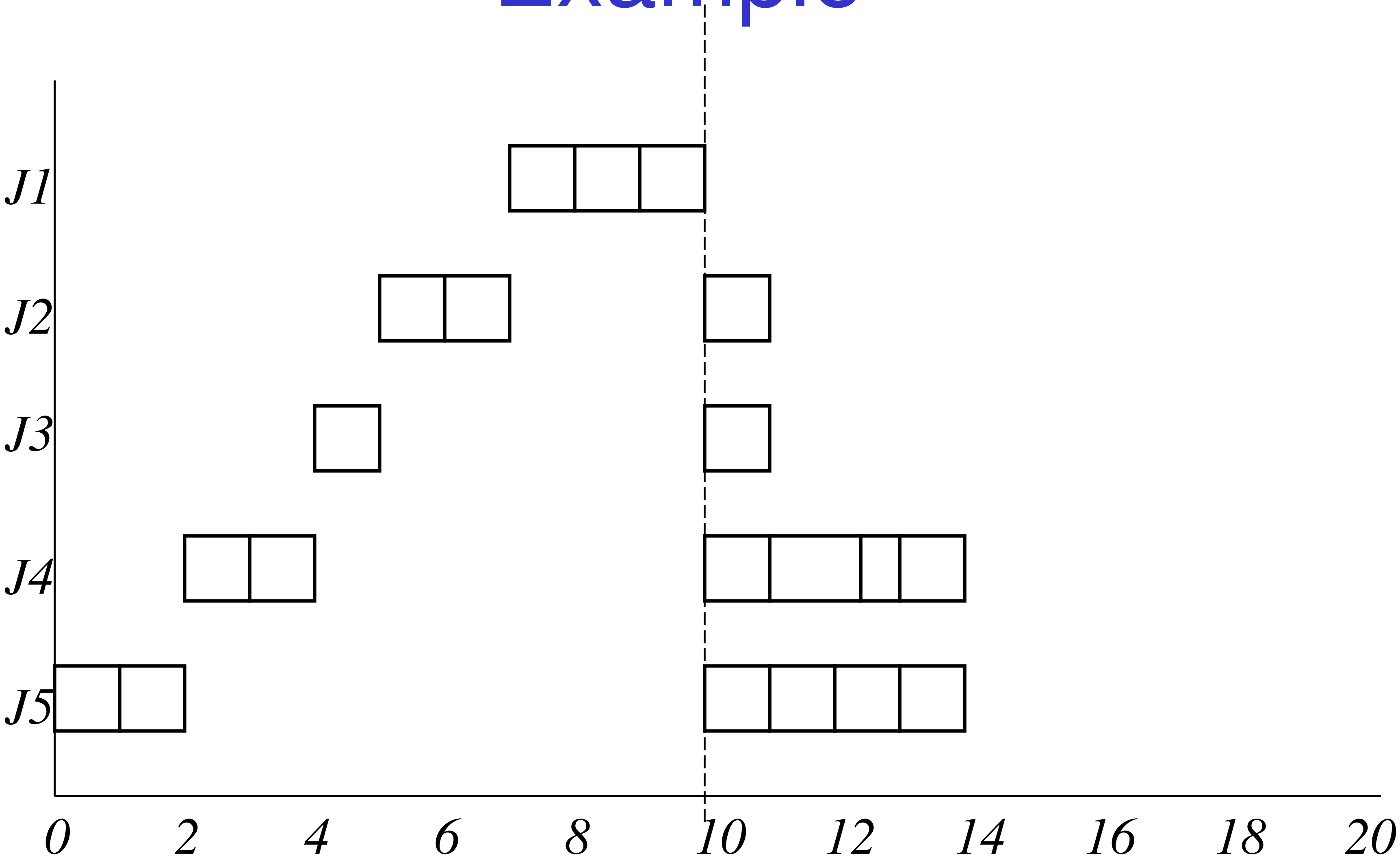


THE UNIVERSITY OF
NEW SOUTH WALES

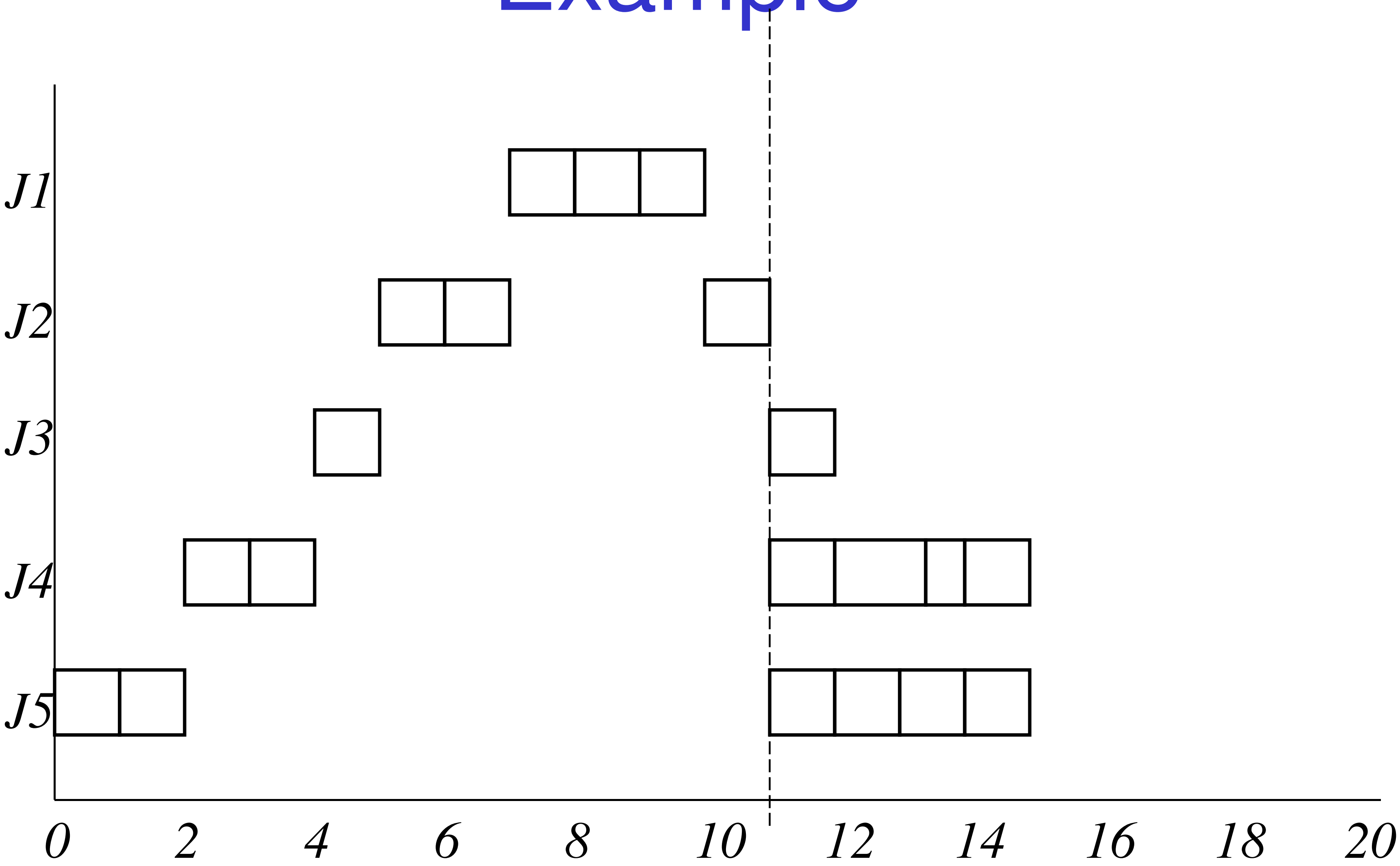
Example



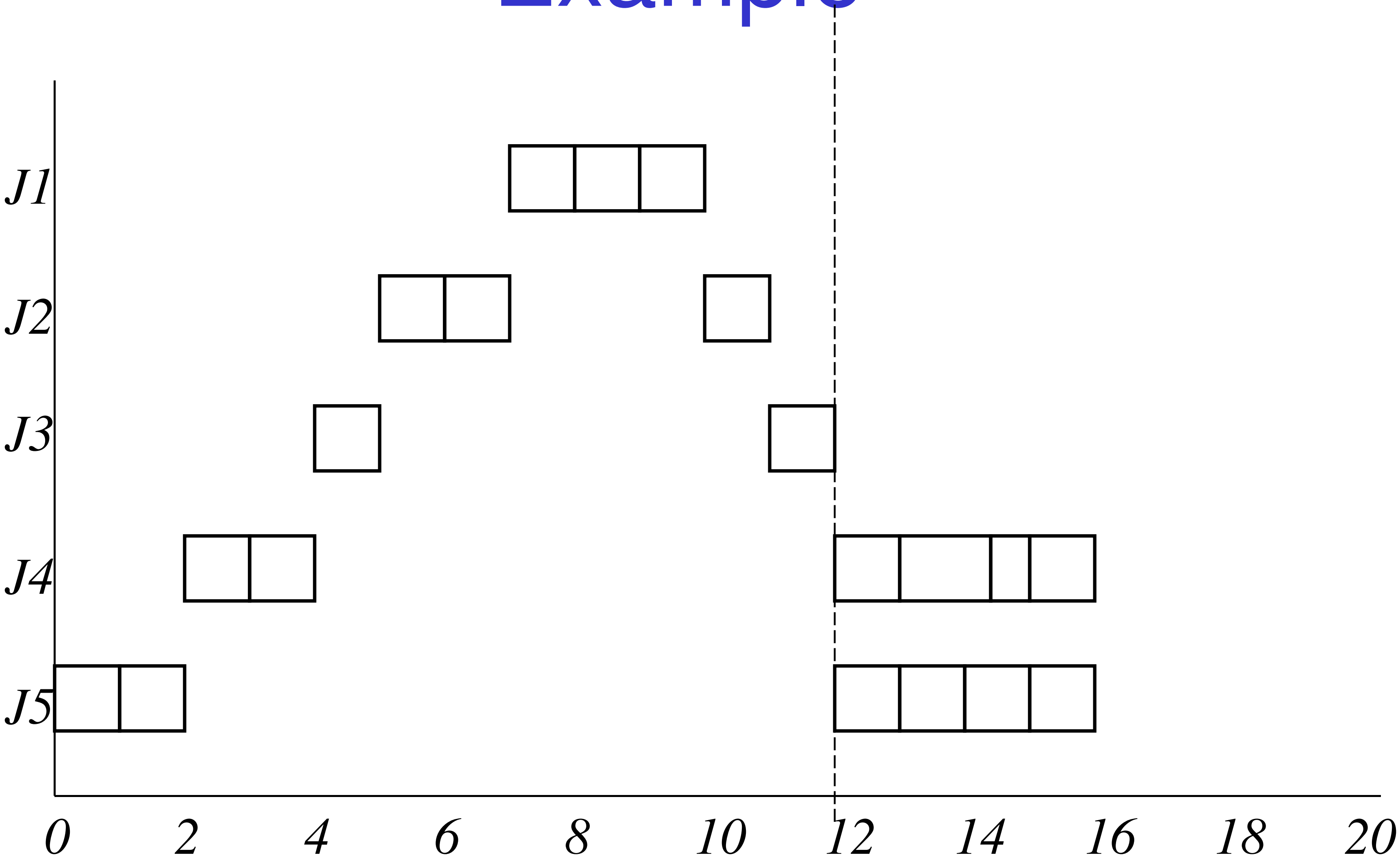
Example



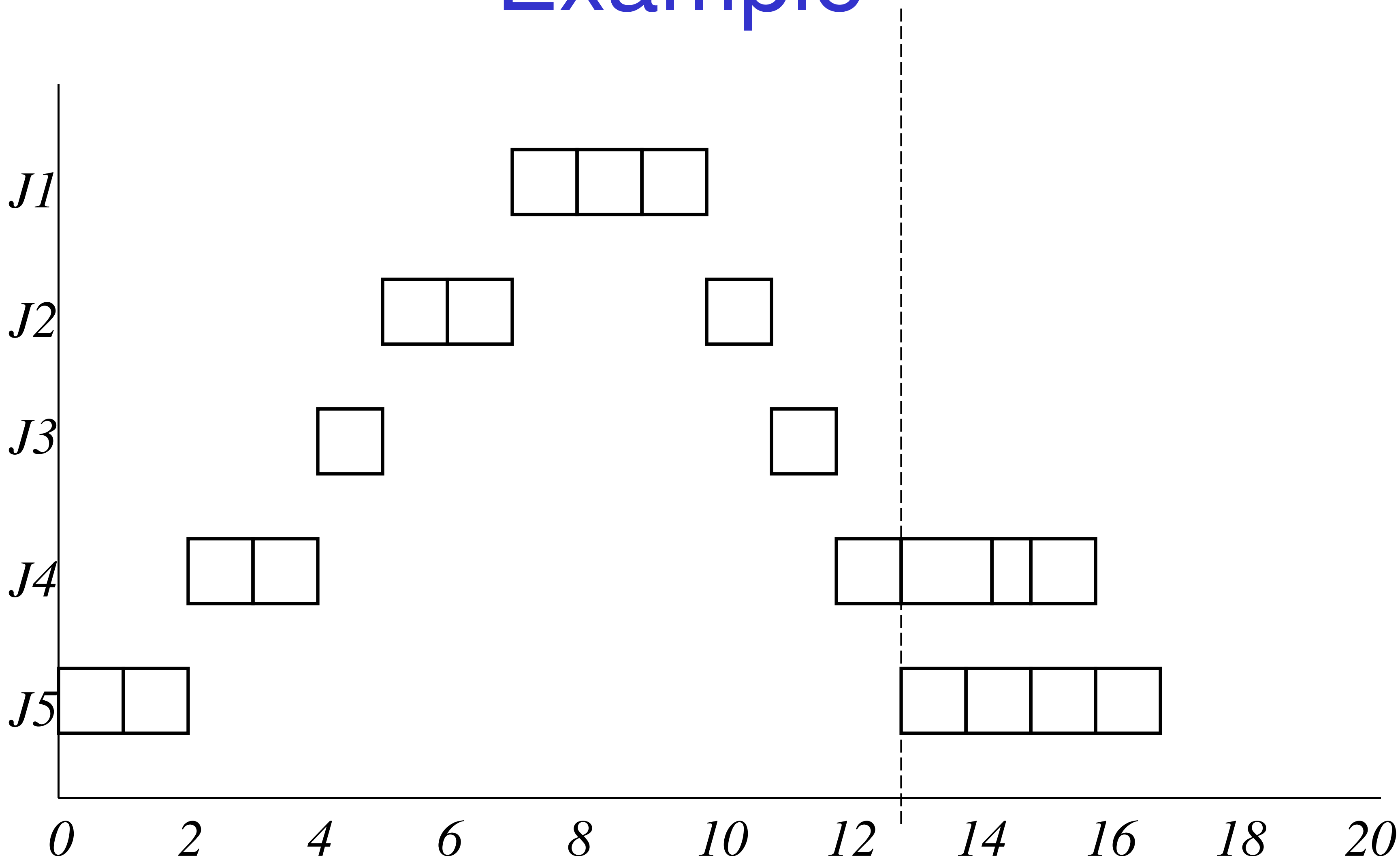
Example



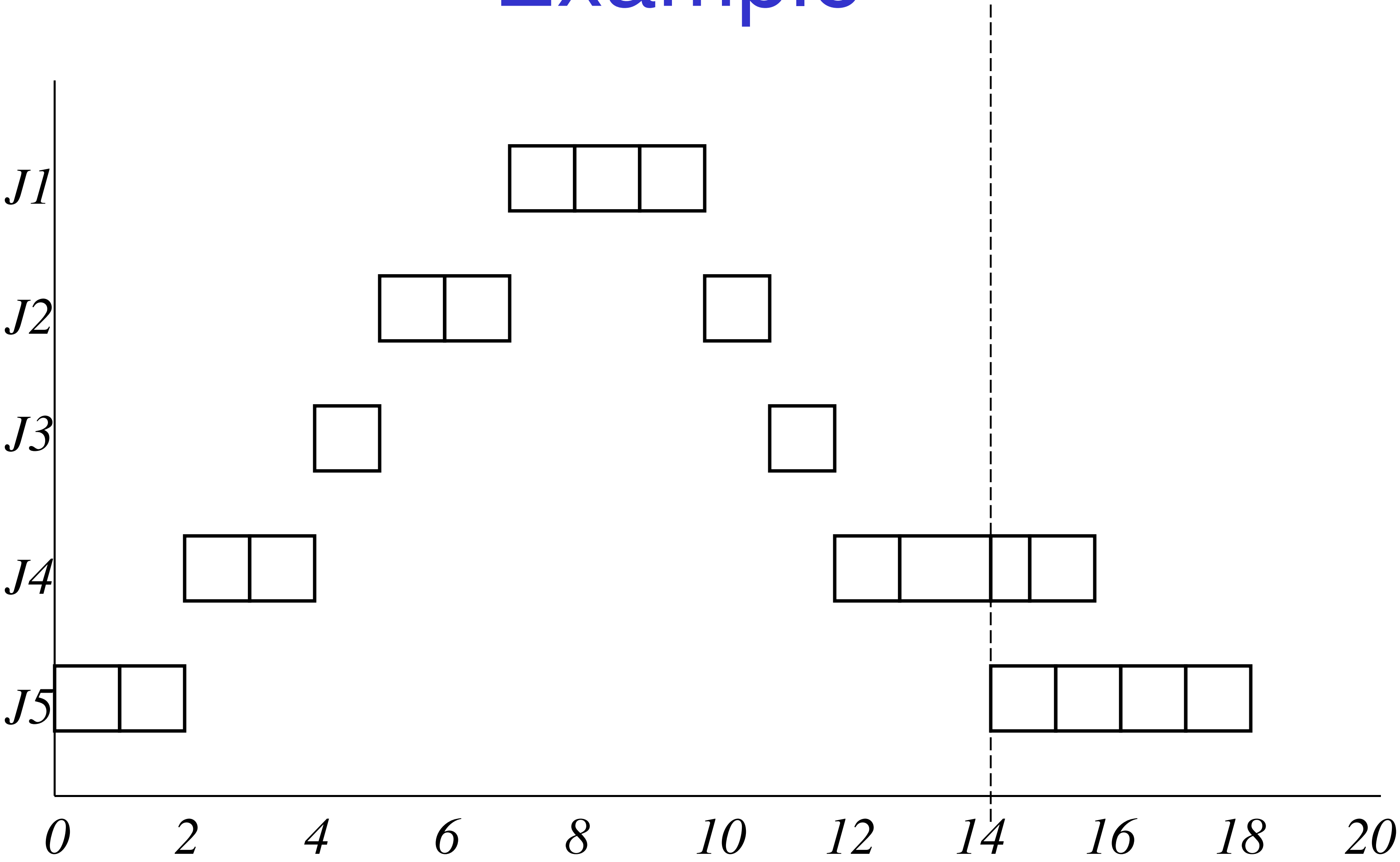
Example



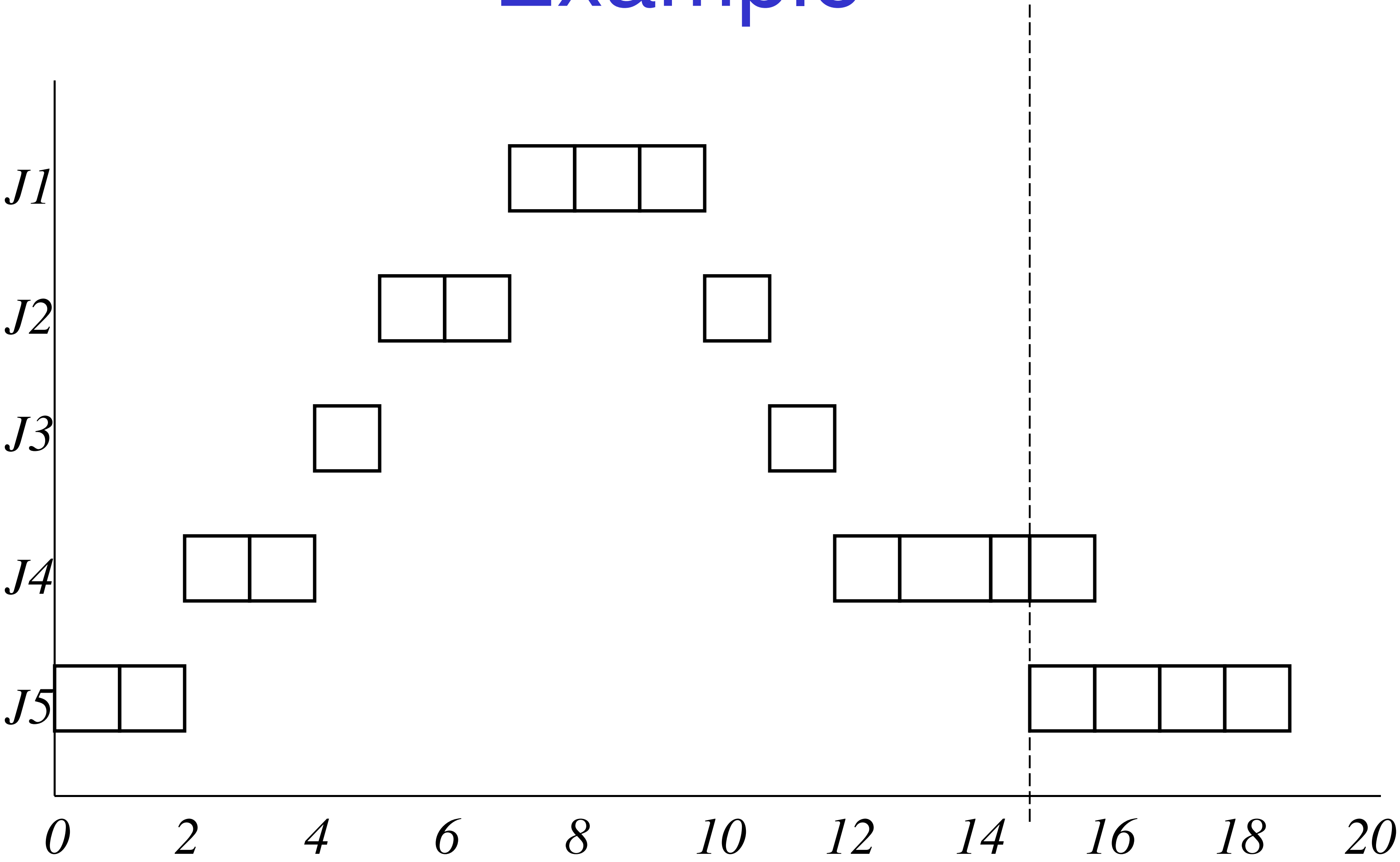
Example



Example

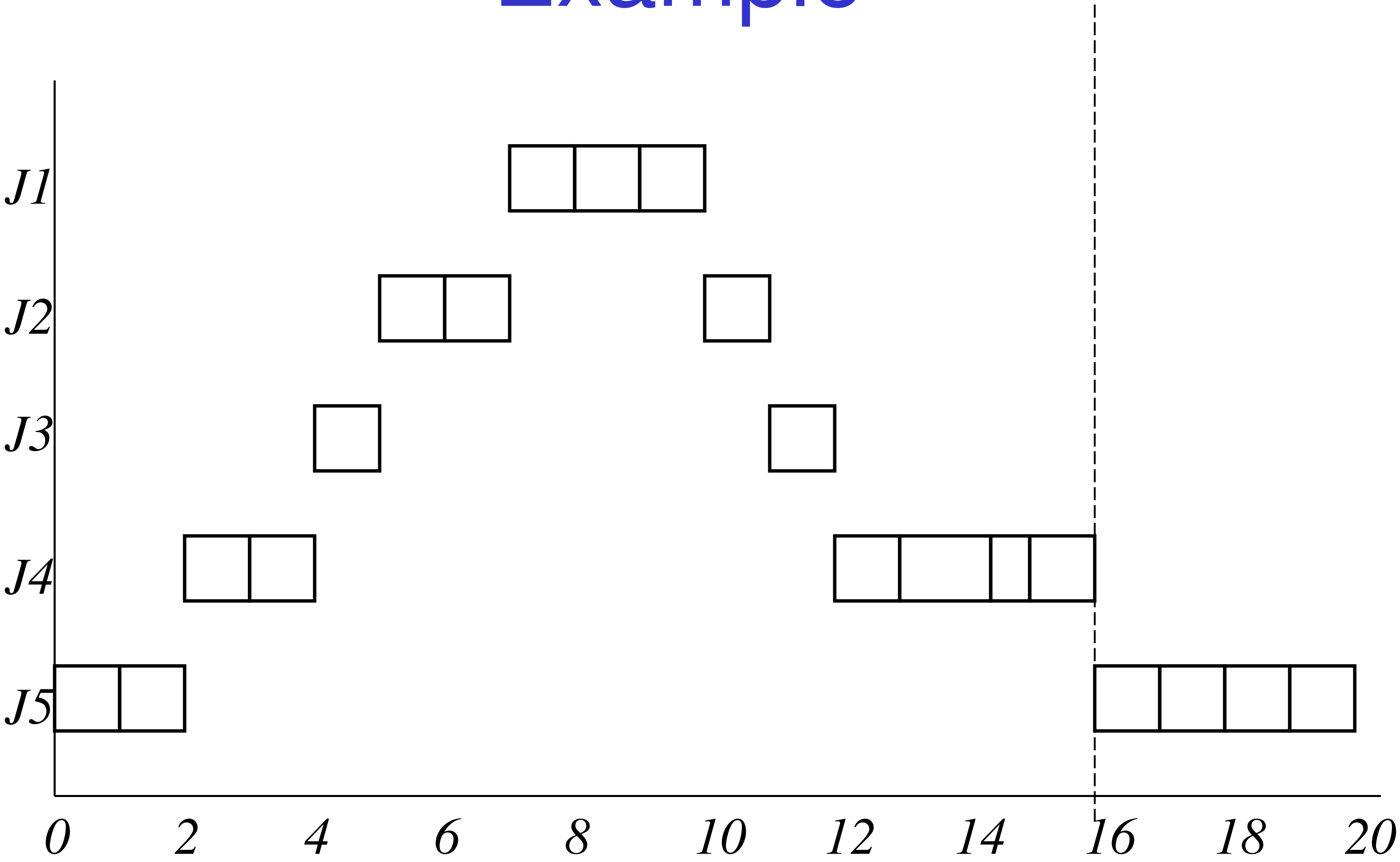


Example

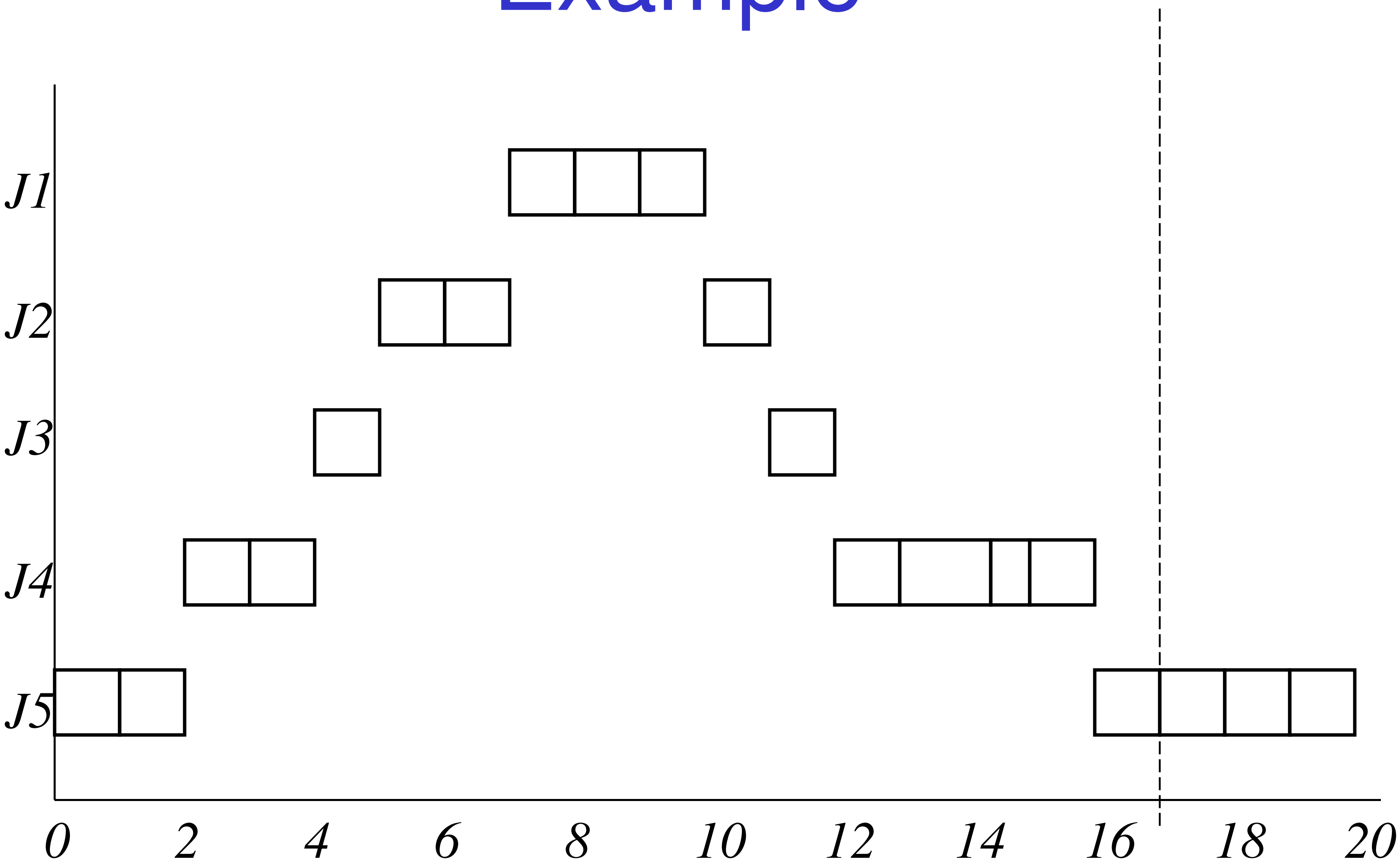


THE UNIVERSITY OF
NEW SOUTH WALES

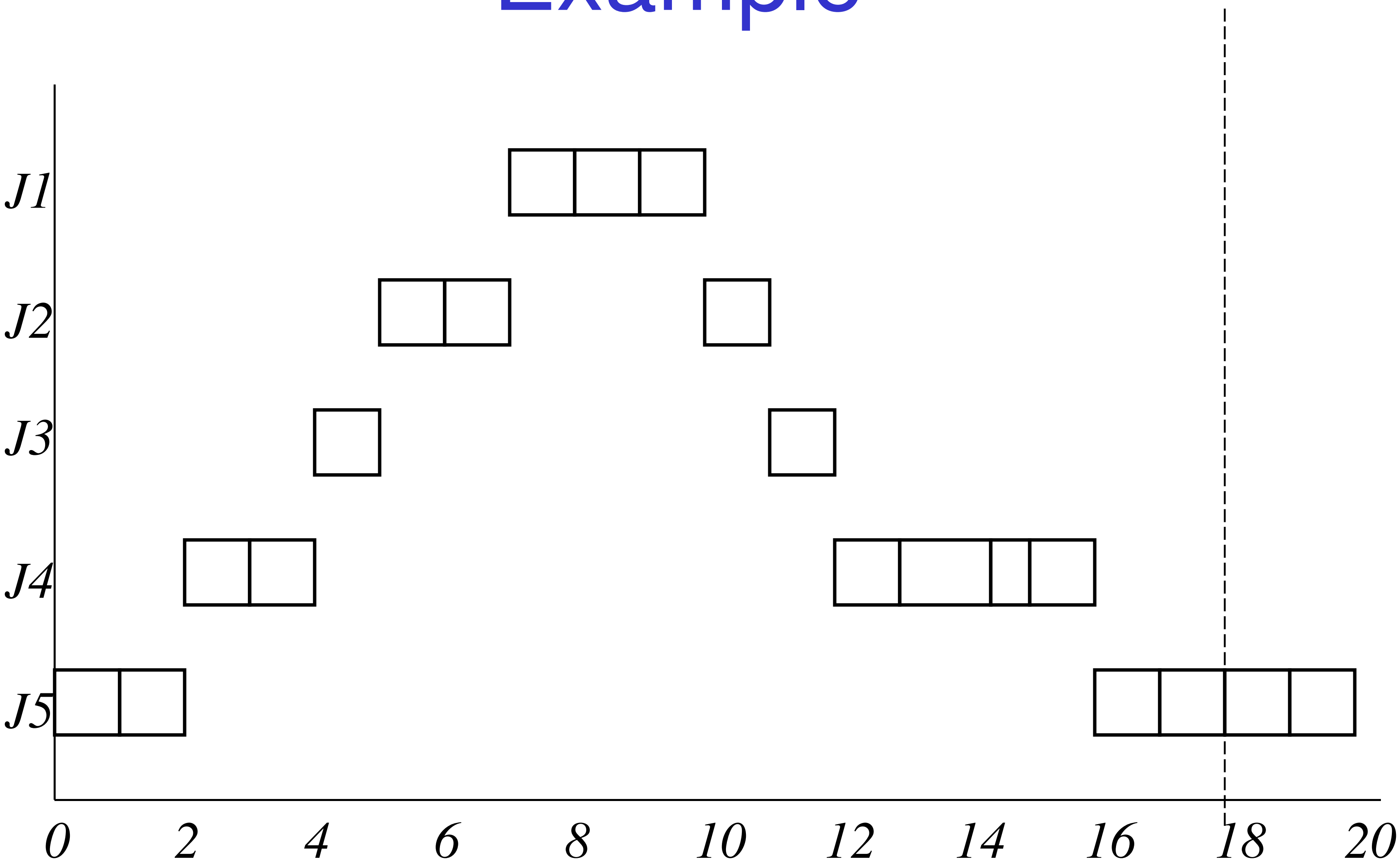
Example



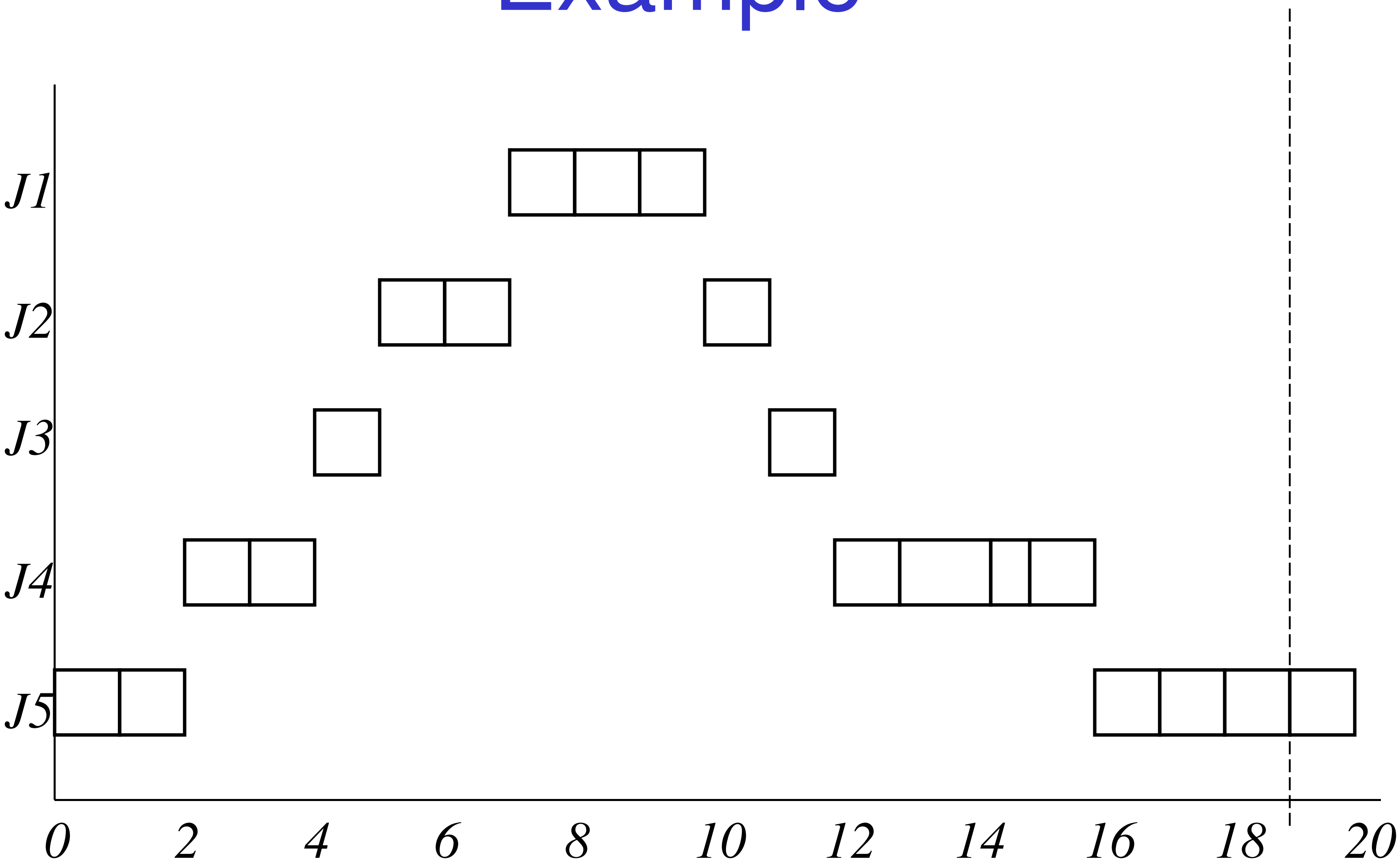
Example



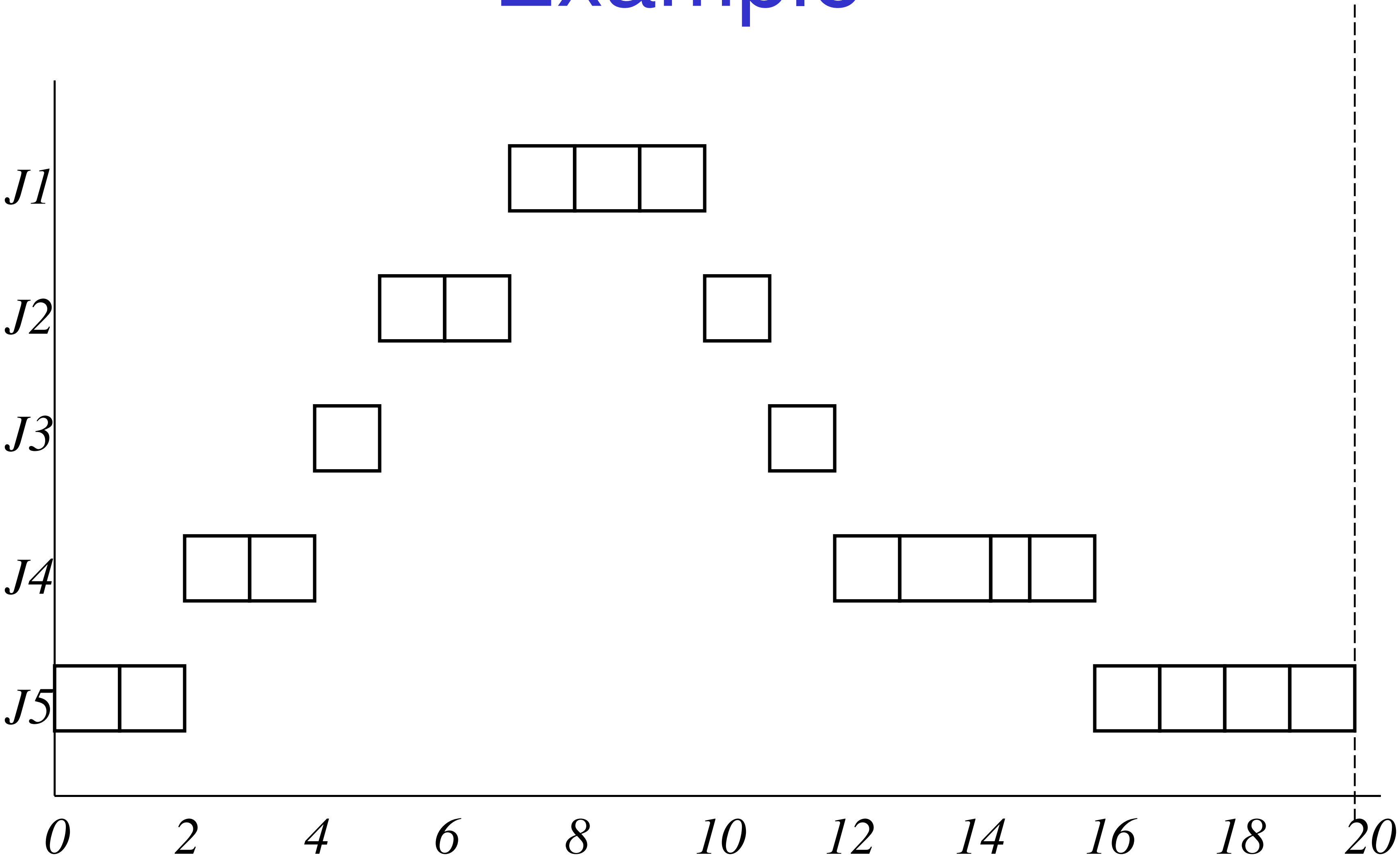
Example



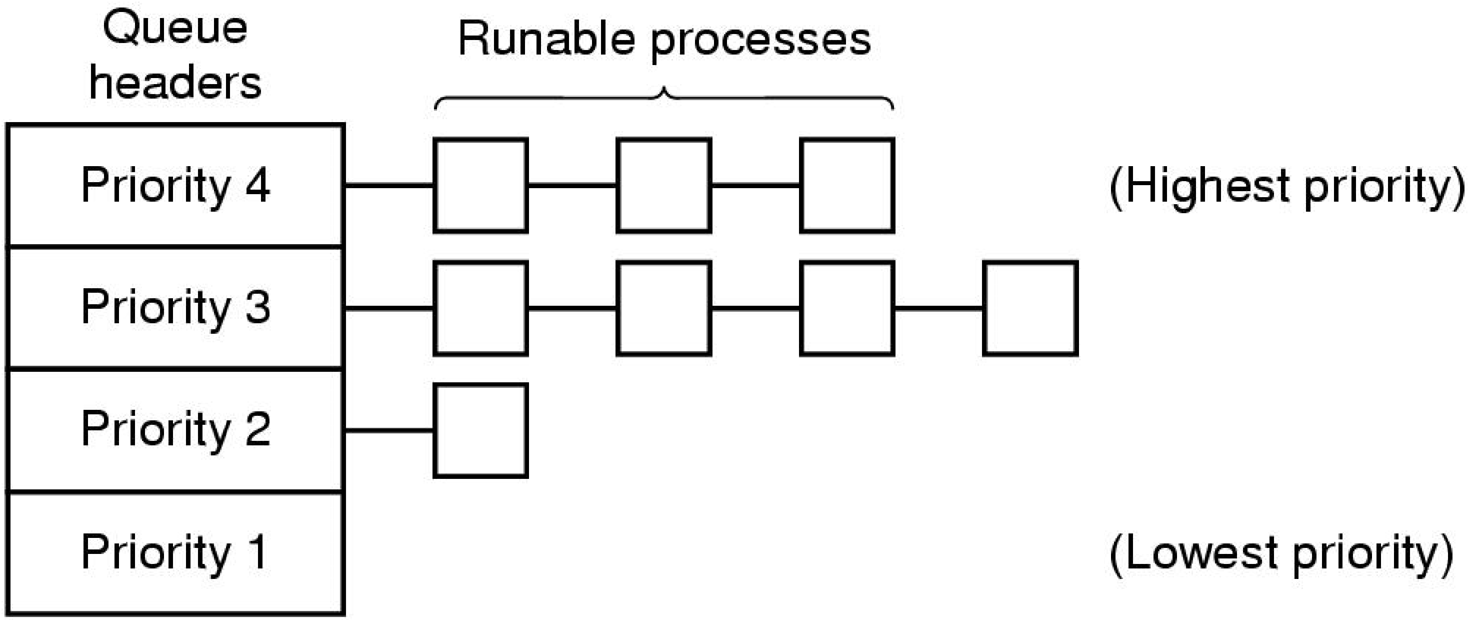
Example



Example



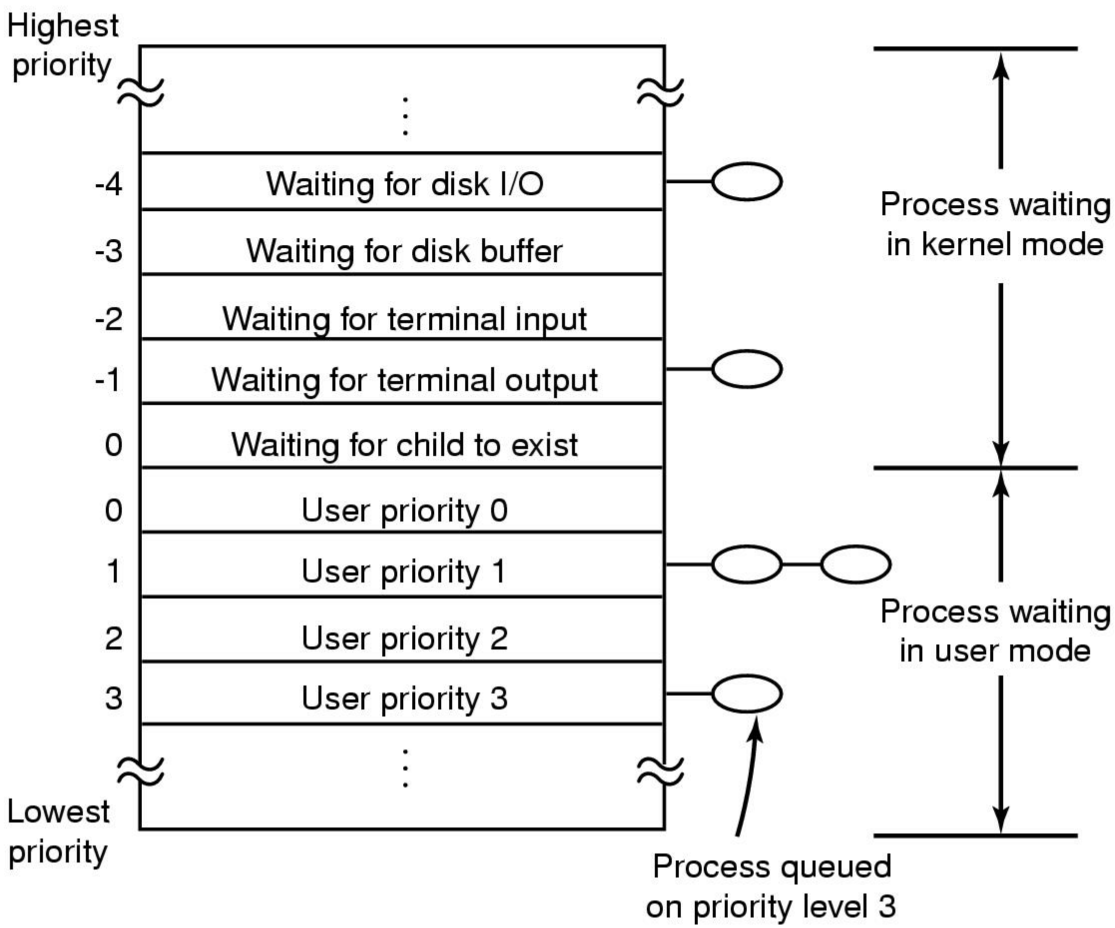
Priorities



- 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

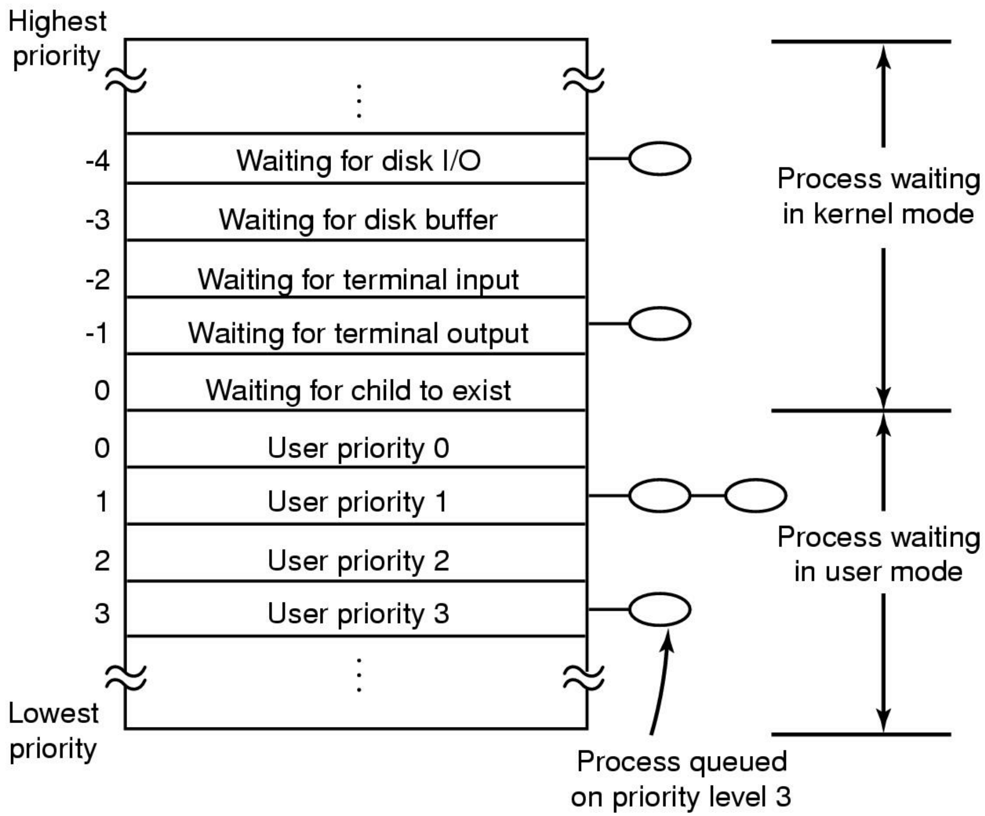
Traditional UNIX Scheduler

- 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



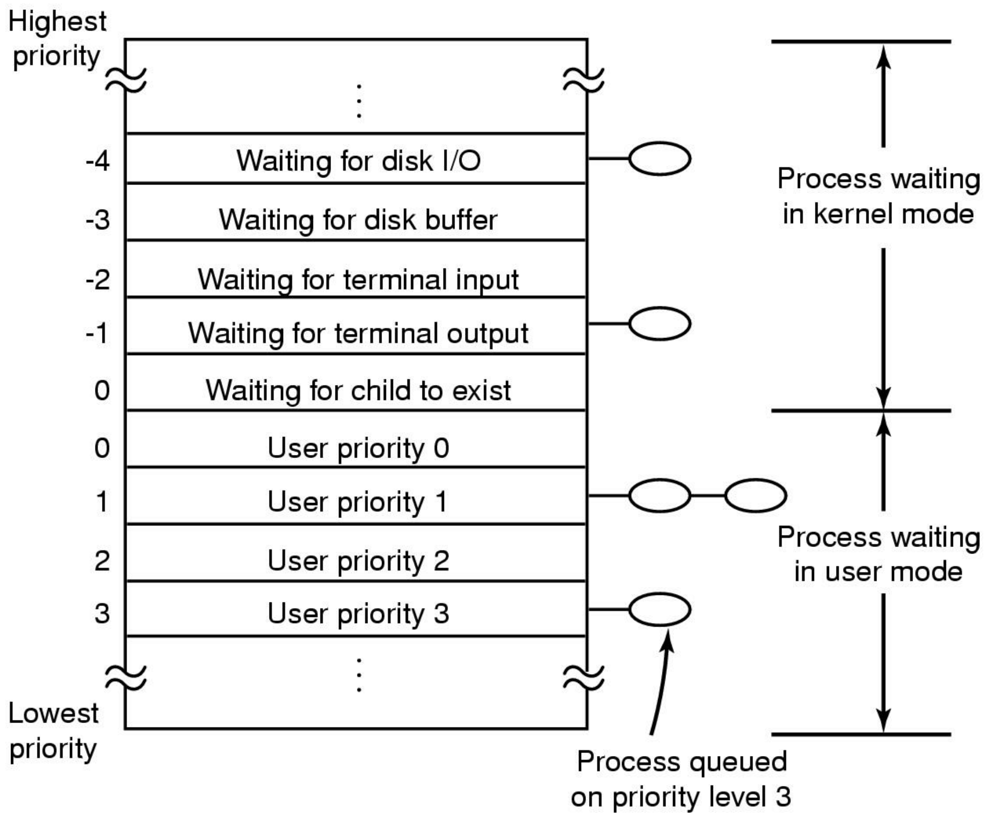
Traditional UNIX Scheduler

- 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



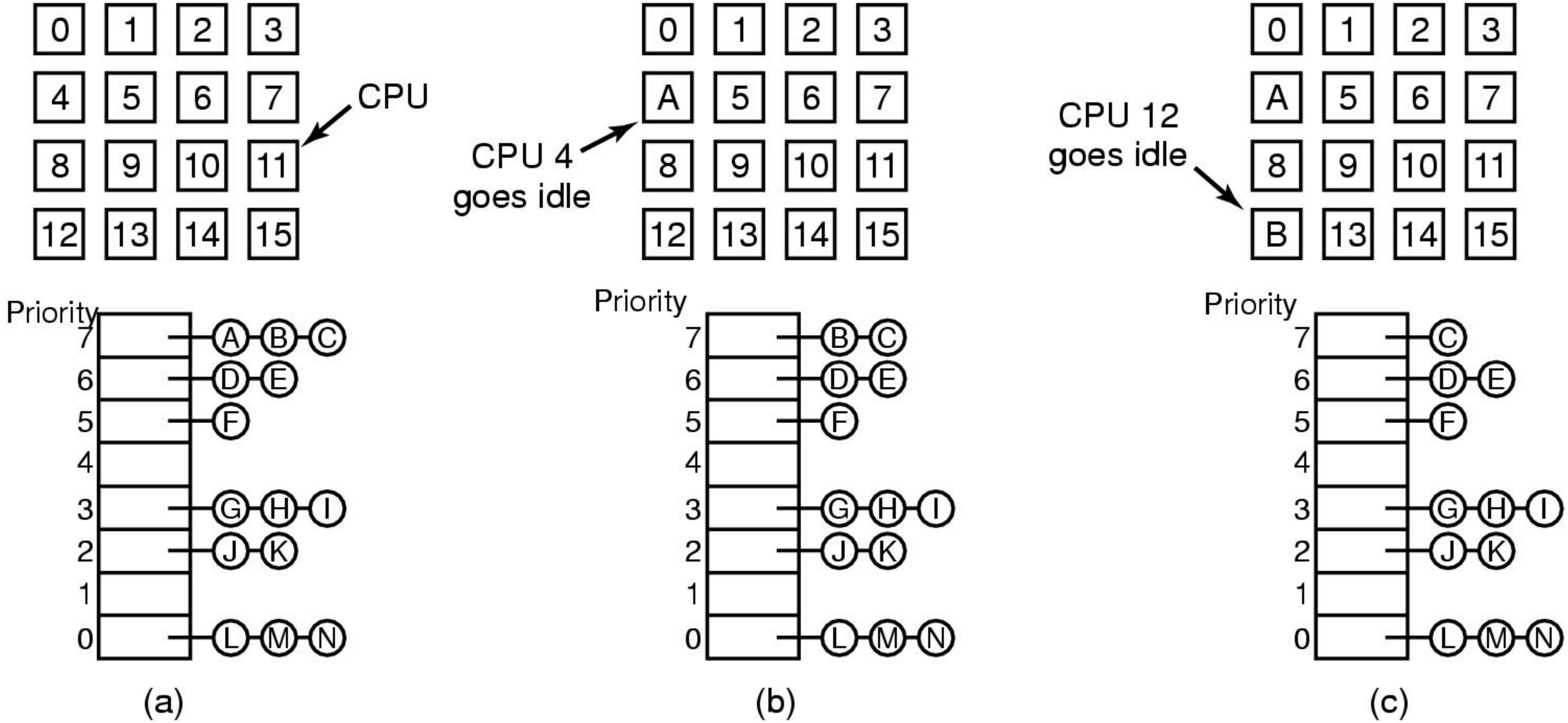
THE UNIVERSITY OF NEW SOUTH WALES

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:

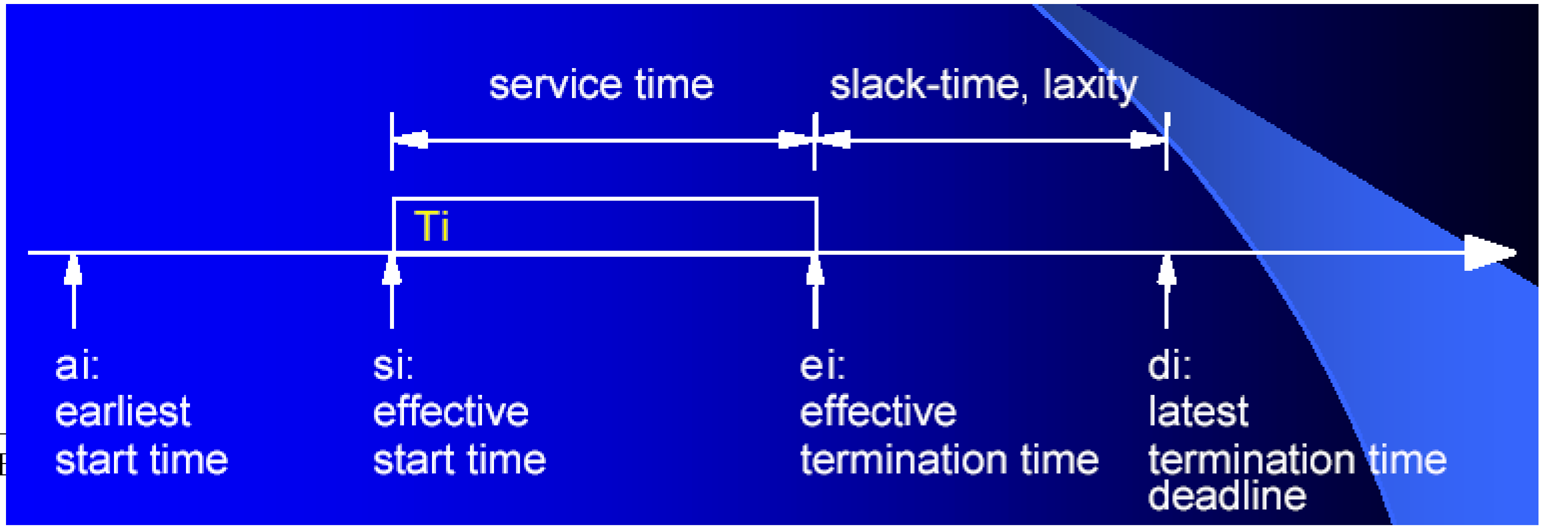
1. Multi-media: 100 frames per day might be dropped (late)
2. Car navigation: 5 late announcements per week are acceptable
3. Washing machine: washing 10 sec over time might occur once in 10 runs, 50 sec once in 100 runs.

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

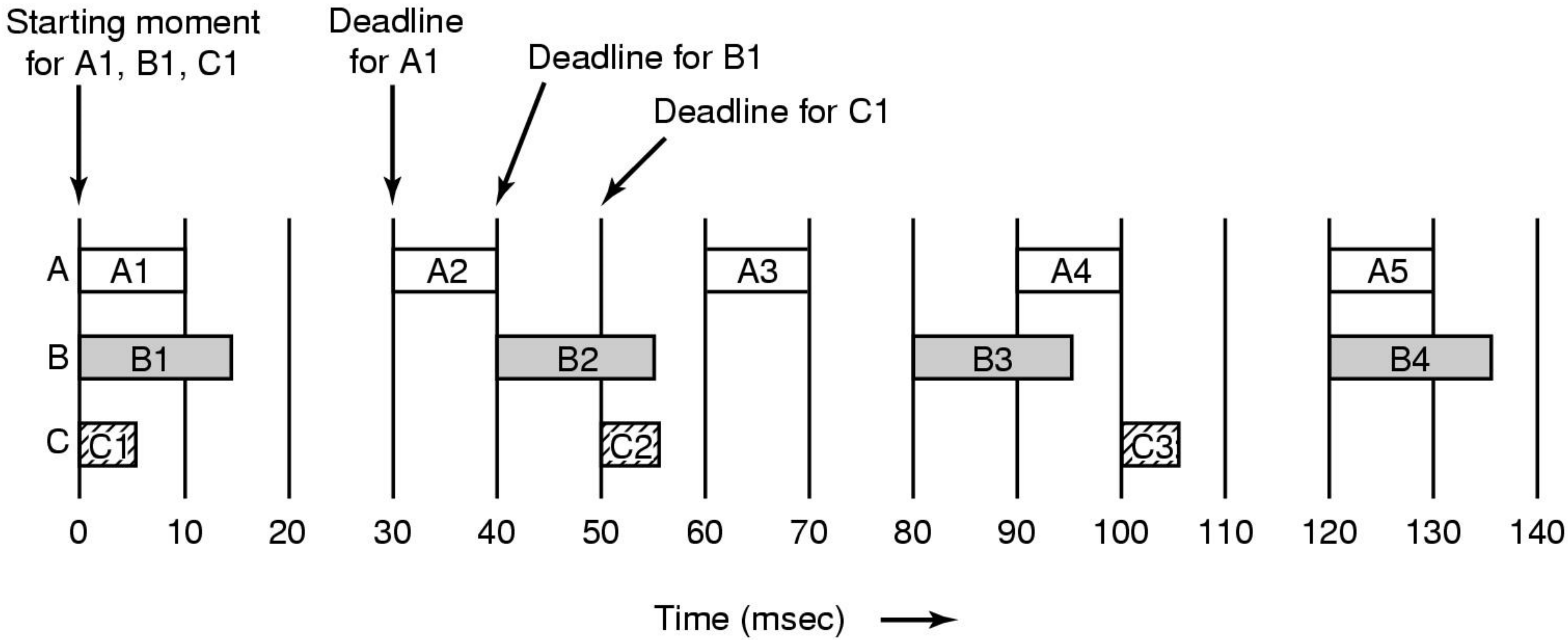
$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

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



THE UNIVERSITY OF NEW SOUTH WALES

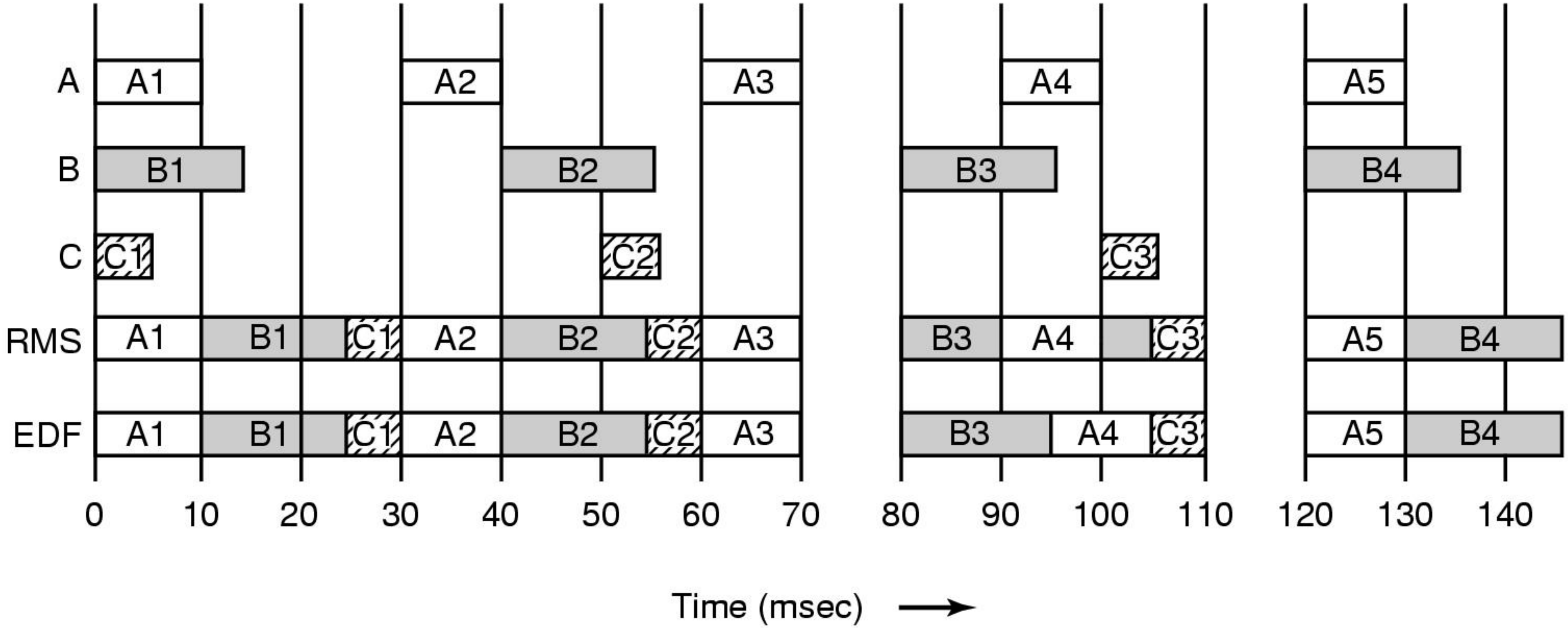
Is the Example Schedulable

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

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

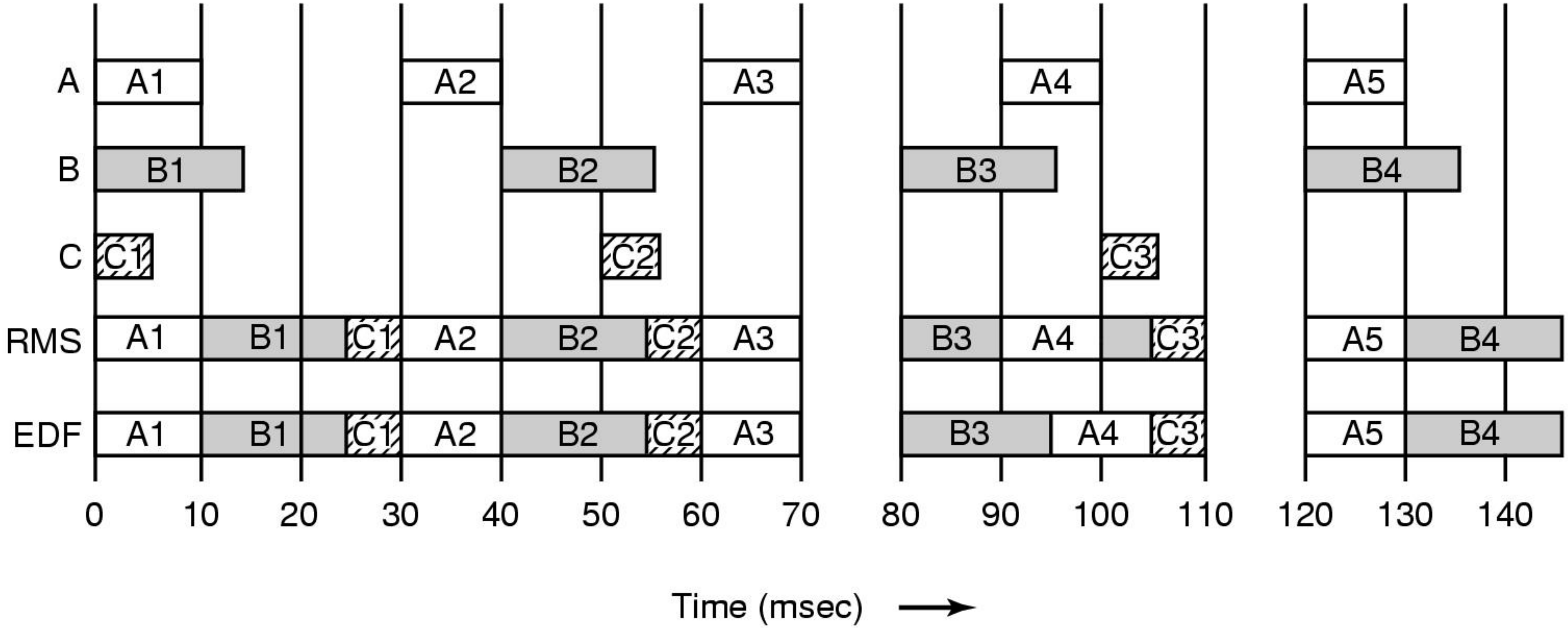
- YES

Two Schedules: RMS and EDF



THE UNIVERSITY OF NEW SOUTH WALES

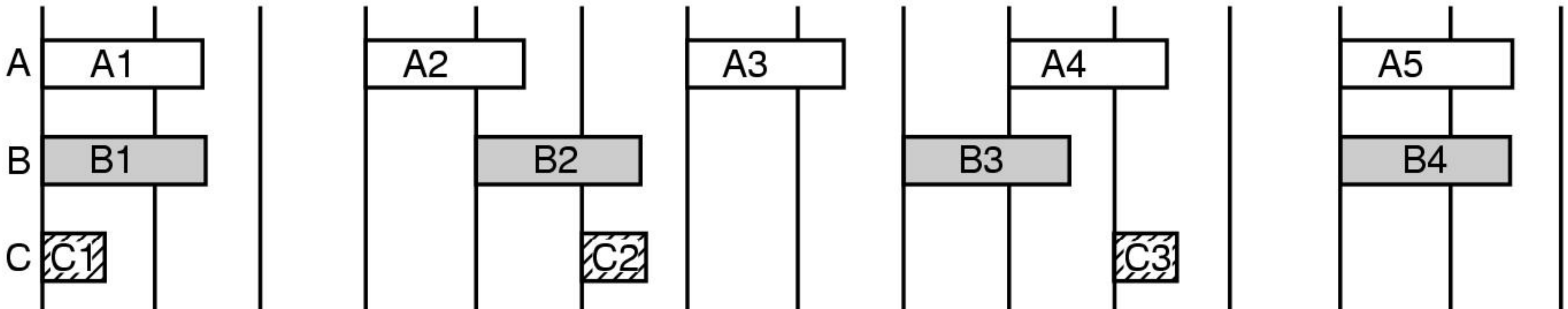
Two Schedules: RMS and EDF



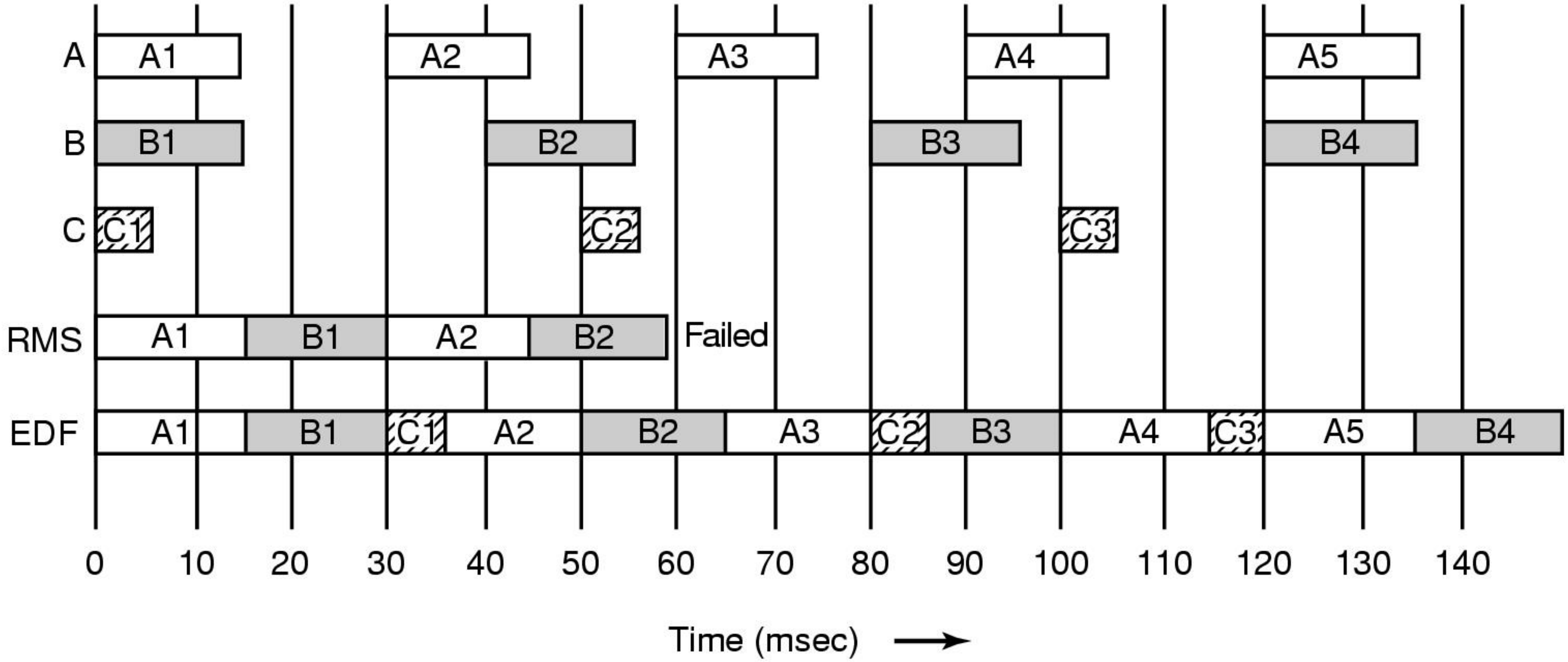
Let's Modify the Example Slightly

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

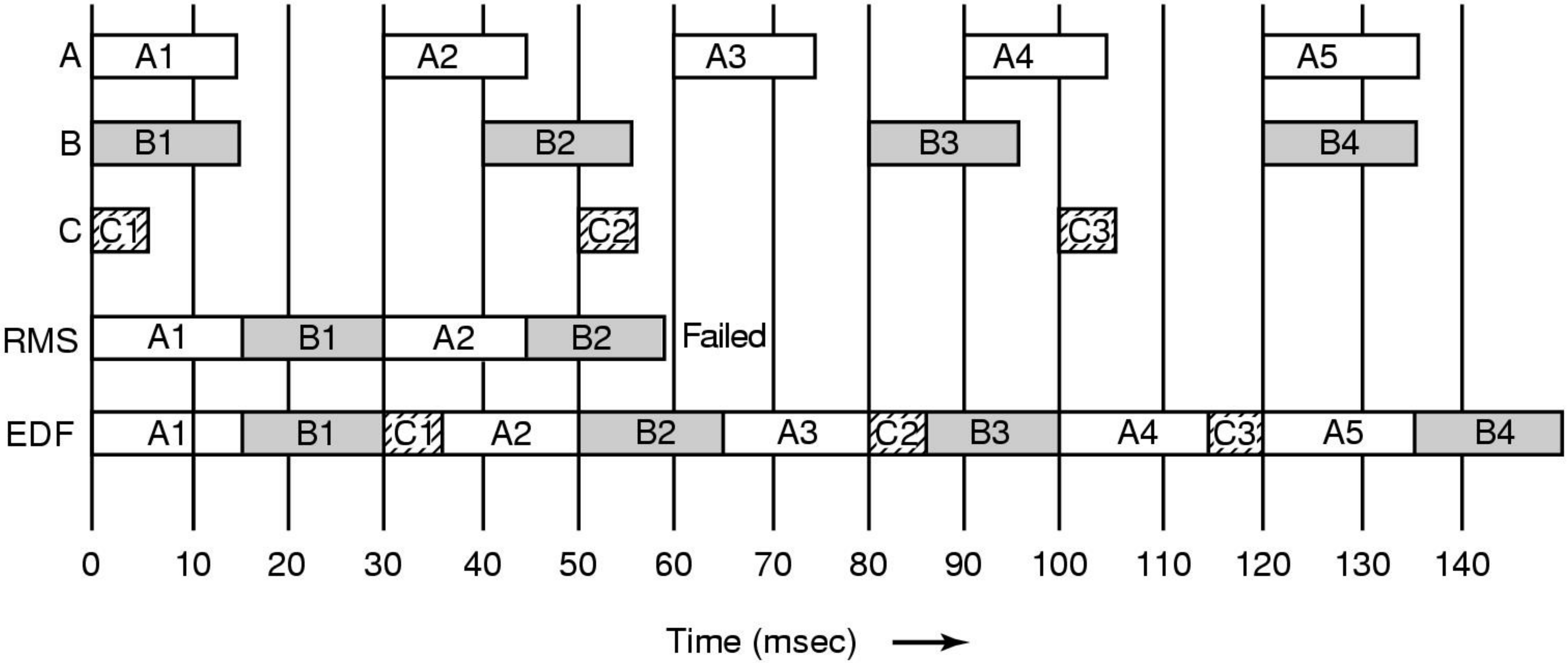
$$\frac{15}{30}+\frac{15}{40}+\frac{5}{50}=0.975$$



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
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 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