



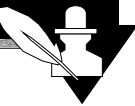
# 6

## Scheduling

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The Australian National University



## Concurrent & Distributed Systems



### References for this chapter

[Bacon98]

J. Bacon  
*Concurrent Systems*  
1998 (2nd Edition)  
Addison Wesley Longman Ltd,  
ISBN 0-201-17767-6

[Stallings2001] – Chapter 3,4

William Stallings  
*Operating Systems*  
Prentice Hall, 2001

all references and some links are available on the course page



## Concurrent & Distributed Systems

### Scheduling



### Purpose of scheduling

A scheduling scheme provides two features:

- **Ordering the use of resources** (e.g. CPUs, networks)
- **Predicting the worst-case behaviour** of the system when the scheduling algorithm is applied  
... in case that some or all information about the expected resource requests are known

A prediction can then be used

- ☞ at compile-run: to **confirm the overall resource requirements** of the application, or
- ☞ at run-time: to **permit acceptance** of additional usage/reservation requests.



## Concurrent & Distributed Systems

### Scheduling



### Criteria for scheduling methods

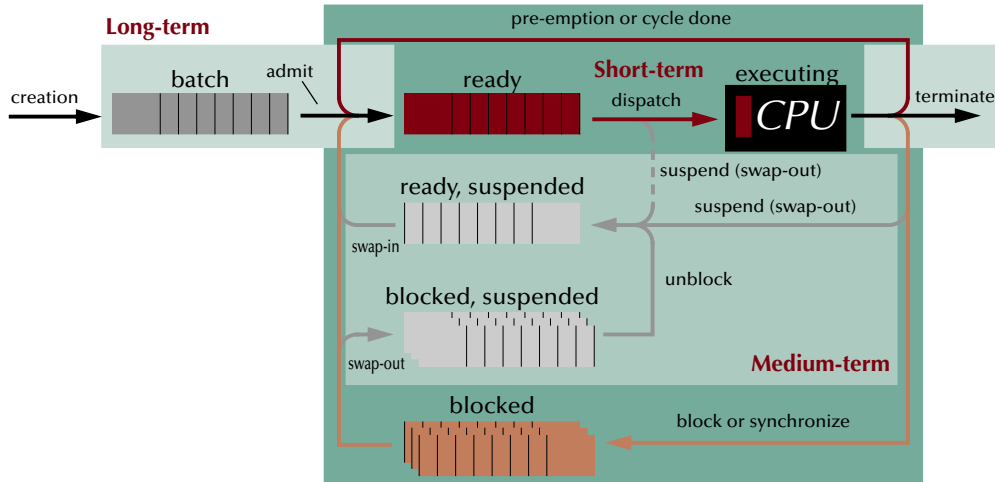
	<b>Performance criteria:</b> minimize the ...	<b>Predictability criteria:</b> minimize the diversion from given
Process / user perspective:		
<b>Waiting time</b>	maximum / average / variance	minimal and maximal waiting times
<b>Response time</b>	maximum / average / variance	minimal and maximal response times
<b>Turnaround time</b>	maximum / average / variance	deadlines
System perspective:		
<b>Throughput</b>	maximum / average / variance of CPU time per process	—
<b>Utilization</b>	CPU idle time	—



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## Scheduling

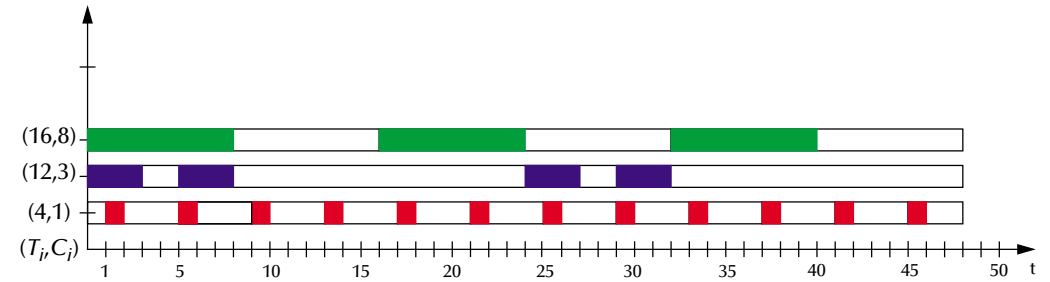
### Time scales of scheduling



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## Scheduling

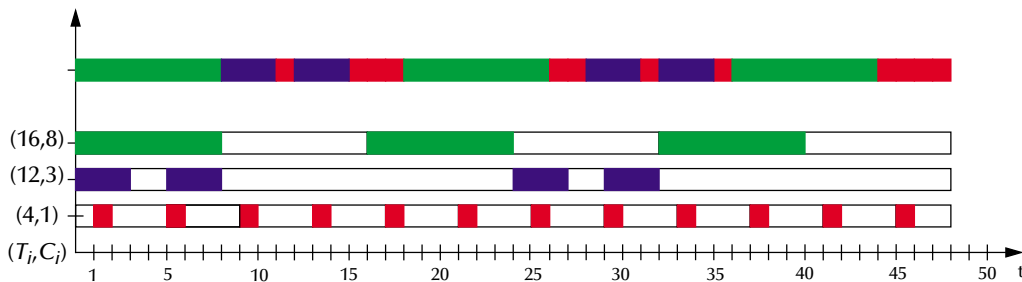
### Example: Requested times



# Concurrent & Distributed Systems

## Scheduling

First come, first served (FCFS) – bad case: (arrival order: ■, ■, ■)



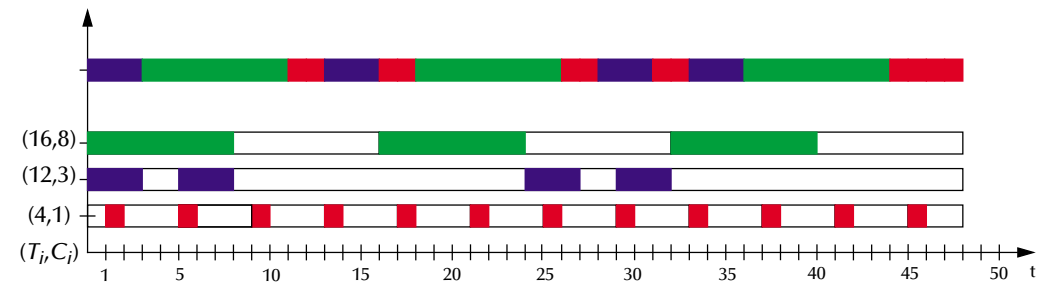
Waiting time: 0...11; average: 5.95 – Turnaround time: 3...12; average: 8.47



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## Scheduling

First come, first served (FCFS) – nice case: (arrival order: ■, ■, ■)



Waiting time: 0...11; average: 5.47 – Turnaround time: 3...12; average: 8.00

☛ The actual average waiting time for FCFS may vary here between: 5.47 and 5.95

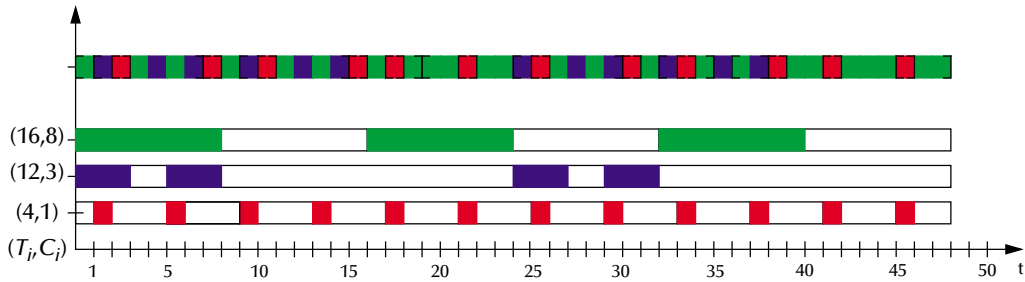


# Concurrent & Distributed Systems



## Scheduling

### Round robin (RR) – pre-emption



Waiting time: 0...4; average: 1.21 – Turnaround time: 1...19; average: 5.63

- ☞ Waiting and average turnaround time is going down, but maximal turnaround time is going up ... assuming that task-switching is free and always possible



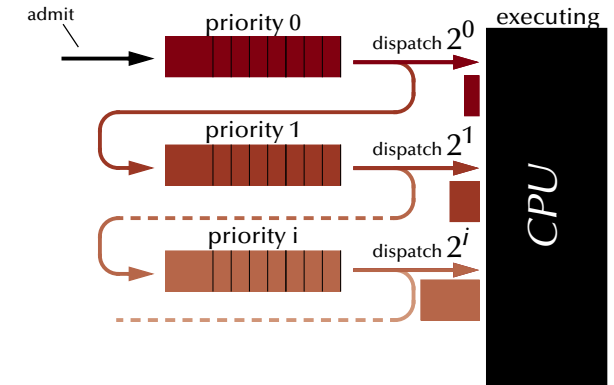
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## Scheduling

### Feedback with $2^i$ pre-emption intervals – pre-emption

- implement multiple hierarchical ready-queues
- fetch processes from the highest filled ready queue
- dispatch more CPU time for lower priorities ( $2^i$  units)



- ☞ processes on lower ranks may suffer starvation
- ☞ new and short tasks will be preferred

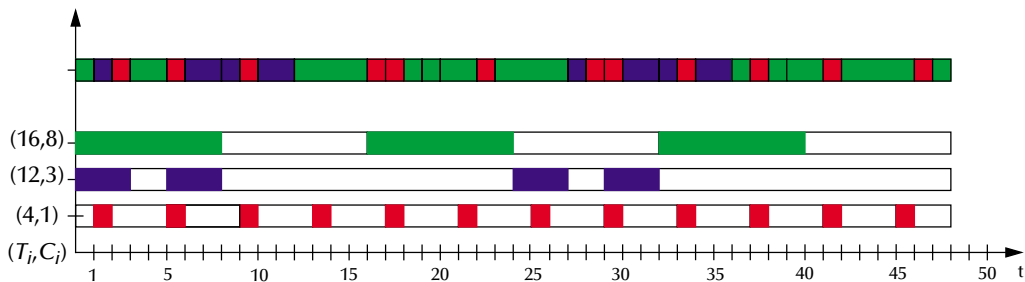


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## Scheduling

### Feedback with $2^i$ pre-emption intervals – pre-emption



Waiting time: 0...6; average: 1.79 – Turnaround time: 1...21; average: 5.63

- ☞ less task switches than RR, but long processes can suffer starvation!

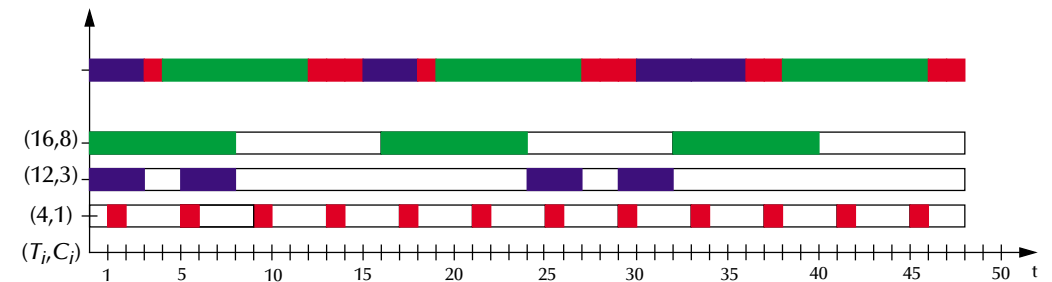


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## Scheduling

### Shortest job first (SJF) – $C_i$ is known



Waiting time: 0...10; average: 3.47 – Turnaround time: 1...14; average: 6.00

- ☞ on average this is doing better than FCFS

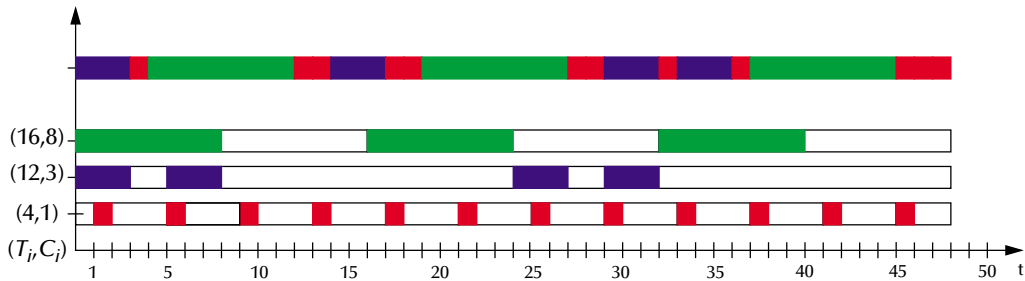


# Concurrent & Distributed Systems



## Scheduling

### Highest response ratio first (HRRF) – $C_i$ is known



Response ratio:  $(W_i + C_i)/C_i$  – Waiting time: 0...9; average: 4.11 – Turnaround time: 1...13; average 6.63

☞ on average this is doing worse than SJF, but the maximal waiting and turnaround times and variance might be reduced!

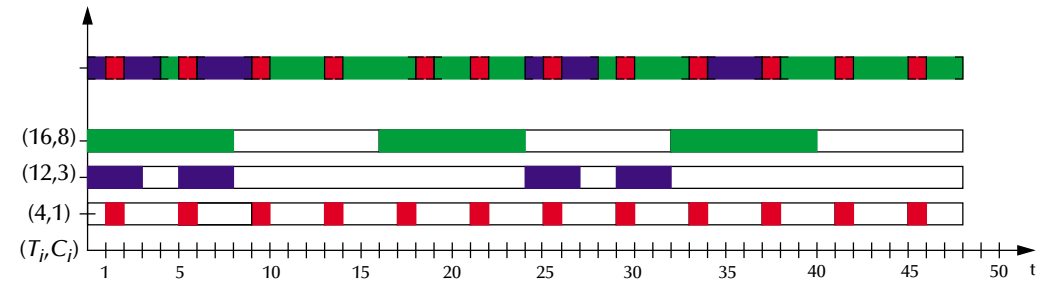


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## Scheduling

### Shortest remaining time first (SRTF) – $C_i$ is known + pre-emption



Waiting time: 0...6; average: 1.05 – Turnaround time: 1...18; average 4.42

☞ on average this is doing better than FCFS, SJF or HRRF, but the maximal turnaround time is going up and there are many task-switches!

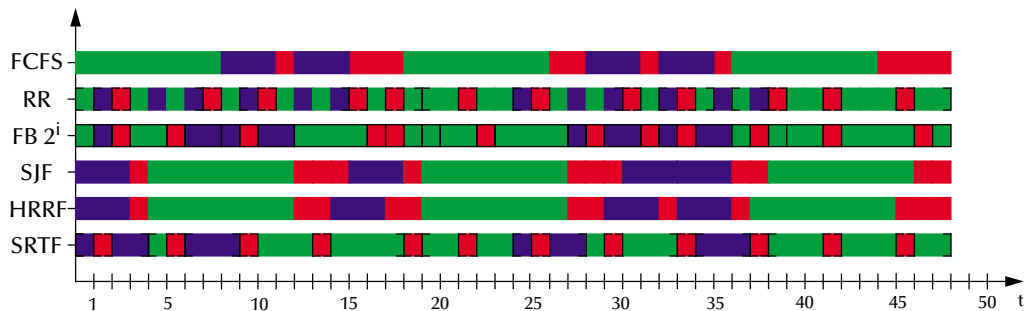


# Concurrent & Distributed Systems



## Scheduling

### Non-realtime scheduling methods



☞ CPU utilization: 100% in all cases.

☞ Pre-emptive methods perform better, assuming that the overhead is negligible.

☞ Knowledge of  $C_i$  (computation times) has a significant impact on scheduler performance.



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## Non-realtime scheduling methods

	Selection	Pre-emption	Waiting in high load situations	Turnaround	Preferred processes	Starvation possible?
FCFS	$\max(W_i)$	no	possibly long	possibly long	long	no
RR	equal share	yes	bound	possibly long	none	no
Feedback	priority queues	yes	short on average	very short on average, large maximum	short	yes
SJF	$\min(C_i)$	no	short on average	short on average	short	yes
HRRF	$\max\left(\frac{W_i + C_i}{C_i}\right)$	no	short on average, lower variance	short on average, lower variance	balanced, towards short	no
SRTF	$\min(C_i - E_i)$	yes	very short on average	very short on average, large maximum	short	yes



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## Predictable scheduling

### Towards predictable scheduling ...

- Task behaviours are more specified (restricted).
  - Task requirements are more specific (time scopes).
  - Task sets are often fully or mostly static.
  - Sporadic and urgent requests (e.g. user interaction, alarms) need to be addressed.
- CPU-utilization and throughput (system oriented performance measures) are not important!



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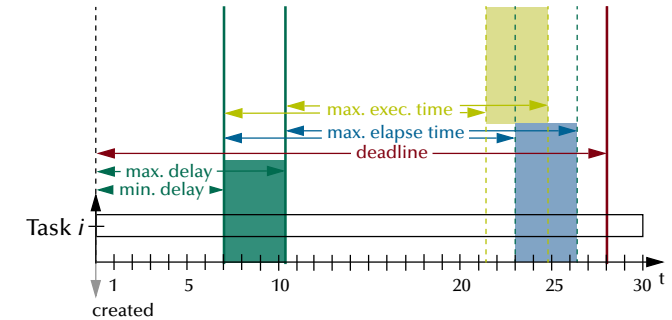


## Specifying timing requirements

### Temporal scopes

#### Common attributes:

- Minimal & maximal delay after creation
- Maximal elapsed time
- Maximal execution time
- Absolute deadline



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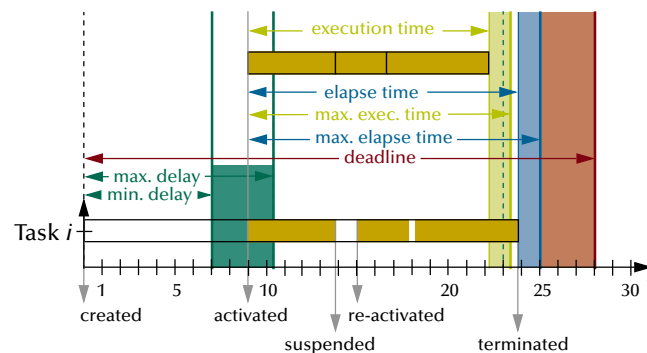


## Specifying timing requirements

### Temporal scopes

#### Common attributes:

- Minimal & maximal delay after creation
- Maximal elapsed time
- Maximal execution time
- Absolute deadline



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## Specifying timing requirements

### Some common scope attributes

#### Temporal Scopes can be:

<b>Periodic</b>	– e.g. controllers, samplers, monitors
<b>Aperiodic</b>	– e.g. 'periodic on average' tasks, burst requests
<b>Sporadic / Transient</b>	– e.g. mode changes, occasional services

#### Deadlines (absolute, elapse, or execution time) can be:

<b>Hard</b>	– single failure leads to severe malfunction
<b>Firm</b>	– results are meaningless after the deadline
<b>Soft</b>	– only multiple or permanent failures threaten the whole system
	– results may still be useful after the deadline



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## Predictable scheduling

### A simple process model

- The number of processes in the system is fixed.
  - All processes are periodic and all periods are known.
  - All deadlines are identical with the process cycle times (periods).
  - The worst case execution time is known for all processes.
  - All processes are independent.
  - All processes are released at once.
  - The task-switching overhead is negligible.
- ☞ this model can only be applied to a very specific group of systems.  
(more real-world extensions to this model will be discussed in other courses).

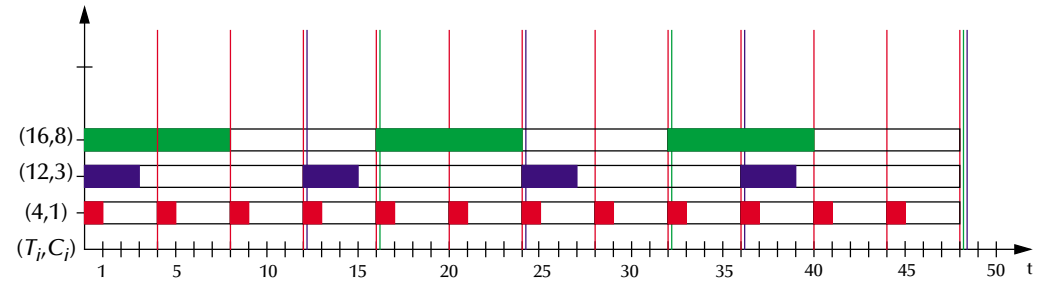


# Concurrent & Distributed Systems



## Predictable scheduling

### Introducing deadlines



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## Dynamic scheduling

### Earliest deadline first (EDF)

1. Determine (one of) the processe(s) with the closest deadline.
  2. Execute this process
    - 2-a until it finishes
    - 2-b or until another process' deadline is found closer than the current one.
- ☞ Pre-emptive scheme  
☞ Dynamic scheme, since the dispatched process is selected at run-time, due to the current deadlines.

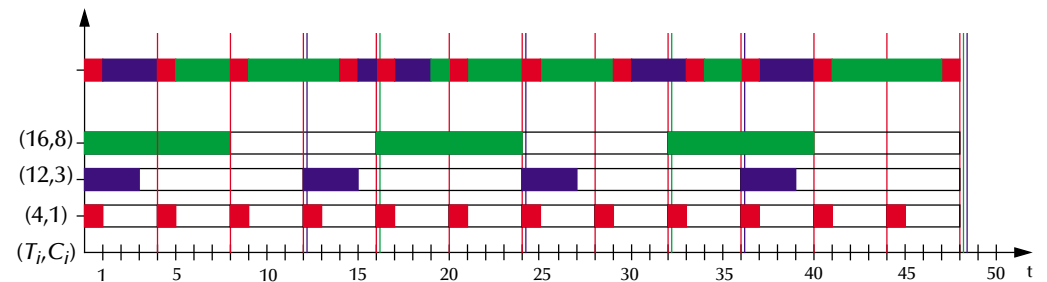


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## Dynamic scheduling: Earliest Deadline First (EDF)

### Earliest deadline first



1. Schedule the earliest deadline first
2. Avoid task switches (in case of equal deadlines)

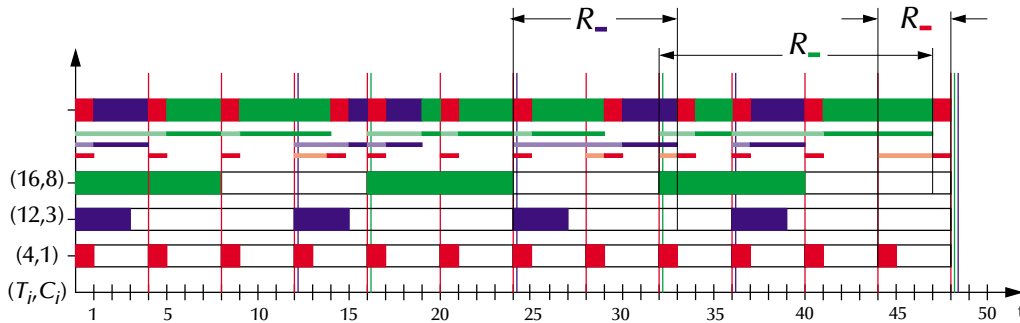


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## Dynamic scheduling: Earliest Deadline First (EDF)

### Earliest deadline first: Response times



worst case response times  $R_i$  (maximal time in which the request from task  $T_i$  is served):

☞ can be close or identical to deadlines.

☞ small or none spare capacity, if any task misses its expected computation time.

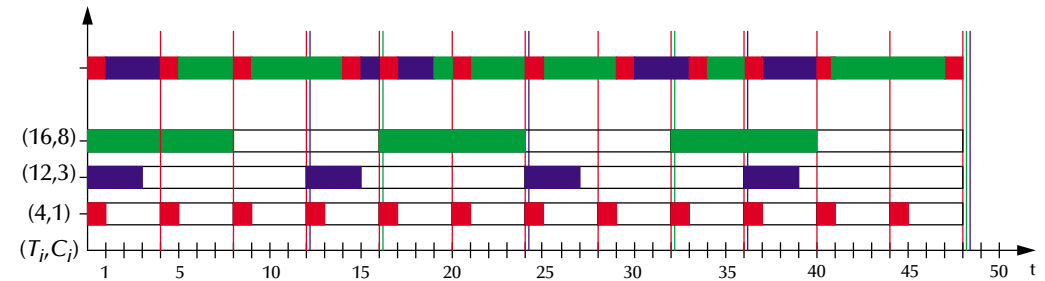


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## Dynamic scheduling: Earliest Deadline First (EDF)

### Earliest deadline first: Maximal utilization



☞ maximal possible utilization:  $\sum_{i=1}^n \frac{C_i}{T_i} \leq 1$  ☞ sufficient & necessary test!  
 with  $C_i, T_i$  the computation and cycle times of task  $i$   
 (the deadlines  $D_i$  are assumed to be identical with the cycles times  $T_i$  here)



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## Static scheduling

### Fixed Priority Scheduling (FPS), rate monotonic

1. Each process is assigned a fixed priority according to its cycle time  $T_i$ :

$$T_i < T_j \Rightarrow P_i > P_j$$

2. At any point in time: dispatch the process with the highest priority

☞ Pre-emptive scheme

☞ Static scheme, since the dispatch order of processes is fixed and calculated off-line.



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## Static scheduling

### Fixed Priority Scheduling (FPS), rate monotonic

Rate monotonic ordering is **optimal**  
(in the framework of fixed priority schedulers)

i.e. **if** a process set is schedulable under a FPS-scheme, **then** it is also schedulable by applying rate monotonic priorities.

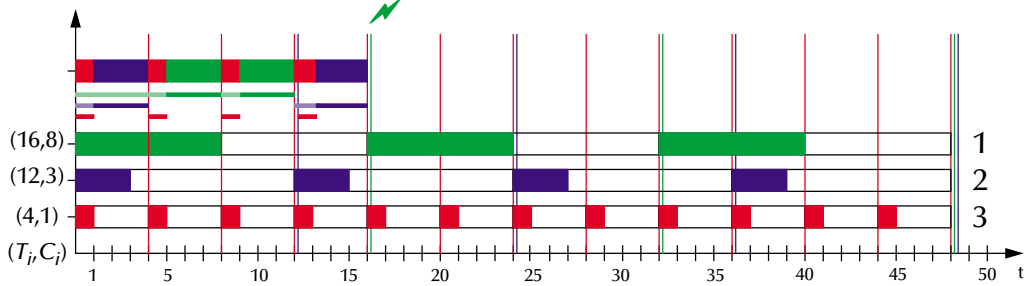


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Rate monotonic priorities



max. utilization test:  $\sum_{i=1}^n \frac{C_i}{T_i} \leq N \left( 2^{\frac{1}{N}} - 1 \right)$  ☞ sufficient, but not necessary test!

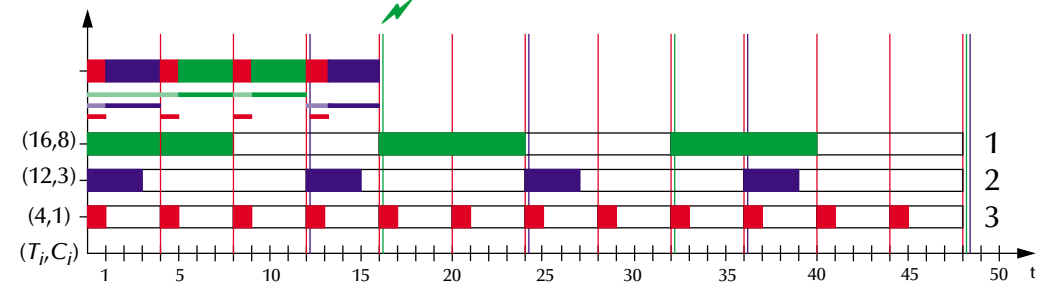


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Rate monotonic priorities



utilization test:  $\sum_{i=1}^n \frac{C_i}{T_i} = 1 > 0.779 \approx N \left( 2^{\frac{1}{N}} - 1 \right)$  ☞ not guaranteed!

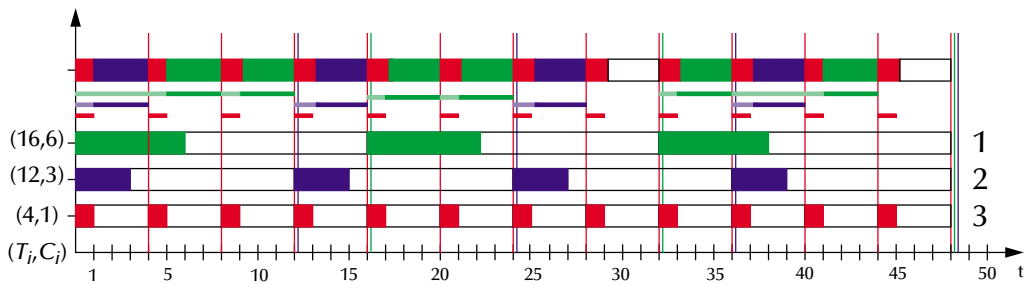


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Rate monotonic priorities (reduced requests)



☞ utilization:  $\frac{6}{16} + \frac{3}{12} + \frac{1}{4} = 0.875 > 0.779 \approx 3 \left( 2^{\frac{1}{3}} - 1 \right)$ ;  $\sum_{i=1}^n \frac{C_i}{T_i} \leq N \left( 2^{\frac{1}{N}} - 1 \right)$  ☞ not guaranteed!

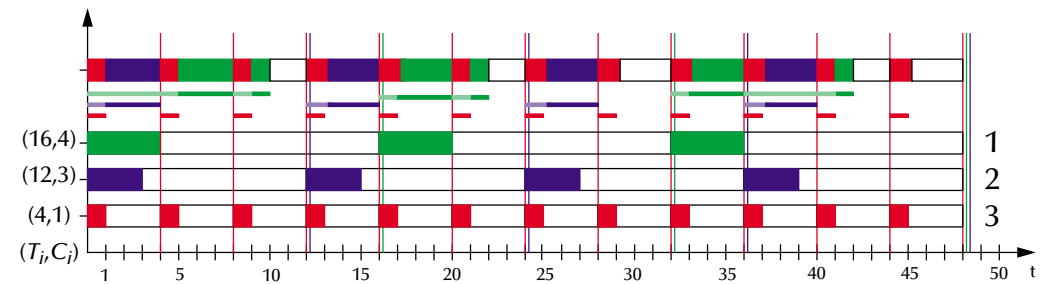


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Rate monotonic priorities (further reduced requests)



☞ utilization:  $\frac{4}{16} + \frac{3}{12} + \frac{1}{4} = 0.75 \leq 0.779 \approx 3 \left( 2^{\frac{1}{3}} - 1 \right)$ ;  $\sum_{i=1}^n \frac{C_i}{T_i} \leq N \left( 2^{\frac{1}{N}} - 1 \right)$  ☞ guaranteed!

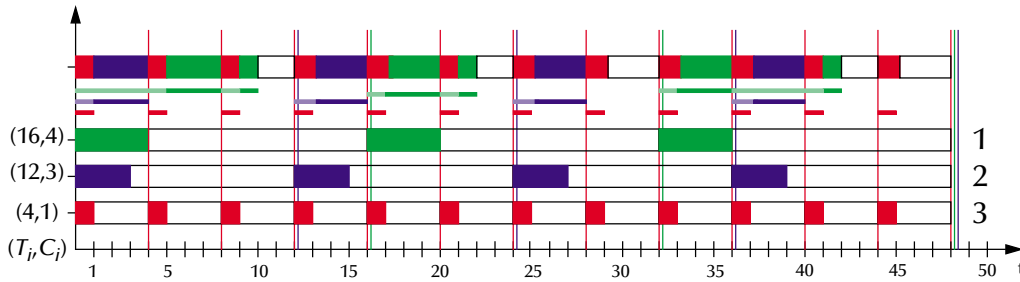


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)



calculate the worst case response times for each task individually.

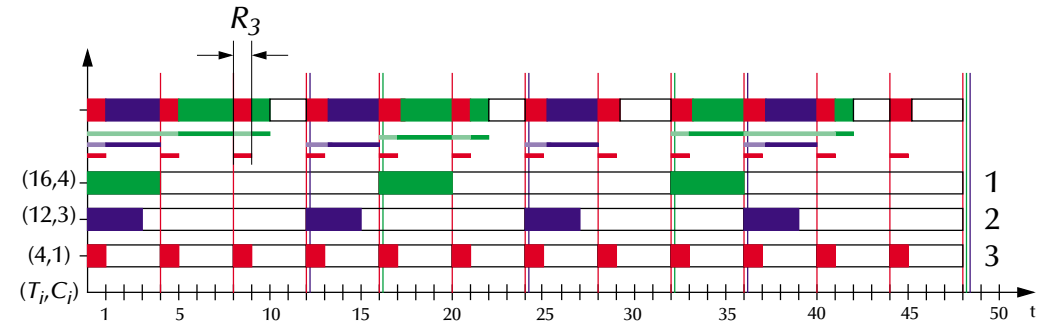


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)



for the highest priority task:  $R_3 = C_3$

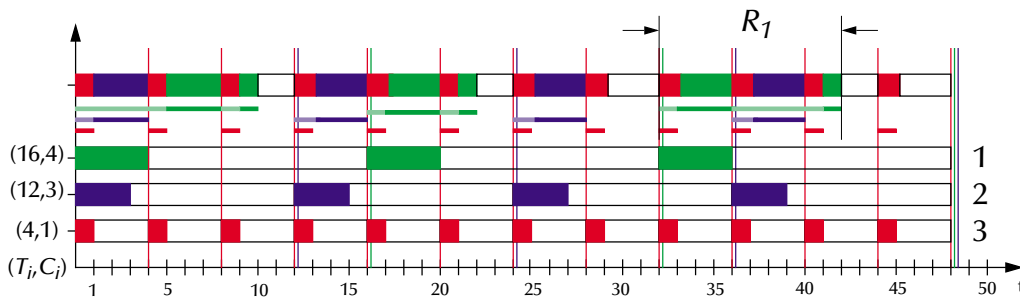


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)



for other tasks:  $R_j = C_j + I_j = \text{computation } C_j + \text{interference } I_j$

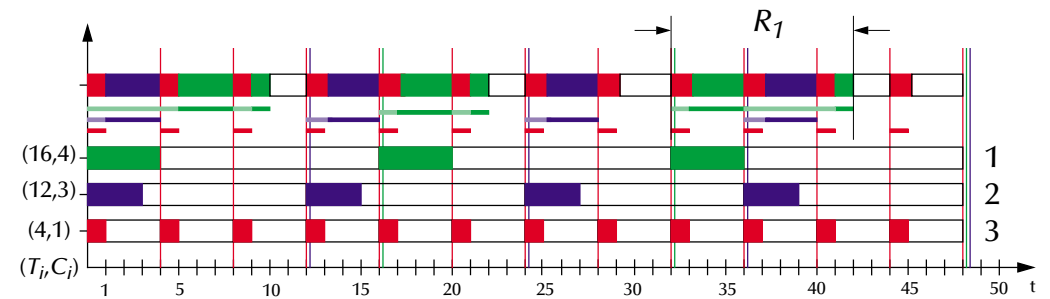


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)



$$\text{for other tasks: } R_j = C_j + \sum_{i>j} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

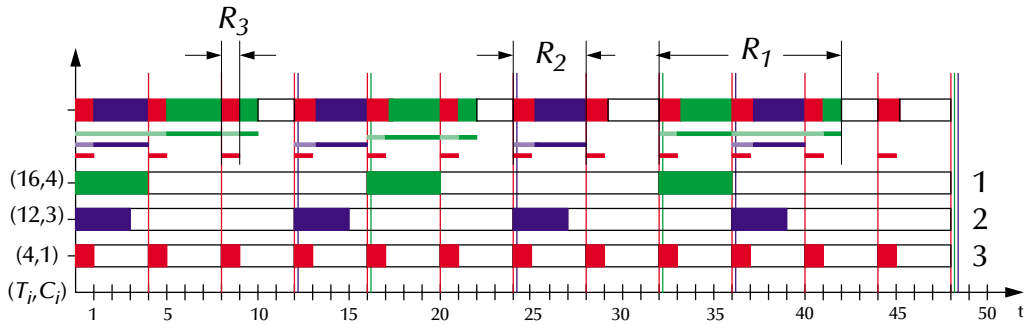


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (further reduced requests)



$$\checkmark R_3 = 1\checkmark; R_2 = 4\checkmark; R_1 = 10\checkmark \text{ and } \sum_{i=1}^n \frac{C_i}{T_i} \leq N \left( 2^{\frac{1}{N}} - 1 \right) \checkmark$$

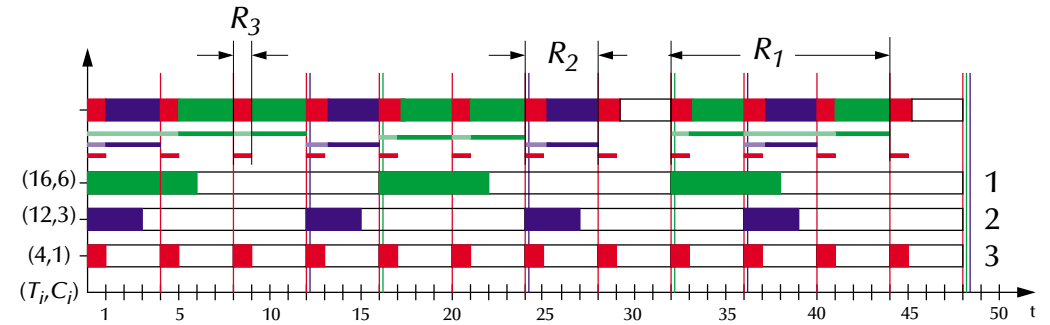


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (reduced requests)



$$\checkmark R_3 = 1\checkmark; R_2 = 4\checkmark; R_1 = 12\checkmark \text{ but } \sum_{i=1}^n \frac{C_i}{T_i} > N \left( 2^{\frac{1}{N}} - 1 \right) \times$$

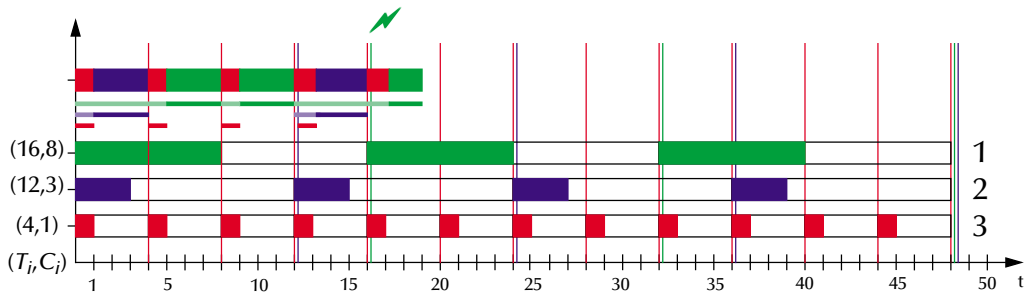


# Concurrent & Distributed Systems



Static scheduling: Fixed Priority Scheduling (FPS), rate monotonic

Response time analysis (full requests)



$$\checkmark R_3 = 1\checkmark; R_2 = 4\checkmark; R_1 = 19 \times \text{ and } \sum_{i=1}^n \frac{C_i}{T_i} > N \left( 2^{\frac{1}{N}} - 1 \right) \times$$

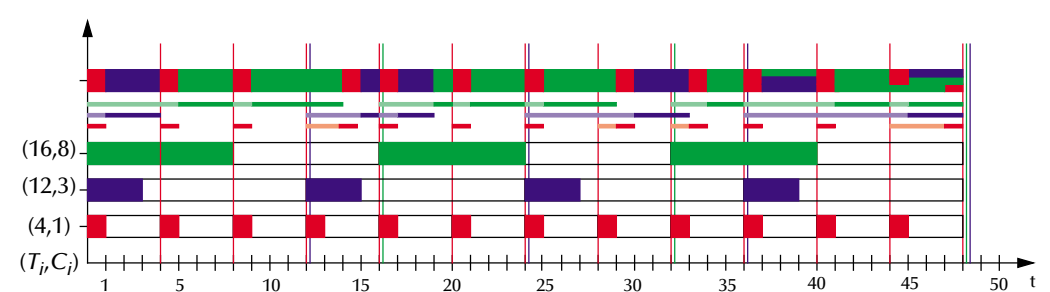


# Concurrent & Distributed Systems



Dynamic scheduling: Earliest Deadline First (EDF)

Response time analysis (full requests)



testing all combinations in a hyper-period: LCM of  $\{T_i\}$  — here: 48

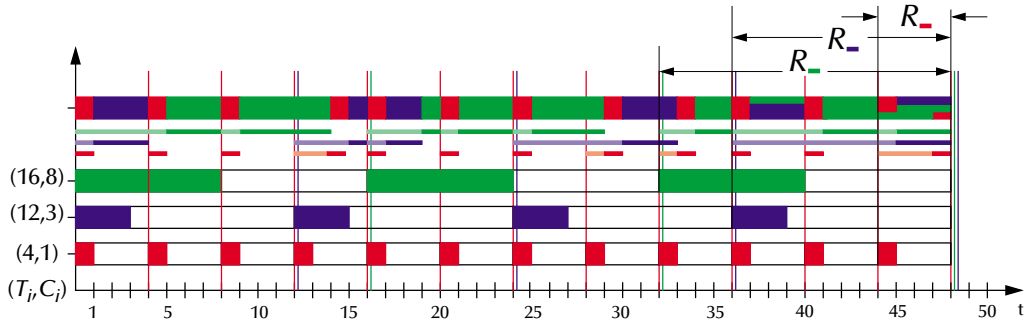


# Concurrent & Distributed Systems



## Dynamic scheduling: Earliest Deadline First (EDF)

### Response time analysis (full requests)



testing all combinations in a hyper-period: LCM of  $\{T_i\}$  – here: 48

$$R_-: 16 \leq 16\checkmark = T_-; \quad R_-: 12 \leq 12\checkmark = T_-; \quad R_-: 4 \leq 4\checkmark = T_-$$

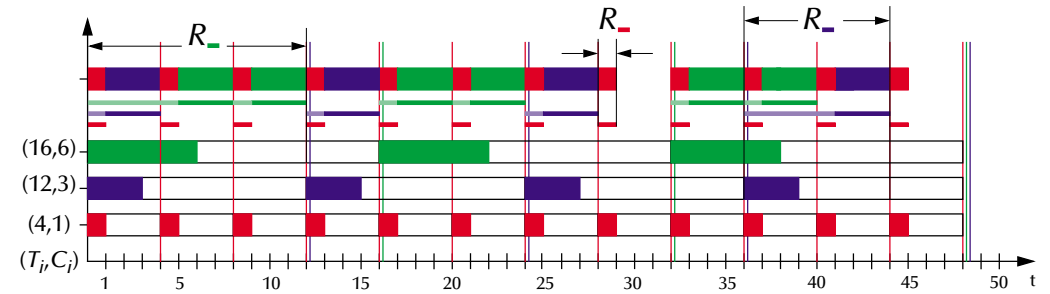


# Concurrent & Distributed Systems



## Dynamic scheduling: Earliest Deadline First (EDF)

### Response time analysis (reduced requests)



relaxed task-set changes:

$$R_-: 16 \rightarrow 12 \leq 16\checkmark = T_-; \quad R_-: 12 \rightarrow 8 \leq 12\checkmark = T_-; \quad R_-: 4 \rightarrow 1 \leq 4\checkmark = T_-$$

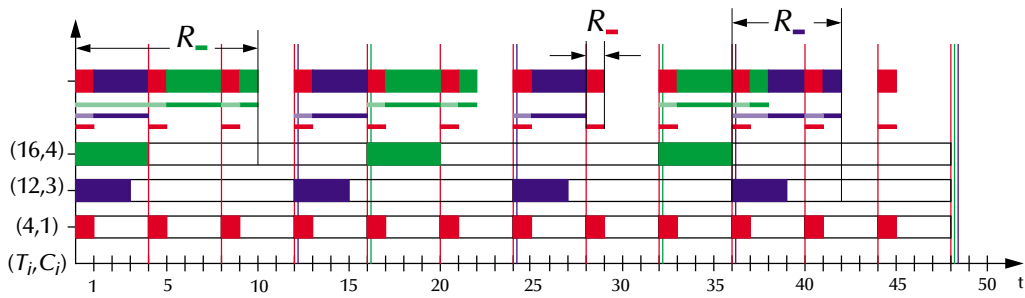


# Concurrent & Distributed Systems



## Dynamic scheduling: Earliest Deadline First (EDF)

### Response time analysis (further reduced requests)



further relaxed task-set changes:

$$R_-: 12 \rightarrow 10 \leq 16\checkmark = T_-; \quad R_-: 8 \rightarrow 6 \leq 12\checkmark = T_-; \quad R_-: 1 \rightarrow 1 \leq 4\checkmark = T_-$$



# Concurrent & Distributed Systems



## Real-time scheduling

### Response time analysis (comparison)

	Fixed Priority Scheduling		Earliest Deadline First	
	utilization test	response times $\{R_j\}$	utilization test	response times $\{R_j\}$
$\{(T_j, C_j)\} = \{(16, 8); (12, 3); (4, 1)\}$	✗ (1.000)	$\{\ast, 4, 1\}$	✓ (1.000)	$\{16, 12, 4\}$
$\{(T_j, C_j)\} = \{(16, 6); (12, 3); (4, 1)\}$	✗ (0.875)	$\{12, 4, 1\}$	✓ (0.875)	$\{12, 8, 1\}$
$\{(T_j, C_j)\} = \{(16, 4); (12, 3); (4, 1)\}$	✓ (0.750)	$\{10, 4, 1\}$	✓ (0.750)	$\{10, 6, 1\}$
	$\sum_{i=1}^n \frac{C_i}{T_i} \leq N \left( 2^{\frac{1}{N}} - 1 \right)$	$C_i + \sum_{j>i} \left\lceil \frac{R_j}{T_j} \right\rceil C_j$	$\sum_{i=1}^n \frac{C_j}{T_i} \leq 1$	check full hyper-cycle



## Real-time scheduling

### Fixed Priority Scheduling ↔ Earliest Deadline First

- EDF can handle higher (full) utilization than FPS.
- FPS is easier to implement and implies less run-time overhead
- Graceful degradation features (resource is over-booked):
  - FPS: processes with lower priorities will always miss their deadlines first.
  - EDF: any process can miss its deadline and can trigger a cascade of failed deadlines.
- Response time analysis and utilization tests:
  - FPS:  $O(n)$  utilization test — response time analysis: fixed point equation
  - EDS:  $O(n)$  utilization test — response time analysis: fixed point equation in hyper-cycle



	Selection	Pre-emption	Waiting	Turnaround	Preferred processes	Starvation possible?
FCFS	$\max(W_i)$	no	possibly long	possibly long	long	no
RR	equal share	yes	bound	possibly long	none	no
Feedback	priority queues	yes	short on average	very short on average, large maximum	short	yes
SJF	$\min(C_i)$	no	short on average	short on average	short	yes
HRRF	$\max((W_i + C_i)/C_i)$	no	short on average, lower variance	short on average, lower variance	balanced	no
SRTF	$\min(C_i - E_i)$	yes	very short on average	very short on average, large maximum	short	yes
FPS	$\max(P_i)$	yes	priority based	priority based	higher priority	yes
EDF	$\min(D_i)$	yes	deadline based	often close to deadlines	most urgent	no



## Summary

### Scheduling

- **Basic performance based scheduling**
  - $C_i$  is not known: first-come-first-served (FCFS), round robin (RR), and feedback-scheduling
  - $C_i$  is known: shortest job first (SJF), highest response ration first (HRRF), shortest remaining time first (SRTF)-scheduling
- **Basic predictable scheduling**
  - Fixed Priority Scheduling (FPS) with Rate Monotonic (RMPO)
  - Earliest Deadline First (EDF)