# CSE 120: Principles of Operating Systems
# Lecture 4: Scheduling

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# The CPU Scheduling Problem

- Scheduling: which process gets CPU and when
- Given multiple processes, but only one CPU
- How much CPU time does each process get?
- Possibilities
  - Keep CPU till done
  - Each process uses CPU a bit and passes it on
  - Each process gets proportional to what they pay
- Which is the best policy?

# There is No Single Best Policy

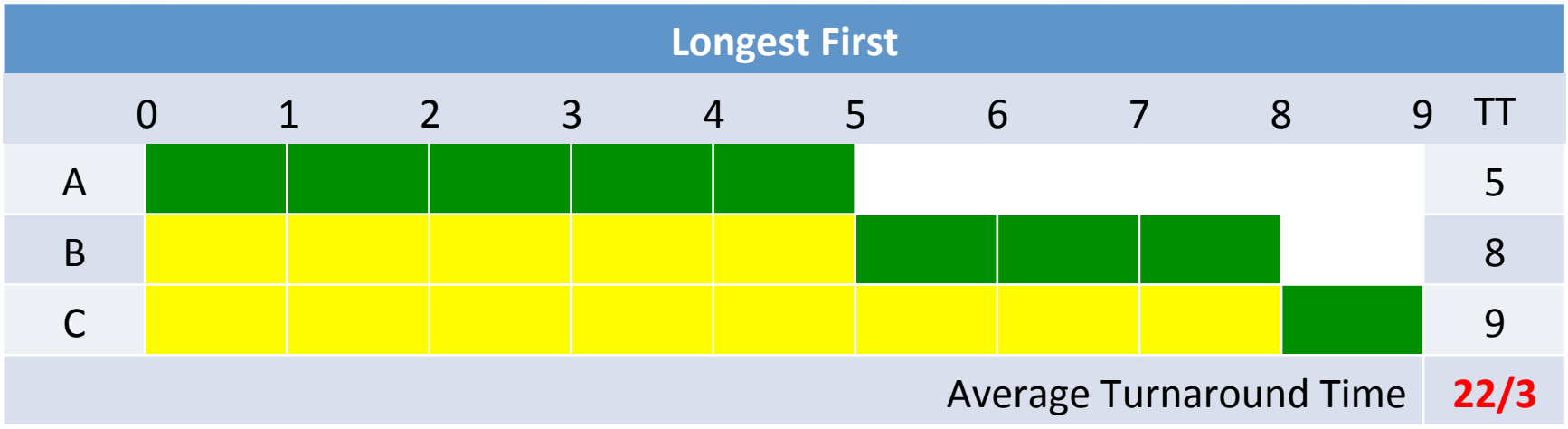
- Depends on the goals of the system
- Different for
  - your personal computer
  - large time-shared computer
  - computer controlling a nuclear power plant
- Might even have multiple (conflicting) goals

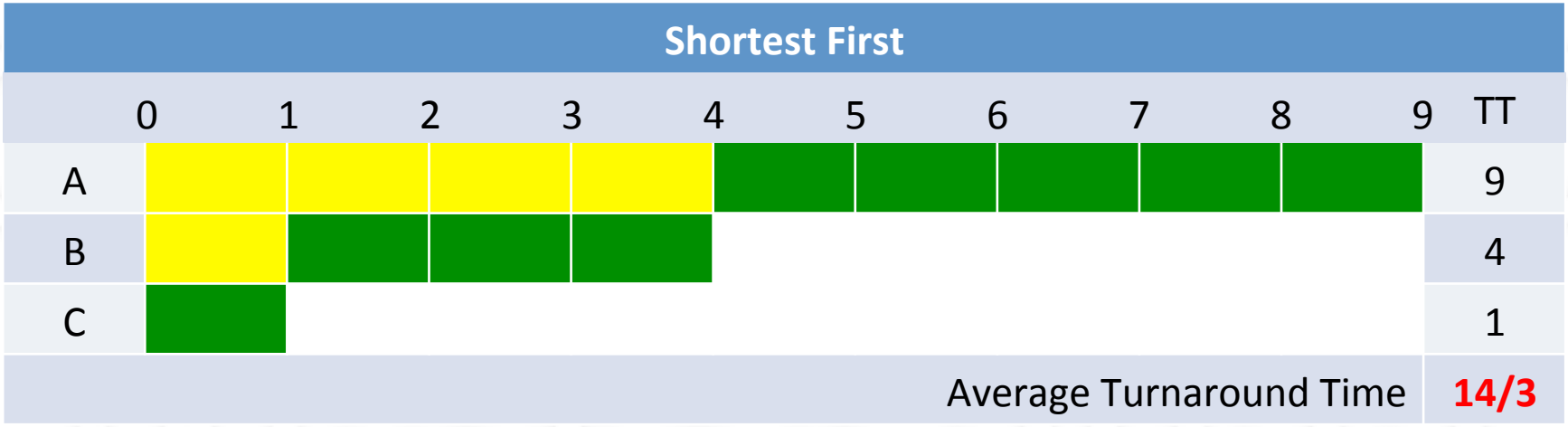
# Scheduling: An Example

| Process | Arrival Time | Service Time |
|---|---|---|
| A | 0 | 5 |
| B | 0 | 3 |
| C | 0 | 1 |

- Arrival time: time that process is created
- Service time: CPU time needed to complete
- Turnaround time: from arrival to departure
  - Process arrives, waits for CPU, then uses (in bursts)
  - Departs after CPU usage equals service time
- What order minimizes average turnaround time?

# Longest First vs. Shortest First



# Shortest First Is Provably Optimal

- Given n processes with service times $S_1$, … , $S_n$
  - Note: processes are numbered 1, 2, 3, …, *n*
- Average turnaround time computed as follows

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  - $[S_1 + (S_1 + S_2) + (S_1 + S_2 + S_3) + \ldots + (S_1 + \ldots + S_n)] / n$

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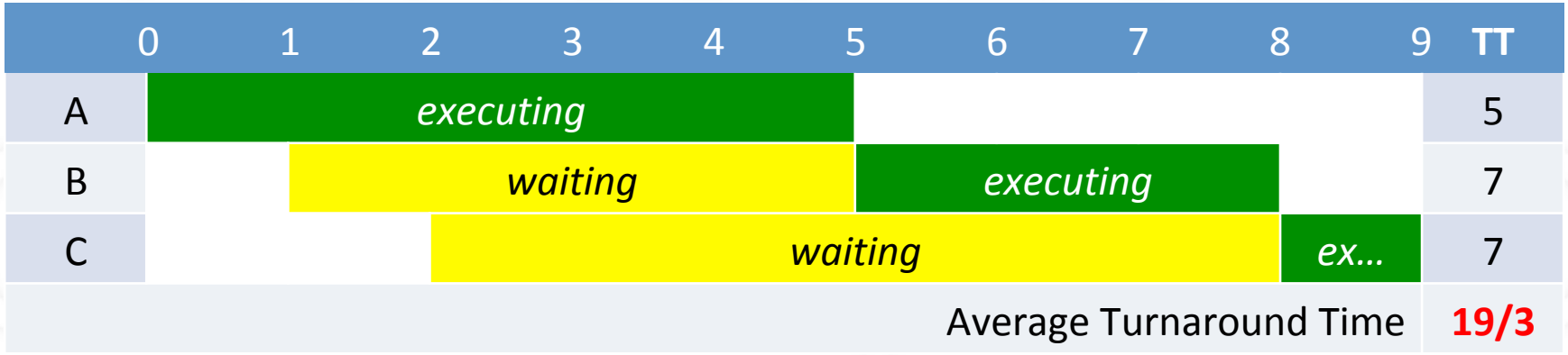
  - $[(n \times S_1) + ((n\text{-}1) \times S_2) + ((n\text{-}2) \times S_3) + \ldots + S_n] / n$

# Shortest First Is Provably Optimal

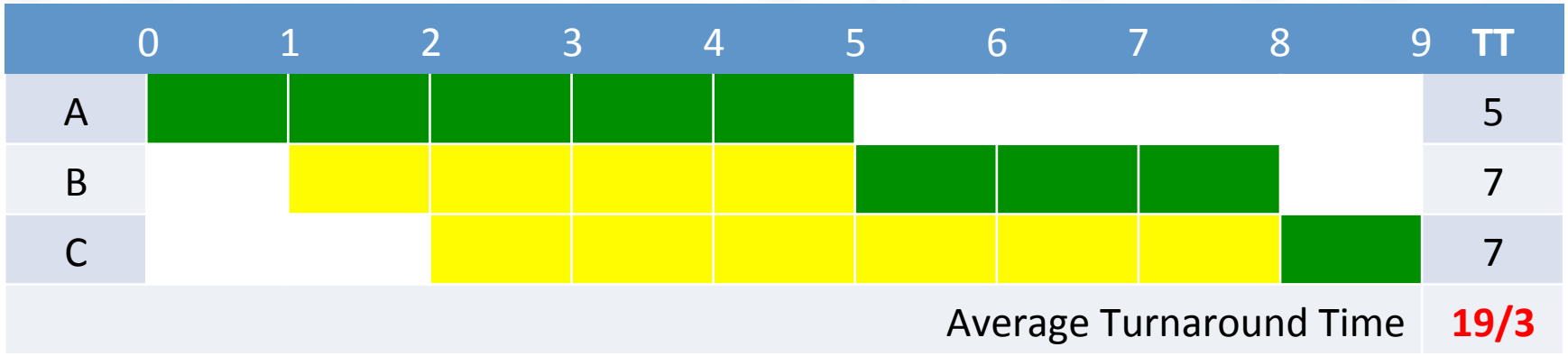
- Given n processes with service times $S_1$, … , $S_n$
  - Note: processes are numbered 1, 2, 3, …, *n*
- Average turnaround time computed as follows
  - $[S_1 + (S_1 + S_2) + (S_1 + S_2 + S_3) + \ldots + (S_1 + \ldots + S_n)] / n$
  - $[(n \times S_1) + ((n\text{-}1) \times S_2) + ((n\text{-}2) \times S_3) + \ldots + S_n] / n$
- In general: order by shortest to longest
  - $S_1$ has maximum weight (*n*), minimize it
  - $S_2$ has next-highest (*n*-1), minimize it after $S_1$ ; …

# Consider Different Arrival Times

| Process | Arrival Time | Service Time |
|---|---|---|
| A | 0 | 5 |
| B | 1 | 3 |
| C | 2 | 1 |

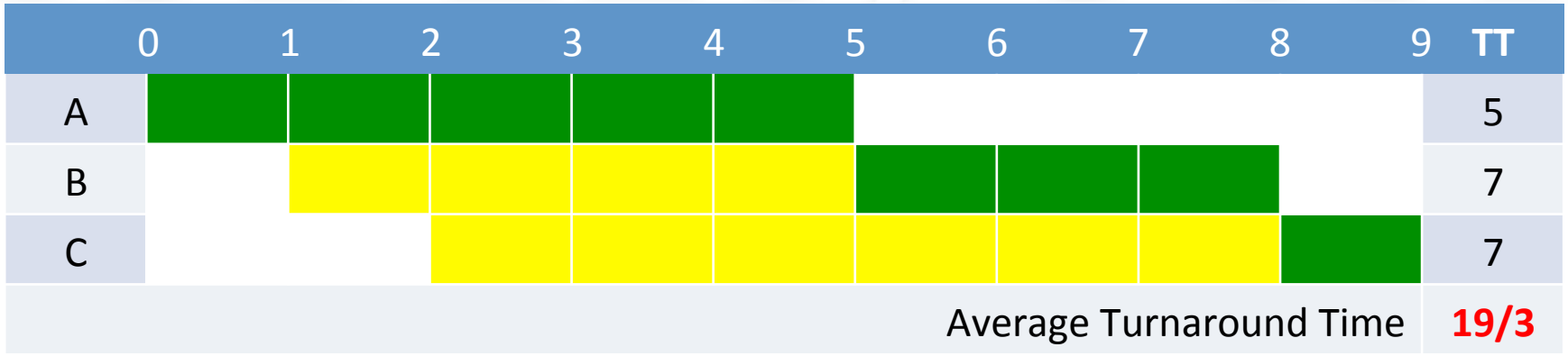


# FCFS: First Come First Served




- Allocate CPU to processes in order of arrival
- A B]A B]A CB]A CB]A CB]A CB]A C]B C]B C]B C
  - A At 0, A arrives and runs at 0
  - B]A At 1-, B arrives, enters queue (A still running)
  - B]A At 1, B is in the queue, A is running

# FCFS: First Come First Served

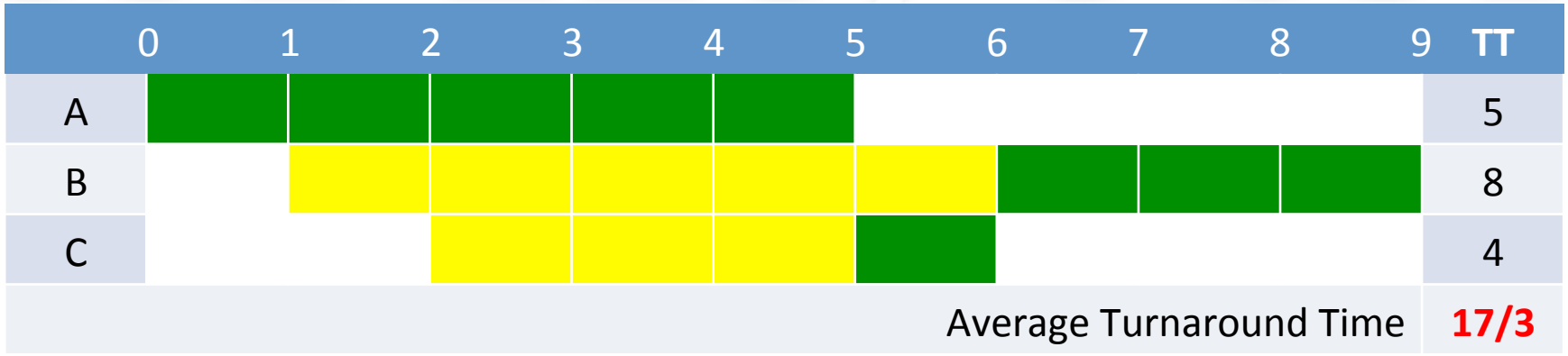



- Allocate CPU to processes in order of arrival
- A B]A B]A CB]A CB]A CB]A CB]A C]B C]B C]B C
- Average turnaround time = (5 + 7 + 7)/3 = 6.3
- Non-preemptive, simple, no starvation
- Poor for short processes

# RR: Round Robin

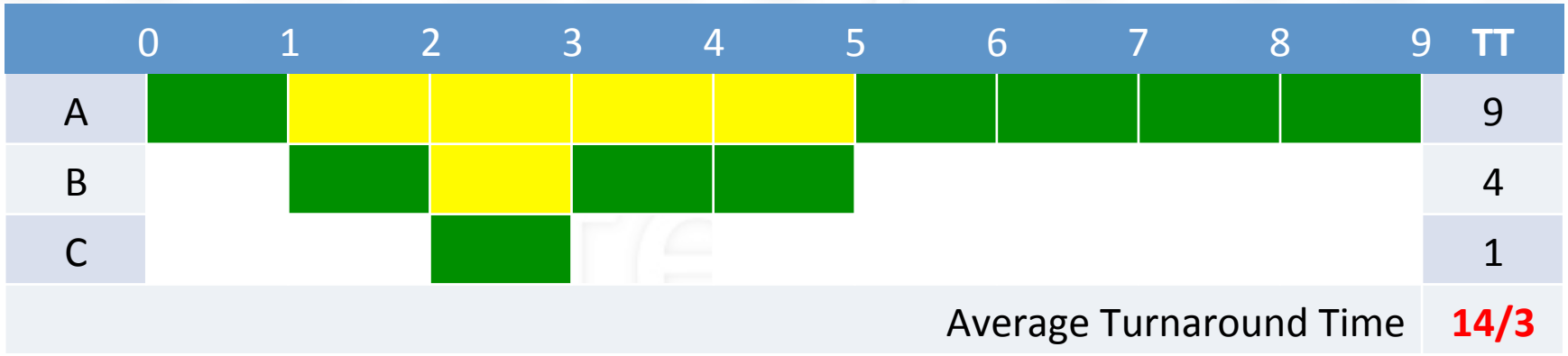

- Time-slice: each process gets quantum in turn
- A B]A A]B CA]B BC]A AB]C A]B B]A A]B A A
- Average turnaround time = (9 + 6 + 2)/3 = 5.7
- Preemptive, simple, no starvation
- Process waits at most (*n* - 1) x quantum

# SPN: Shortest Process Next




- Select process with shortest service time
- A B]A B]A BC]A BC]A BC]A BC]A B]C B B B
- Average turnaround time = (5 + 8 + 4)/3 = 5.7
- Optimal for non-preemptive, allows starvation
- Assumes service times are known

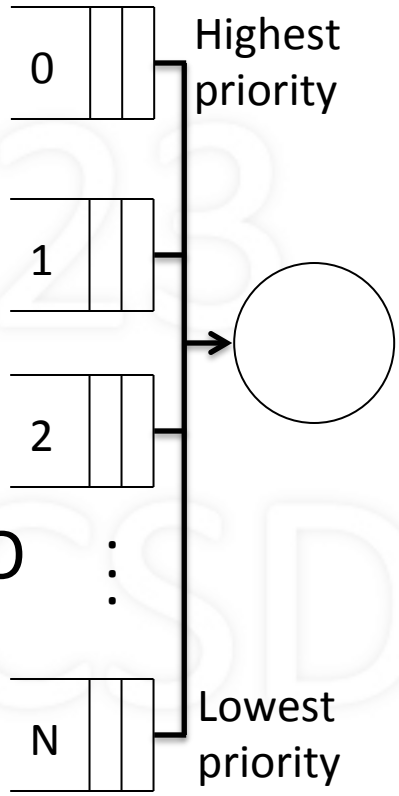
# SRT: Shortest Remaining Time



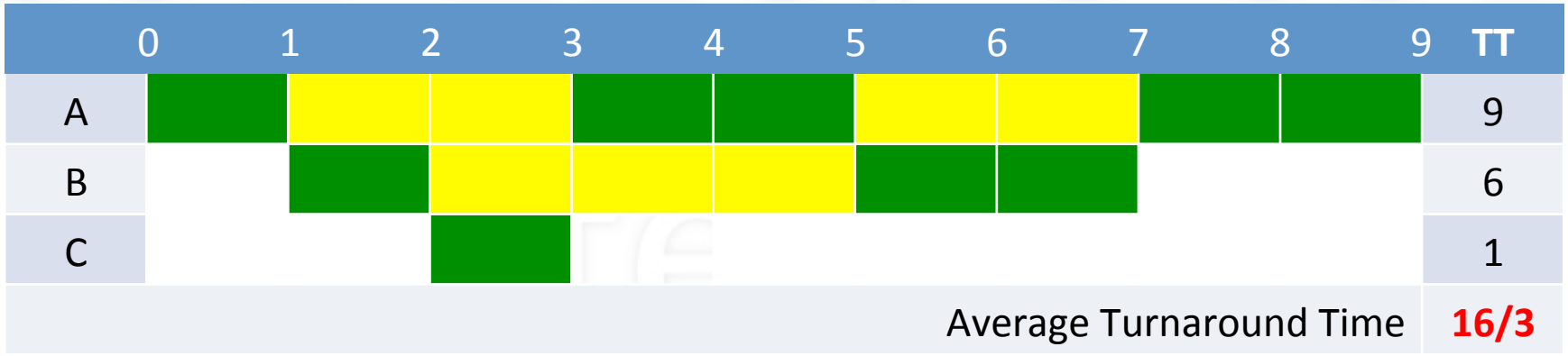

- Select process with shortest remaining time
- A B]A A]B AC]B AB]C A]B A]B A A A A
- Average turnaround time = (9 + 4 + 1)/3 = 4.7
- Assumes service times are known
- Optimal for preemptive, but allows starvation

# Multi-Level Feedback Queues

- Priority queues: 0 (high), …, *N* (low)
- New processes enter queue 0
- Select from highest priority queue
- Run for T = $2^k$ quantums
  - Used T: move to next lower queue, FIFO
  - Used < T: back to same queue, RR
    - Due to yield or higher priority arrival
- Periodically boost (e.g., all to highest queue)

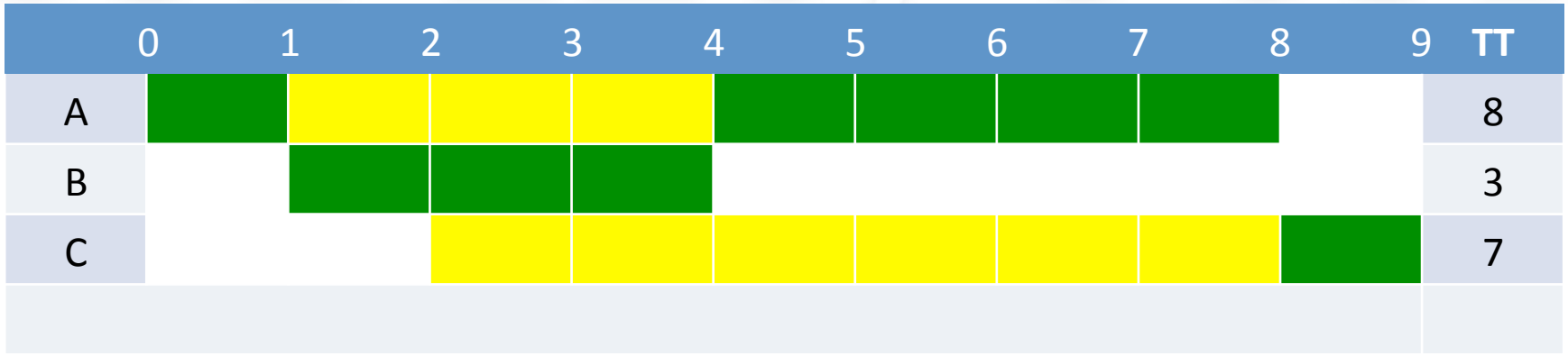


# Multi-Level Feedback Queues




- Select from highest queue *k*, run $2^k$ quantums
- A $B]_0A$ $A]_1B$ $A]_1C]_0B$ $BA]_1C$ $B]_1A(2)$ $A]_2B(2)$ A
- Average Turnaround Time = (9 + 6 + 1)/3 = 5.3
- Complex, adaptive, highly responsive
- Favors shorter over longer, possible starvation

# Priority Scheduling




- Select process with highest priority
  - Example: $P_A$ = medium, $P_B$ = high, $P_C$ = low
- $A_M$ $B_H$]$A_M$ $A_M$]$B_H$ $C_L$$A_M$]$B_H$ $C_L$$A_M$]$B_H$(2) $C_L$]$A_M$(4) C
- Allows scheduling based on external criteria
  - E.g., priority = 1/CPU_time_used, or = *f* (*pay*)

# Fair Share (Proportional Share)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 100% | 50% | 33% | 50% | 40% | 50% | 43% | 50% | 44% | 50% |
| B | 0% | 50% | 33% | 25% | 20% | 17% | 14% | 13% | 11% | 10% |
| C | 0% | 0% | 33% | 25% | 40% | 33% | 43% | 38% | 44% | 40% |

- Each process requests some CPU utilization
  - Utilization: what percentage of time resource is used
  - Example of requests: A: 50%; B: 10%; C: 40%
- Goal: utilization over long run, actual ≈ request
- How do we determine who runs each quantum?
- Select process with minimum actual/request ratio

# FS Example: A 50%, B 10%, C 40%

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | | | | | | | | | | |
| B | | | | | | | | | | |
| C | | | | | | | | | | |

- At time 0 A: 0/50 B: 0/10 C: 0/40
- All 0, so arbitrary select A

# FS Example: A 50%, B 10%, C 40%

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 100% | | | | | | | | | |
| B | 0% | | | | | | | | | |
| C | 0% | | | | | | | | | |

- After 1q A: 100/50 B: 0/10 C: 0/40
- A got 100%, but only requested 50% (100/50)
  - Got *more* than its fair share (100/50 = 2 > 1)!
- Both B, C got 0%, less than their fair shares
- Select process with min actual/request ratio: B

# FS Example: A 50%, B 10%, C 40%

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 100% | 50% | | | | | | | | |
| B | 0% | 50% | | | | | | | | |
| C | 0% | 0% | | | | | | | | |

- After 2q  A: 50/50  B: 50/10  C: 0/40
- A got 50%: used 1 out of 2q; same for B
  - A got *exactly* its fair share (50/50 = 1)
  - B got *more* than its fair share (50/10 = 5 > 1)
- Select process with min actual/request ratio: C

# FS Example: A 50%, B 10%, C 40%

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 100% | 50% | 33% | | | | | | | |
| B | 0% | 50% | 33% | | | | | | | |
| C | 0% | 0% | 33% | | | | | | | |

- After 3q A: 33/50 B: 33/10 C: 33/40
- A got 33% as it used 1 out of 3; same for B, C
  - A, C got *less* than their fair share (33/50, 33/40 < 1)
  - B got *more* than its fair share (33/10 > 1)
- Select process with min actual/request ratio: A

# FS Example: A 50%, B 10%, C 40%

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 100% | 50% | 33% | 50% | | | | | | |
| B | 0% | 50% | 33% | 25% | | | | | | |
| C | 0% | 0% | 33% | 25% | | | | | | |

- After 4q A: 50/50 B: 25/10 C: 25/40
- A got 50% as it used 2 out of 4
- B and C got 25%, using 1 out of 4
- A got its fair share; B got more; C got less
- Select process with min actual/request ratio: C

# FS Example: A 50%, B 10%, C 40%

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 100% | 50% | 33% | 50% | 40% | 50% | 43% | 50% | 44% | 50% |
| B | 0% | 50% | 33% | 25% | 20% | 17% | 14% | 13% | 11% | 10% |
| C | 0% | 0% | 33% | 25% | 40% | 33% | 43% | 38% | 44% | 40% |

- After 10q A: 50/50 B: 10/10 C: 40/40
- Recall goal: over long run, actual ≈ request
  - Process utilizations are what they requested!
- However, algorithm shown is inefficient
  - Each q, each p: calculate actual/request, select min

# Stride Scheduling

- For processes A, B, C … with requests $R_A$, $R_B$, $R_C$ …
- Calculate ***strides***: $S_A = 1/R_A$, $S_B = 1/R_B$, $S_C = 1/R_C$ …
- For each process *x*, maintain ***pass*** value $P_x$ (init 0)
- Schedule: repeat every quantum
  - Select process *x* with minimum pass value $P_x$, run
  - Increment pass value by stride value: $P_x = P_x + S_x$
- Optimization: use only integers for $R_x$, $S_x$ and $P_x$
  - Calculate $S_x = L/R_x$ using very large L, e.g., L = 100000

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | | | | | |
| quantum 2 | | | | | |
| quantum 3 | | | | | |
| quantum 4 | | | | | |
| quantum 5 | | | | | |
| quantum 6 | | | | | |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- All pass values 0, select one arbitrarily: A

# Stride Scheduling Example

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| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | | | | | |
| quantum 3 | | | | | |
| quantum 4 | | | | | |
| quantum 5 | | | | | |
| quantum 6 | | | | | |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 2000$, $P_B$ and $P_C = 0$; select B (or C)

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | | | | | |
| quantum 4 | | | | | |
| quantum 5 | | | | | |
| quantum 6 | | | | | |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 2000$, $P_B = 10000$, $P_C = 0$; select C

# Stride Scheduling Example

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|---|---|---|---|---|---|
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| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | | | | | |
| quantum 5 | | | | | |
| quantum 6 | | | | | |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 2000$, $P_B = 10000$, $P_C = 2500$; select A

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | | | | | |
| quantum 6 | | | | | |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 4000$, $P_B = 10000$, $P_C = 2500$; select C

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | | | | | |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 4000$, $P_B = 10000$, $P_C = 5000$; select A

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | A | 6000 | 10000 | 5000 | C |
| quantum 7 | | | | | |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 6000$, $P_B = 10000$, $P_C = 5000$; select C

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | A | 6000 | 10000 | 5000 | C |
| quantum 7 | C | 6000 | 10000 | 7500 | A |
| quantum 8 | | | | | |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 6000$, $P_B = 10000$, $P_C = 7500$; select A

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | A | 6000 | 10000 | 5000 | C |
| quantum 7 | C | 6000 | 10000 | 7500 | A |
| quantum 8 | A | 8000 | 10000 | 7500 | C |
| quantum 9 | | | | | |
| quantum 10 | | | | | |

- $P_A = 8000$, $P_B = 10000$, $P_C = 7500$; select C

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | A | 6000 | 10000 | 5000 | C |
| quantum 7 | C | 6000 | 10000 | 7500 | A |
| quantum 8 | A | 8000 | 10000 | 7500 | C |
| quantum 9 | C | 8000 | 10000 | 10000 | A |
| quantum 10 | | | | | |

- $P_A = 8000$, $P_B = 10000$, $P_C = 10000$; select A

# Stride Scheduling Example

| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | A | 6000 | 10000 | 5000 | C |
| quantum 7 | C | 6000 | 10000 | 7500 | A |
| quantum 8 | A | 8000 | 10000 | 7500 | C |
| quantum 9 | C | 8000 | 10000 | 10000 | A |
| quantum 10 | A | 10000 | 10000 | 10000 | … will repeat |

- $P_A = 10000$, $P_B = 10000$, $P_C = 10000$

# Stride Scheduling Example

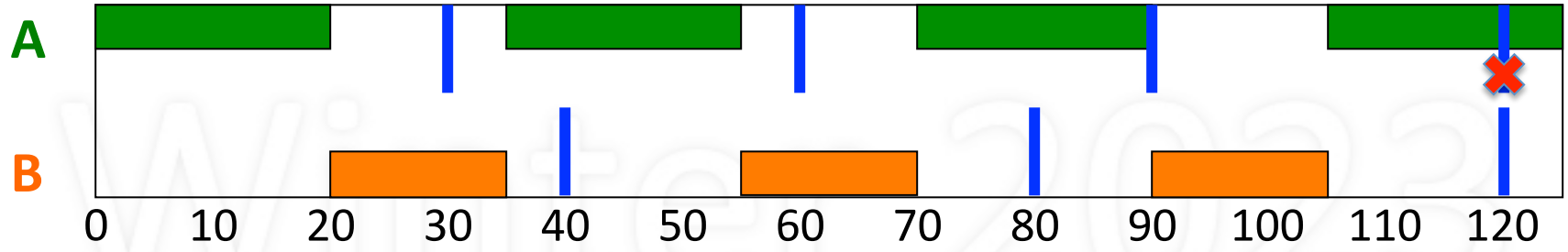
| Process *x* | Runs Now | A | B | C | To Run Next |
|---|---|---|---|---|---|
| Requested Utilization: $R_x$ (in %) | | 50 | 10 | 40 | |
| Stride: $S_x = L/R_x$ (L = 100000) | | 2000 | 10000 | 2500 | |
| Pass: $P_x = P_x + S_x$ ; init = 0 | | 0 | 0 | 0 | A |
| quantum 1 | A | 2000 | 0 | 0 | B |
| quantum 2 | B | 2000 | 10000 | 0 | C |
| quantum 3 | C | 2000 | 10000 | 2500 | A |
| quantum 4 | A | 4000 | 10000 | 2500 | C |
| quantum 5 | C | 4000 | 10000 | 5000 | A |
| quantum 6 | A | 6000 | 10000 | 5000 | C |
| quantum 7 | C | 6000 | 10000 | 7500 | A |
| quantum 8 | A | 8000 | 10000 | 7500 | C |
| quantum 9 | C | 8000 | 10000 | 10000 | A |
| quantum 10 | A | 10000 | 10000 | 10000 | … will repeat |

- After 10 quantums, A ran 5; B ran 1; C ran 4

# Real Time Scheduling

- Correctness of real-time systems depend on
  - logical result of computations
  - *and* the timing of these results
- Type of real-time systems
  - Hard vs. soft real-time
  - Periodic vs. aperiodic
- Scheduling
  - Earliest Deadline First (EDF)
  - Rate Monotonic Scheduling (RMS)

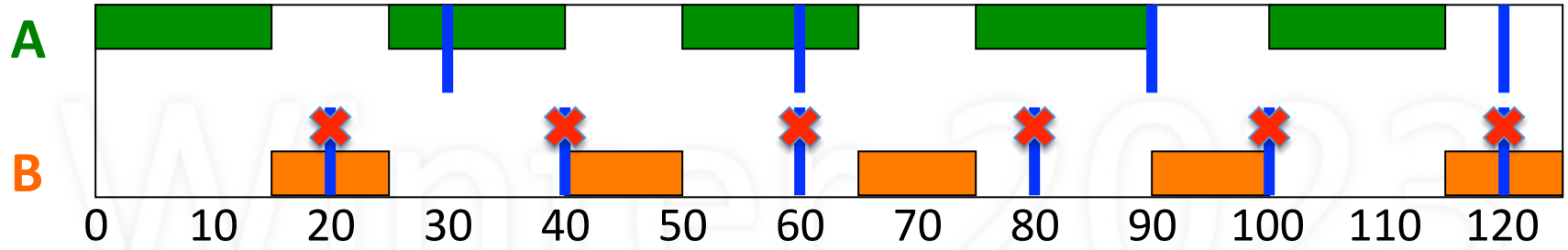
# Periodic Processes (or Tasks)




- Periodic processes: computation is cyclic
- For each process, given

  $C$ = CPU burst, $T$ = period, $U = C/T$ = utilization
- Can processes be ordered so deadlines are met?
- Consider orders: ABABAB…, vs. BABABA…

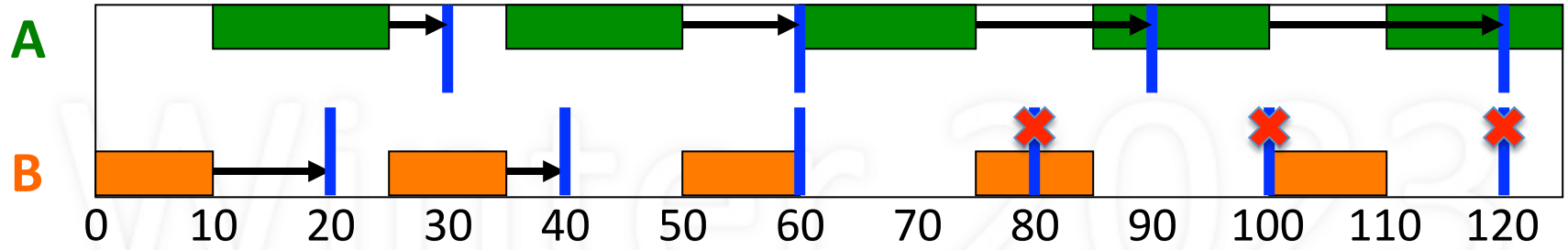
# Periodic Processes




| | *C* | *T* | *U* |
|---|---|---|---|
| A | 15 | 30 | 50% |
| B | 10 | 20 | 50% |

- Sum of utilizations does not exceed 100%
- For order ABABAB…, B misses all deadlines!

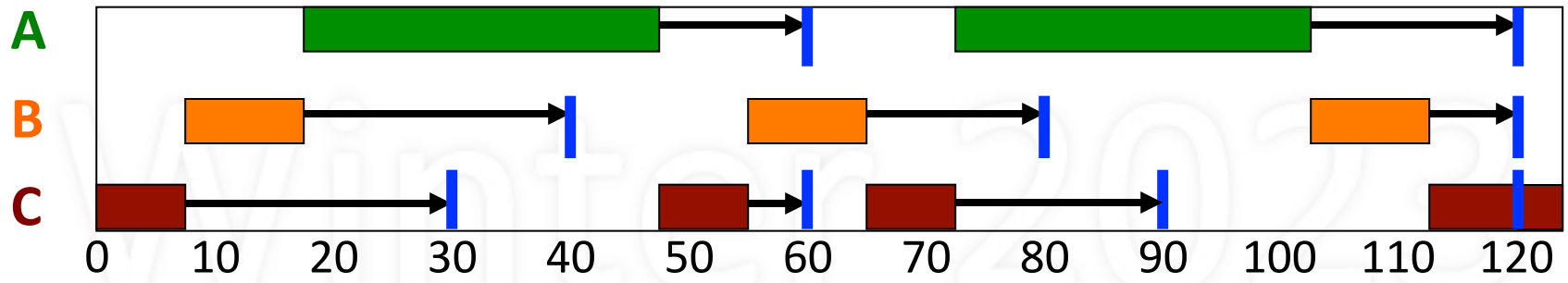
# Periodic Processes




| | *C* | *T* | *U* |
|---|---|---|---|
| A | 15 | 30 | 50% |
| B | 10 | 20 | 50% |

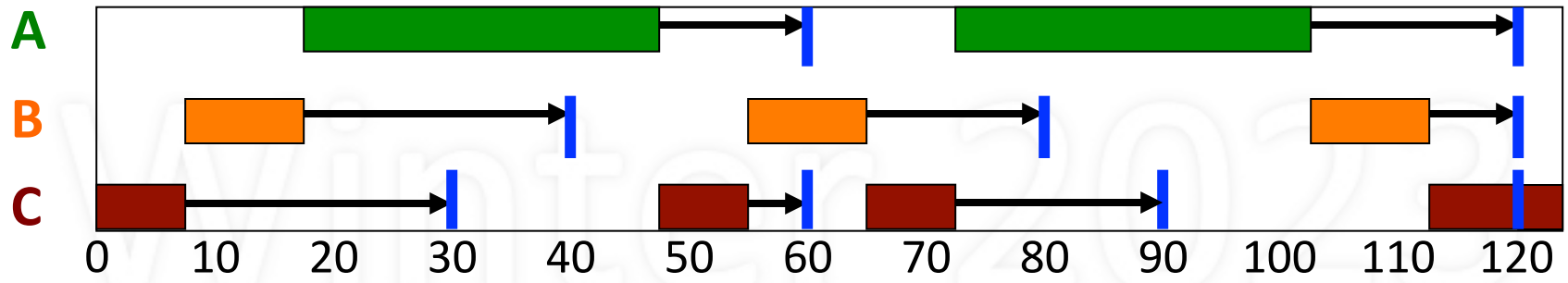
- Sum of utilizations does not exceed 100%
- For order BABABA…, B misses some deadlines

# EDF: Earliest Deadline First




- Schedule process with earliest deadline
- If earlier deadline process appears, preempt
- Works for periodic and aperiodic processes
- Achieves 100% utilization (ignoring overhead!)
- Expensive: requires ordering by deadlines

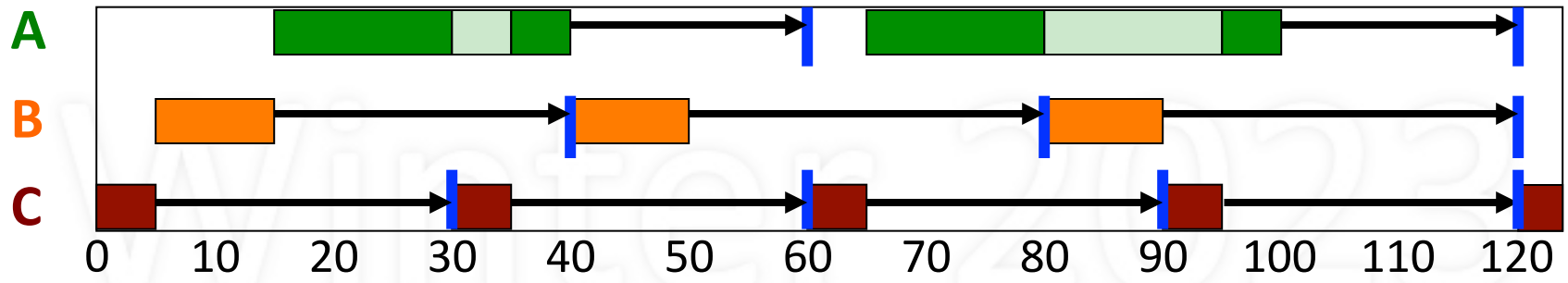
# EDF: Earliest Deadline First




| | *C* | *T* | *U* |
|---|---|---|---|
| A | 30 | 60 | 50% |
| B | 10 | 40 | 25% |
| C | 7.5 | 30 | 25% |

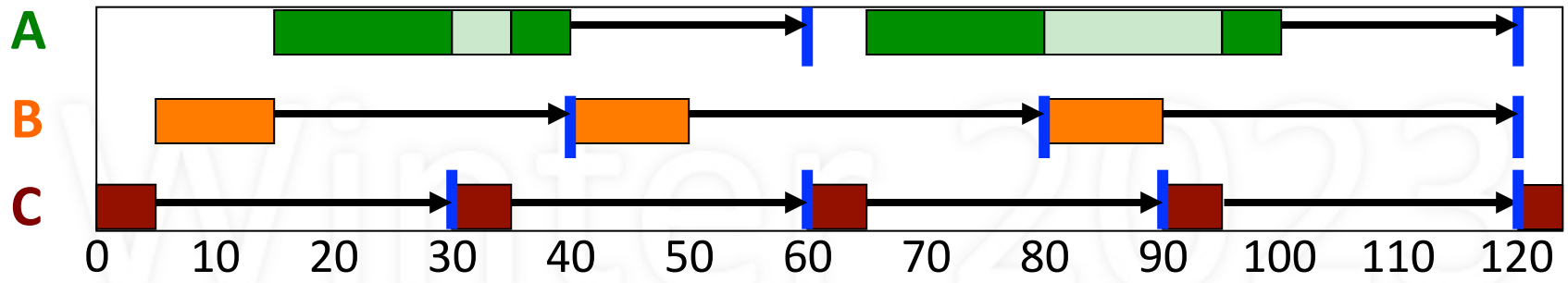
- Meets all deadlines, sum of utilizations = 100%

# RMS: Rate Monotonic Scheduling




- If periodic processes, prioritize based on rates
- At start of period, select highest priority
- Preempt if necessary
- When burst done, wait till next period
- If $U_1 + \ldots + U_n \leq n\,(2^{1/n} - 1)$, all deadlines met

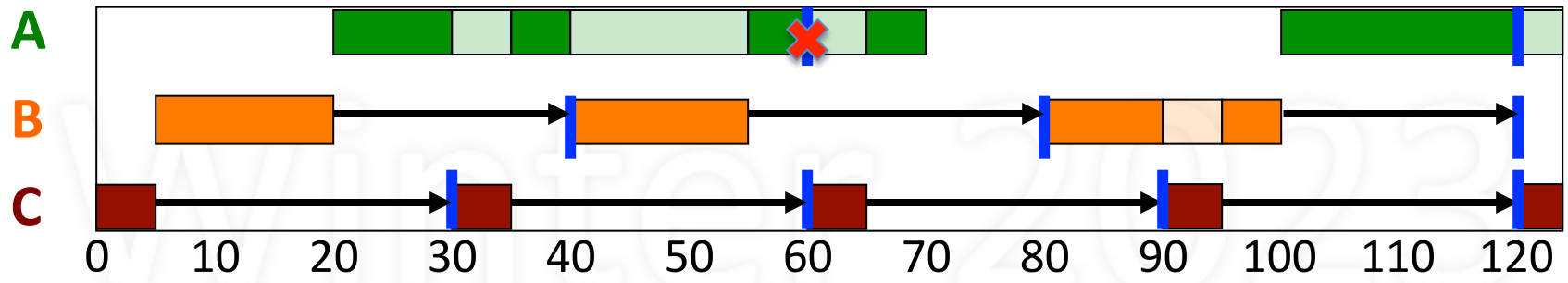
# RMS Test Passes, All Deadlines Met




| | *C* | *T* | *U* | Rate | Prio |
|---|---|---|---|---|---|
| A | 20 | 60 | 33% | 1/60 = 0.017 | Low |
| B | 10 | 40 | 25% | 1/40 = 0.025 | Med |
| C | 5 | 30 | 17% | 1/30 = 0.033 | High |

- Passes: $U_A + U_B + U_C = 75\% \leq 3\,(2^{1/3} - 1) = 78\%$

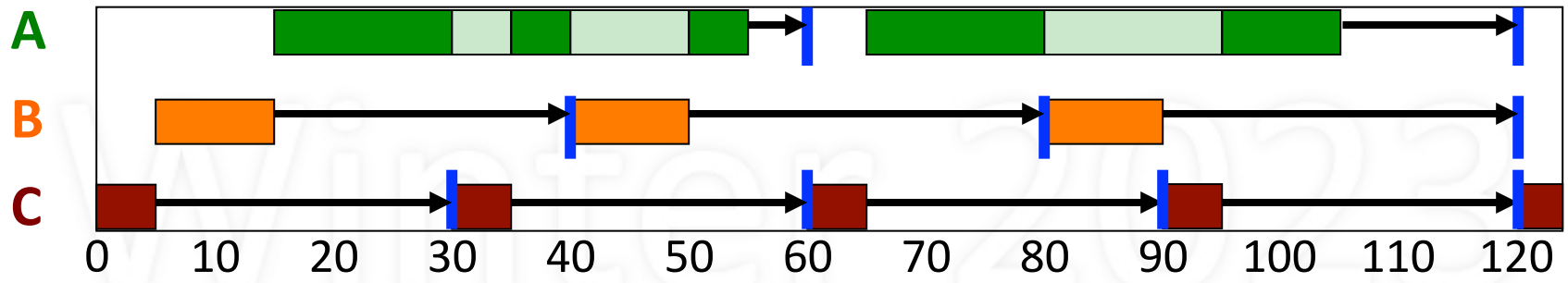
# RMS Test Fails, Deadline Missed




| | *C* | *T* | *U* | Rate | Prio |
|---|---|---|---|---|---|
| A | 25 | 60 | 42% | 1/60 = 0.017 | Low |
| B | 15 | 40 | 38% | 1/40 = 0.025 | Med |
| C | 5 | 30 | 17% | 1/30 = 0.033 | High |

- Fails: $U_A + U_B + U_C = 97\% > 3\,(2^{1/3} - 1) = 78\%$

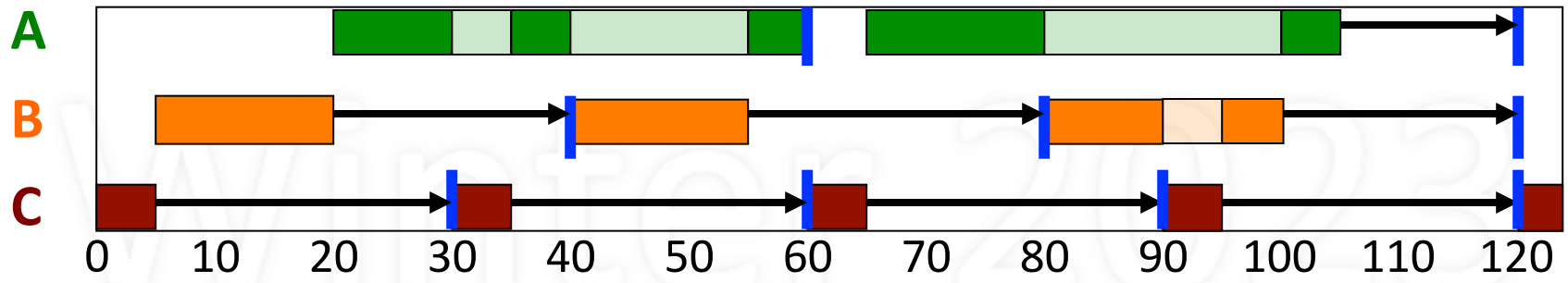
# RMS Test Fails, But Deadlines Met




| | *C* | *T* | *U* | Rate | Prio |
|---|---|---|---|---|---|
| A | 25 | 60 | 42% | 1/60 = 0.017 | Low |
| B | 10 | 40 | 25% | 1/40 = 0.025 | Med |
| C | 5 | 30 | 17% | 1/30 = 0.033 | High |

- Fails: $U_A + U_B + U_C = 84\% > 3\,(2^{1/3} - 1) = 78\%$

# RMS Test Fails, But Deadlines Met




| | *C* | *T* | *U* | Rate | Prio |
|---|---|---|---|---|---|
| A | 20 | 60 | 33% | 1/60 = 0.017 | Low |
| B | 15 | 40 | 38% | 1/40 = 0.025 | Med |
| C | 5 | 30 | 17% | 1/30 = 0.033 | High |

- Fails: $U_A + U_B + U_C = 88\% > 3\,(2^{1/3} - 1) = 78\%$

# RMS Optimal But Limited

- RMS is simple and efficient
  - Static priority scheduling based on rates
- RMS is optimal for static priority algorithms
  - If RMS can't schedule, no other static priority can
- RMS is limited in what it guarantees
  - Utilization bounded by $n\ (2^{1/n} - 1) > ln\ 2 \approx 69\%$
  - Deadline guarantee applies only if test passes
- RMS is limited to periodic processes

# Summary

- CPU scheduling is policy: depends on goals
  - First come first served — very simple, non-preemptive
  - Round robin — simple, preemptive
  - Shortest process next — theoretical, non-preemptive
  - Shortest remaining time — theoretical, preemptive
  - Multi-level feedback — adaptive, responsive, complex
  - Priority — external criteria
  - Fair share — proportional allocation
  - Earliest deadline first — 100% utilization, high overhead
  - Rate monotonic sched — < 100% util, low overhead

# Textbook

- OSP: Chapter 4
- OSC: Chapter 6
  - Lecture-related: 5.1-5.3, 5.6, 5.9
  - Recommended: 5.7-5.8