Problem: We have a set of processes: they all want to execute immediately and they do not want to be interrupted.

Solution: Let's keep some waiting and let's interrupt them.

Question: What metrics are important? Does it matter in what order we schedule processes? Are there optimal solutions?
Problem:

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Question:

- What metrics are important?
- Does it matter in what order we schedule processes?
- Are there optimal solutions?
Assume we have a set of jobs.
Assume we have a set of jobs.

- Each job takes an equal amount of time.
Assume we have a set of jobs.

- Each job takes an equal amount of time.
- All jobs arrive at the same time.
Assume we have a set of jobs.

- Each job takes an equal amount of time.
- All jobs arrive at the same time.
- A job will run to completion.
The unrealistic assumption ...

Assume we have a set of *jobs*.

- Each job takes an equal amount of time.
- All jobs *arrive* at the same time.
- A job will run to completion.
- The jobs only use the CPU (no I/O etc).
Assume we have a set of jobs.

- Each job takes an equal amount of time.
- All jobs arrive at the same time.
- A job will run to completion.
- The jobs only use the CPU (no I/O etc).
- The run-time of each job is known.
Assume we have a set of *jobs*.

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- The jobs only use the CPU (no I/O etc).
- The run-time of each job is known.

*This is unrealistic - we will relax these requirements.*
...every now and then I get a little bit lonely
...every now and then I get a little bit lonely
Performance metrics

\[ T_{\text{turnaround}} = T_{\text{completion}} - T_{\text{arrival}} \]

*How long time does it take to complete the job?*
Assume we have three tasks, all *arrive* at time 0 and take 10 ms to execute.
First Come First Serve (FCFS)

Assume we have three tasks, all *arrive* at time 0 and take 10 ms to execute.

J1: 

J2: 

J3: 

What is the average *T* _turnaround_?
Assume we have three tasks, all \textit{arrive} at time 0 and take 10 ms to execute.
First Come First Serve (FCFS)

Assume we have three tasks, all *arrive* at time 0 and take 10 ms to execute.

J1: 

J2: 

J3: 

What is the average \( T \) turnaround?
First Come First Serve (FCFS)

Assume we have three tasks, all arrive at time 0 and take 10 ms to execute.

J1:

J2:

J3:

What is the average $T_{\text{turnaround}}$?
Assume one task takes 30 ms to execute.
Assume one task takes 30 ms to execute.

What is the average $T_{\text{turnaround}}$?

Can we do better?
Assume one task takes 30 ms to execute.
Assume one task takes 30 ms to execute.

What is the average \( T \) turnaround? Can we do better?
Assume one task takes 30 ms to execute.

What is the average $T_{\text{turnaround}}$?
Assume one task takes 30 ms to execute.

What is the average $T_{\text{turnaround}}$? Can we do better?
Always schedule the shortest job.
Shortest Job First (SJF)

Always schedule the shortest job.

J1: 

J2: 

J3: 

What is the average turnaround?
Always schedule the shortest job.

**Problem solved!**
Shortest Job First (SJF)

Always schedule the shortest job.

J1:  
J2:  
J3:  

What is the average turnaround?
Always schedule the shortest job.

J1: 
J2: 
J3: 

What is the average $T_{\text{turnaround}}$?
Shortest Job First (SJF)

Always schedule the shortest job.

J1: ___________________ 50 ms

J2: ____________ 10 ms

J3: ____________ 20 ms

What is the average $T_{\text{turnaround}}$?  

Problem solved!
What if jobs arrive later?

Assume we have three tasks, one arrive at time 0 and takes 30 ms to execute. Two arrive at time 10 and take 10 ms each.
What if jobs arrive later?

Assume we have three tasks, one arrive at time 0 and takes 30 ms to execute. Two arrive at time 10 and take 10 ms each.

J1:

J2:

J3:
What if jobs arrive later?

Assume we have three tasks, one arrive at time 0 and takes 30 ms to execute. Two arrive at time 10 and take 10 ms each.

J1:  

J2:  

J3:
What if jobs arrive later?

Assume we have three tasks, one arrive at time 0 and takes 30 ms to execute. Two arrive at time 10 and take 10 ms each.

![Diagram showing task execution times](image)
What if jobs arrive later?

Assume we have three tasks, one arrive at time 0 and takes 30 ms to execute. Two arrive at time 10 and take 10 ms each.

J1: 

J2: 

J3: 

0 10 20 30 40 50 60 ms
What if jobs arrive later?

Assume we have three tasks, one arrive at time 0 and takes 30 ms to execute. Two arrive at time 10 and take 10 ms each.

We need to preempt the execution of a job.
Let’s always schedule the task that has the shortest time left to completion.

J1:

J2:

J3:
Shortest Time-to-Completion First (STCF)

Let’s always schedule the task that has the shortest time left to completion.

J1: 

J2: 

J3: 

ms

0 10 20 30 40 50 60
Shortest Time-to-Completion First (STCF)

Let’s always schedule the task that has the shortest time left to completion.

J1: 

J2: 

J3: 

The policy is also known as Preemptive Shortest Job First (PSJF)
If we actually know the total execution time of each job as they arrive, then ....
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Shortest Time-to-Completion First is an optimal policy.
If we actually know the total execution time of each job as they arrive, then ....

Shortest Time-to-Completion First is an optimal policy.

*The problem is that we do not know the total execution time beforehand.*
If we actually know the total execution time of each job as they arrive, then ....

Shortest Time-to-Completion First is an optimal policy.

*The problem is that we do not know the total execution time beforehand.*

*There might be more important metrics than turnaround time.*
Talk about ...
In an interactive environment we might want to minimize *response time*. 
In an interactive environment we might want to minimize response time.

\[ T_{\text{response}} = T_{\text{first scheduled}} - T_{\text{arrival}} \]
In an interactive environment we might want to minimize response time.

\[ T_{\text{response}} = T_{\text{first scheduled}} - T_{\text{arrival}} \]

*The response might not be completed unless the job completes but it’s an ok metrics.*
Try Shortest Job First

Assume we have three jobs that all arrive at time 0 and all take 40 ms to complete.
Assume we have three jobs that all arrive at time 0 and all take 40 ms to complete.

J1: 
J2: 
J3: 

What is the average response time?
Assume we have three jobs that all arrive at time 0 and all take 40 ms to complete.

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What is the average response time?
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What is the average response time?
Round-robin

Preempt a job in order to improve response time, give each job a time-slice of 10 ms.
Round-robin

Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

J1: 

J2: 

J3: 

J1: |---|
J2: [-----]
J3: |---|

What is the average response time?
What is the average turnaround time?
How to choose the time-slice?
Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

J1: ---
J2: [blue]-----
J3: [green]---
Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

What is the average response time?

What is the average turnaround time?

How to choose the time-slice?
Round-robin

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What is the average response time?

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How to choose the time-slice?
Round-robin

Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

J1:

J2:

J3:
Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

What is the average response time?

What is the average turnaround time?

How to choose the time-slice?
Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

What is the average response time?
Round-robin

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What is the average response time? What is the average turnaround time?
Round-robin

Preempt a job in order to improve response time, give each job a time-slice of 10 ms.

What is the average response time?  
What is the average turnaround time?  
How to choose the time-slice?
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1:

J2:
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1: 

J2: ---
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1: \[\text{I/O}\]

J2: \[\text{---}\]
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1: I/O

J2:
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1: I/O  I/O

J2: I/O-operations
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1: I/O I/O

J2: I/O
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.

J1: I/O I/O I/O

J2:
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.
Assume we have two processes, each take 40 ms of CPU time but one will do I/O-operations every 10 ms.
An I/O-operation will take time to complete and we (the CPU) could do some useful work while a process is waiting.
An I/O-operation will take time to complete and we (the CPU) could do some useful work while a process is waiting.
An I/O-operation will take time to complete and we (the CPU) could do some useful work while a process is waiting.

A process is descheduled if it is preempted or if it initiates a I/O-operation.
much better

J1:

J2:
much better

J1: 

J2: 

0 10 20 30 40 50 60 70 80 90 100 110 120 ms
much better

J1: I/O

J2:
much better
much better

J1: I/O I/O

J2: - - -

ms
much better

J1: I/O I/O I/O

J2: I/O I/O I/O

0 10 20 30 40 50 60 70 80 90 100 110 120 ms
much better

J1: I/O I/O I/O

J2: I/O I/O I/O
much better

J1: I/O I/O I/O I/O

J2: I/O I/O I/O

0 10 20 30 40 50 60 70 80 90 100 110 120 ms
much better

J1: [I/O] [I/O] [I/O]

J2: [ ] [ ] [ ] [ ]
the challenge

Ideal world:

- Each job takes an equal amount of time.
the challenge

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- Each job takes an equal amount of time.
- All jobs *arrive* at the same time.
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... What do we do?

Can we design scheduling policies that give us good turn-around time and short response time?
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Real world:

Jobs take different amount of time.
Jobs arrive at different time.
We can preempt job.
Jobs do use I/O.
Run-time is not known.

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- .... What do we do?

Can we design scheduling policies that give us good turn-around time and short response time?
Multi-level Feedback Queue (MLFQ)

Goals:

- Good turnaround time - scheduled jobs so that jobs with short time to completion are not delayed too much.
- Improve responsiveness of interactive jobs - schedule interactive processes more often.

Idea:

- Multiple levels of priority - interactive jobs have higher priority.
- Each level uses round-robin to give processes an equal share.
- Processes can be moved to a higher or lower level depending on their behavior.

How do we identify interactive processes and how do we make sure that they have high priority?
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How do we identify interactive processes and how do we make sure that they have high priority?
Rules of the game: MLFQ

Basic rules:
Rule 1: if Priority(A) > Priority(B) then A is scheduled for execution.
Rule 2: if Priority(A) = Priority(B) then A and B are scheduled in round-robin.
Rule 3: when a new job is created it starts with the highest priority.

Change priority (let’s try this)
Rule 4a: a job that has to be preempted (time-slice consumed) is moved to a lower priority.
Rule 4b: a job that initiates an I/O-operation (or yields) remains on the same level.
Basic rules:

- Rule 1: if \( \text{Priority}(A) > \text{Priority}(B) \) then \( A \) is scheduled for execution.
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fine, no problem ...

Q2:

Q1:

Q0:
fine, no problem ...

Q2: [red box]

Q1:

Q0:
fine, no problem ...

Q2: [rectangle]

Q1: [rectangle]

Q0: [rectangle]
fine, no problem ...

Q2: 
Q1: 
Q0: 

0 10 20 30 40 50 60 70 80 90 100 110 120 ms
fine, no problem ...
fine, no problem ...
Q0: 

Q1: 

Q2: 

ms
Q0:  
Q1:  
Q2:  

I/O

ms

0 10 20 30 40 50 60 70 80 90 100 110 120
fine, no problem ...

Q0:

Q1:

Q2:
fine, no problem ...
fine, no problem ...

Q0:

Q1:

Q2:
fine, no problem ...

Q0:  
Q1:  
Q2:  

I/O  I/O

ms
fine, no problem ...
fine, no problem ...
fine, no problem ...
fine, no problem ...

Q0: 

Q1: 

Q2: 

I/O I/O I/O 

I/O 

ms
fine, no problem ...

Q0:

Q1:

Q2:
fine, no problem...
Rule 5: after some time, move a job to the highest priority.
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Q2:

Q1:

Q0:
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Q0: 

Q1: 

Q2: 

I/O
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**Rule 5**: after some time, move a job to the highest priority.
If the scheduler was constructed given the rules 1-5, how would you write your program?
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If the scheduler was constructed given the rules 1-5, how would you write your program?

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If the scheduler was constructed given the rules 1-5, how would you write your program?

- **Rule 1**: if \( \text{Priority}(A) > \text{Priority}(B) \) then \( A \) is scheduled for execution.
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- **Rule 3**: when a new job is created it starts with the highest priority.
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- Rule 4b: a job that initiates a I/O-operation (or yields) remains on the same level.
- Rule 5: after some time, move a job to the highest priority.
A job is given a *allotted time*, to consume at each priority level.
A job is given a *allotted time*, to consume at each priority level.

- Rule 4: a job that has consumed its allotted time is moved to a lower priority.
A job is given a *allotted time*, to consume at each priority level.

- Rule 4: a job that has consumed its allotted time is moved to a lower priority.
- Rule 5: after some time, move all jobs to the highest priority.
tune the scheduler

Setting the parameters:
Setting the parameters:

- How long is a time slice?
- How many queues should there be?
- How long time should an allotted time be in a specified queue?
- How often should a job be boosted to the highest priority?
Change the perspective

What if: we stop focusing on turnaround time and reaction and start treating every job in a fair manner. Give each job fair share.
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*Give each job fair share.*
Let’s have a lottery:
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and the winner is

We divide the tickets among the jobs: A - 35 tickets, B - 15 tickets and C - 50 tickets.
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A new job can be given a set of tickets as long as we keep track of how many tickets we have.
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We can give a *user* a set of tickets and allow the user to distribute them among its jobs.
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Each user can have its local tickets and then have a local lottery.

We could allow each user to create new tickets, i.e. inflation, if we trust each other.

How to implement?
Each job is given a number that represents the number of tickets it owns.

All jobs are lined up in a row.

Pick a random number from zero to the total number of tickets.

Walk down the line and select the winner.

How does this work?
Why random?
Each job is given a *stride value*, the higher the stride the lower the priority.
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... the pass value is incremented by its stride value.
A deterministic approach: stride scheduling

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- ... the pass value is incremented by its stride value.

*A low stride value will make it more likely to be scheduled soon again.*
In real-time scheduling, we introduce a new requirement: things should be completed within a given time period.

- **Hard**: all deadlines should be met; missing a deadline is a failure.
- **Soft**: deadlines could be missed but the application should be notified and be able to take actions.

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*We often have real-time requirements that are simply met since we happen to have the available resources.*
In hard real-time systems, tasks are known aforehand and described by a triplet $\langle e, d, p \rangle$:

- $e$: the worst case execution time for the task.
- $d$: the deadline, when in the future do we need to finish.
- $p$: the period, how often should the task be scheduled.

$d < p$ : constrained, $d = p$ default, $d > p$ several out-standing
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\[
\begin{align*}
0 & \quad d & \quad p & \quad p+d & \quad 2p & \quad 2p+d & \quad 3p & \quad 3p+d \\
\end{align*}
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\( d < p : \text{constrained, } d = p \text{ default, } d > p \text{ several out-standing} \)
Given a set of tasks: T1: ⟨10, 30, 40⟩, T2: ⟨20, 60, 100⟩, T3: ⟨60, 200, 200⟩, find the scheduling.
Real-time Scheduling

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![Task Scheduling Diagram]
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Given that $p = d$ i.e. a task must be completed within its period.

- **Rate Monotonic Scheduling (RMS):**
  - Schedule the available task with the shortest period
  - Always works if utilization is $< 69\%$ (actually less than $n \times (2^{1/n} - 1)$, where $n$ is the number of processes) could work for higher loads.
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- **Earliest Deadline First (EDF):**
  - Schedule based on the deadline, more freedom to choose tasks.
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T1:

T2:

T3: T3 missed deadline

0 10 20 30 40 50 60 70 80 90 100 110 120
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Why?
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Bonnie Tyler: Turnaround, every now and then...
Bob Marley: Talking 'bout reaction
Rolling Stones: You can't always get what you want.
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Leif "Loket" Olsson: a lottery might work ok

Real-time scheduling: if we actually know the maximum execution time, the deadline and the period.

Multi-core schedulers: you have to think twice before selecting a process.

Linux: Completely Fair Scheduler, schedules in \( O(\log(n)) \) time, similar to strides.
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