CPU Scheduling

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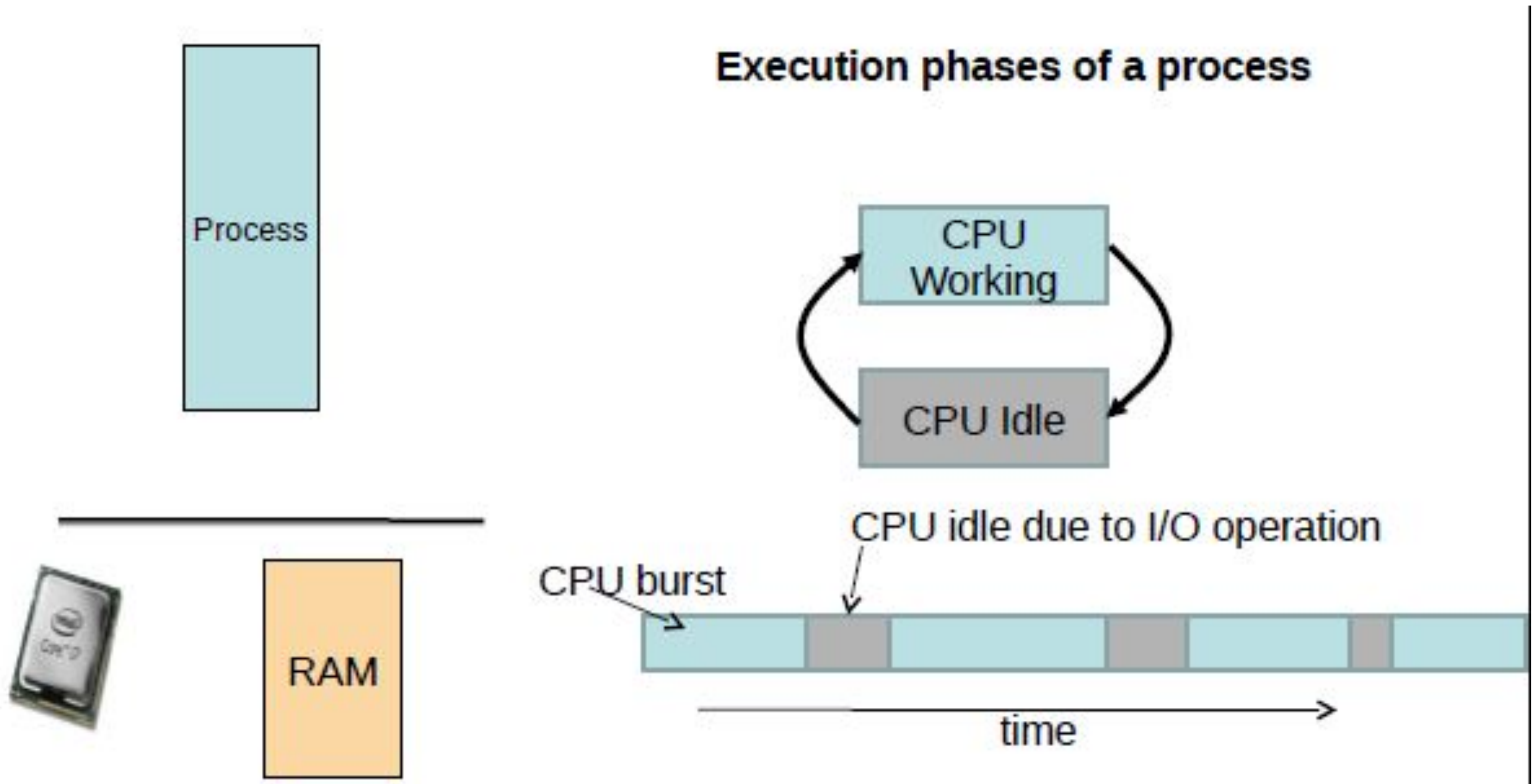
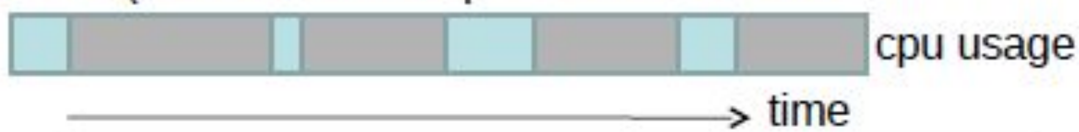
Execution phases of a process



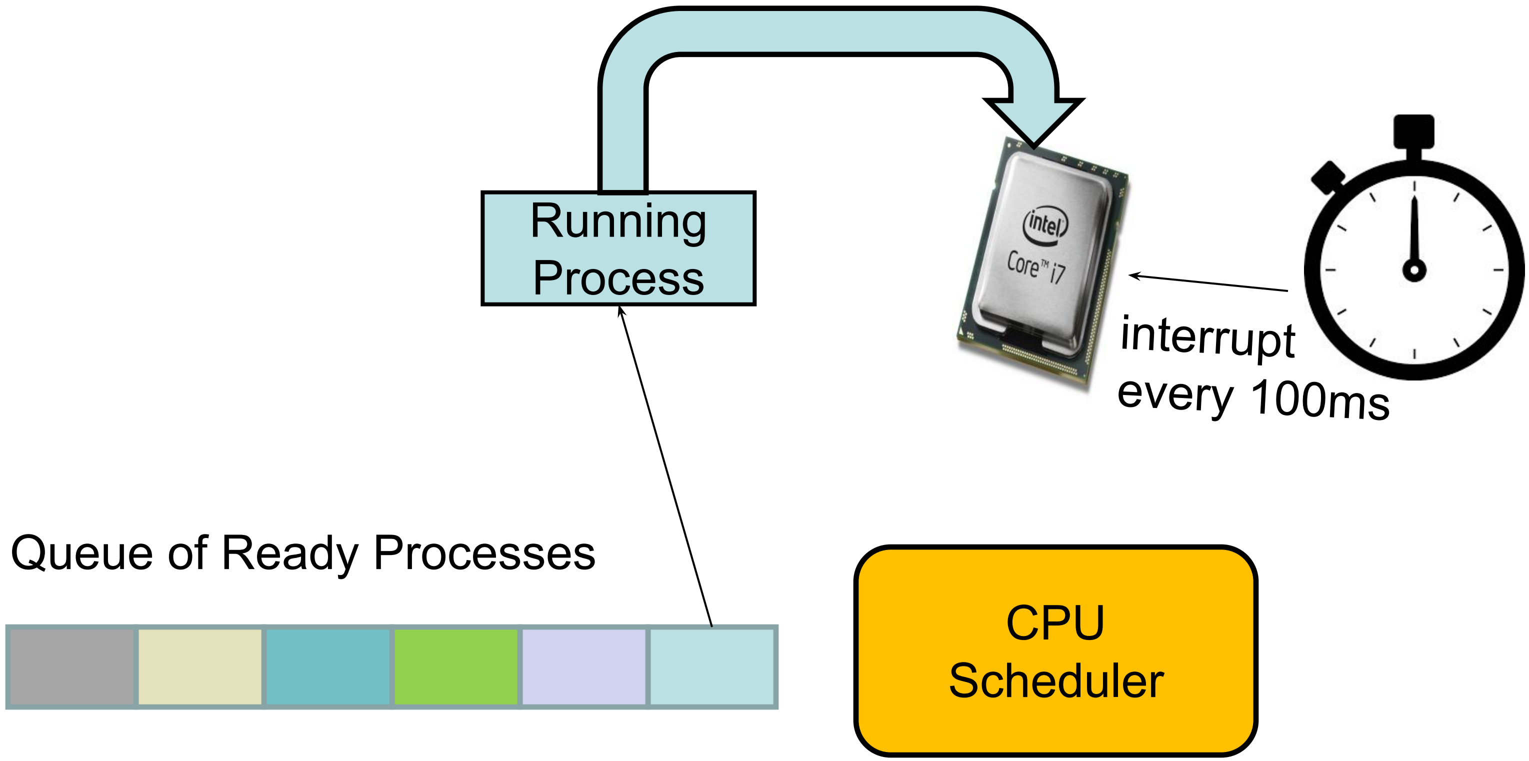
Types of Processes

- I/O bound
  - Has small bursts of CPU activity and then waits for I/O
  - eg. Word processor
  - Affects user interaction (we want these processes to have highest priority)



- CPU bound
  - Hardly any I/O, mostly CPU activity (eg. gcc, scientific modeling, 3D rendering, etc)
    - have long CPU bursts
  - Could do with lower priorities

CPU Scheduler



Scheduler triggered to run when timer interrupt occurs or when running process is blocked on I/O or exits

Scheduler picks another process from the ready queue

Performs a context switch

Schedulers

- Decides which process should run next.
- Objectives:
  - Minimize waiting time
    - Process should not wait long in the ready queue
  - Maximize CPU utilization
    - CPU should not be idle
  - Maximize throughput
    - Complete as many processes as possible per unit time
  - Minimize response time
    - CPU should respond immediately
  - Fairness
    - Give each process a fair share of CPU

FCFS Scheduling (First Come First Serve)

- First job that requests the CPU gets the CPU
- Non preemptive
  - Process continues till the burst cycle ends

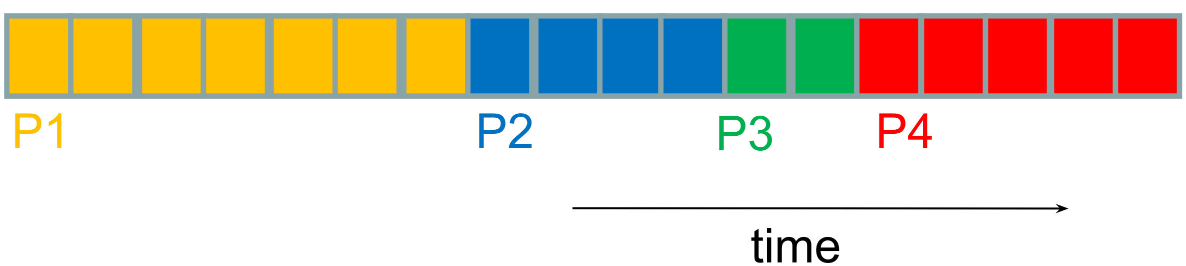
FCFS Example

Process	Arrival Time	Burst Time
P1	0	7
P2	0	4
P3	0	2
P4	0	5

Average Waiting Time
= (0 + 7 + 11 + 13) / 4
= 7.75

Average Response Time
= (0 + 7 + 11 + 13) / 4
= 7.75
(same as Average Waiting Time)

Gantt Chart



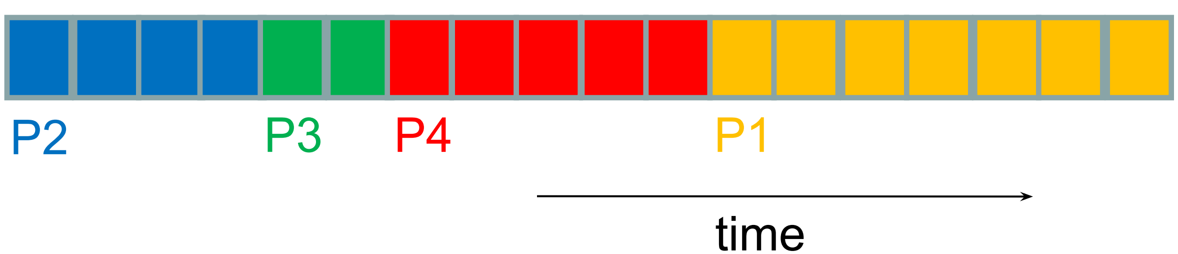
FCFS Example

- Order of scheduling matters

Process	Arrival Time	Burst Time
P1	0	7
P2	0	4
P3	0	2
P4	0	5

Average Waiting Time
= (0 + 4 + 6 + 11) / 4
= 5.25

Gantt Chart



FCFS Pros and Cons

- Advantages
  - Simple
  - Fair (as long as no process hogs the CPU, every process will eventually run)
- Disadvantages
  - Waiting time depends on arrival order
  - short processes stuck waiting for long process to complete

Shortest Job First (SJF) no preemption

- Schedule process with the shortest burst time
  - FCFS if same
- Advantages
  - Reduces average wait time and average response time
- Disadvantages
  - Not practical : difficult to predict burst time
    - Learning to predict future
  - May starve long jobs

CR

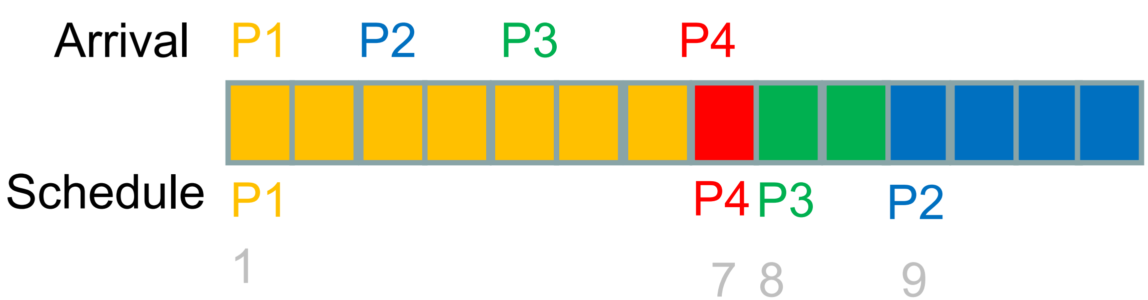
SJF (without preemption)

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	2
P4	7	1

Average wait time
= (0 + 8 + 4 + 0) / 4
= 3

Average response time
= (Average wait time)

Gantt Chart



Shortest Remaining Time First -- SRTF (SJF with preemption)

- If a new process arrives with a shorter burst time than *remaining of current process* then schedule new process
- Further reduces average waiting time and average response time
- Not practical

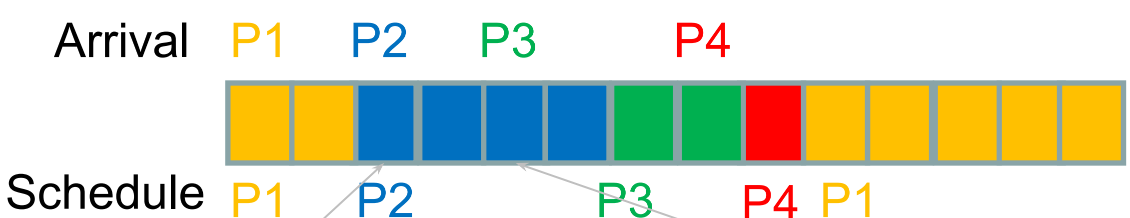
SRTF Example

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	4	2
P4	7	1

Average wait time
= (7 + 0 + 2 + 1) / 4
= 2.5

Average response time
= (0 + 0 + 2 + 1) / 4
= 0.75

Gantt Chart



P2 burst is 4, P1 remaining is 5 (preempt P1)

P3 burst is 2, P2 remaining is 2 (no preemption)

Round Robin Scheduling

- Run process for a time slice then move to FIFO

Round Robin Scheduling

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	3	2
P4	9	1

Time slice = 2

Average Waiting time
= (7 + 4 + 3 + 3) / 4
= 4.25

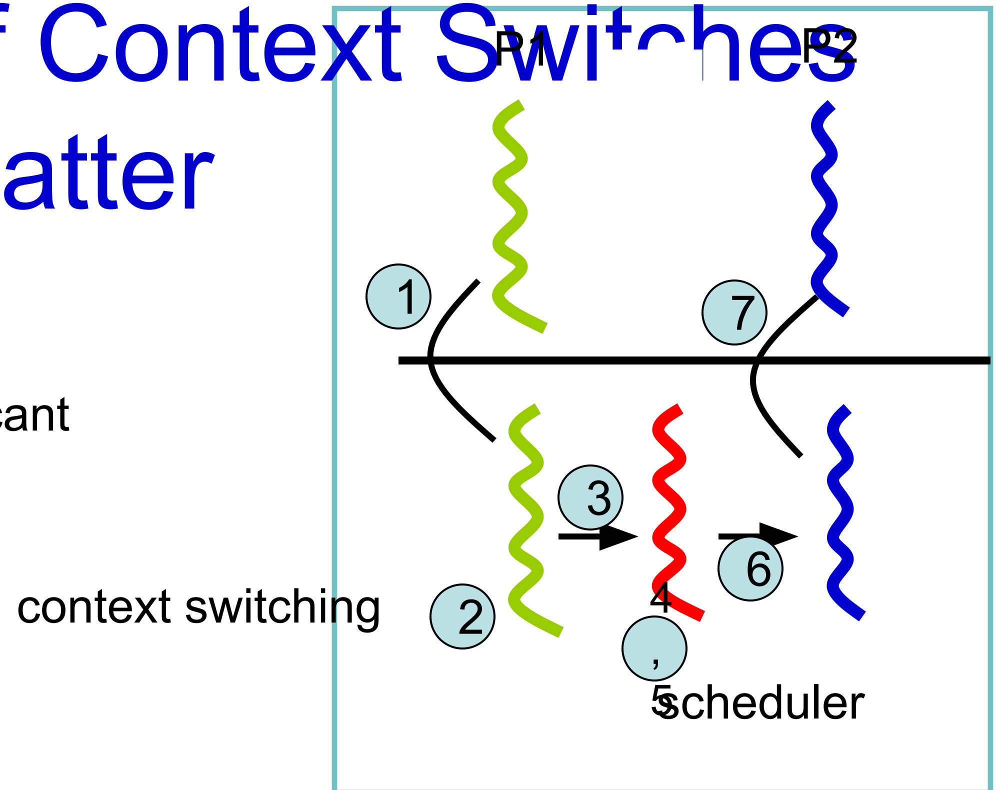
Average Response Time
= (0 + 0 + 3 + 3) / 4
= 1.5

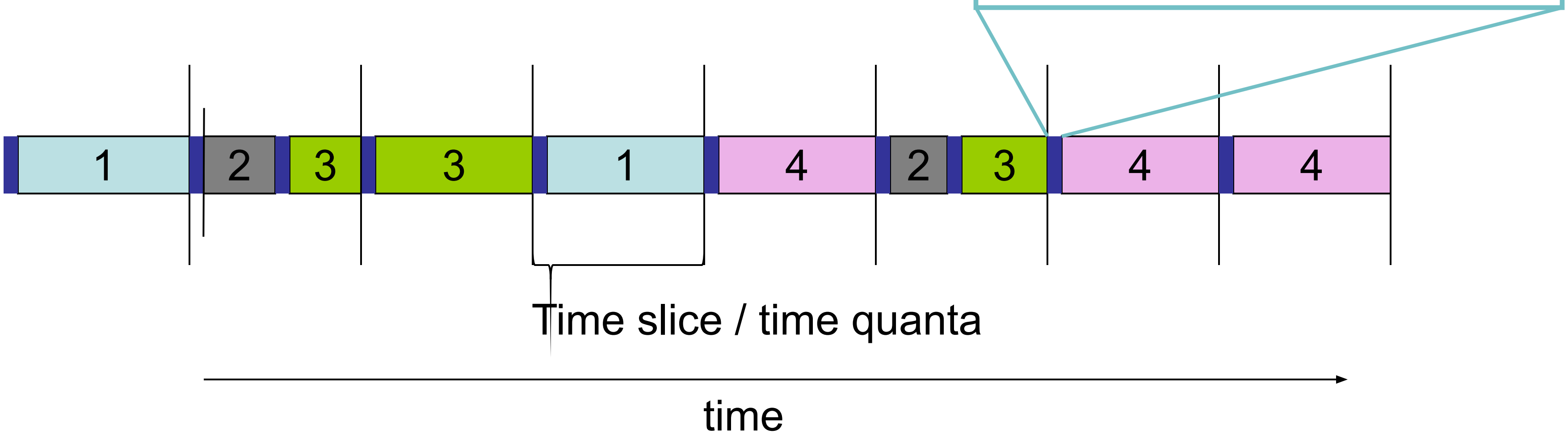
#Context Switches = 7

Arrival	**P1**		**P2**	**P3**						**P4**				
schedule	P1		P2		P1		P3		P2		P1		P4	P1
FIFO			P1	P1 P3	P3 P2		P2 P1		P1	P1 P4	P4 P1		P1	

Why Number of Context Switches Matter

Context switch time could be significant





Recall
Context Switching Overheads

- Direct Factors affecting context switching time
  - Timer Interrupt latency
  - Saving/restoring contexts
  - Finding the next process to execute
- Indirect factors
  - TLB needs to be reloaded
  - Loss of cache locality (therefore more cache misses)
  - Processor pipeline flush

Example (smaller timeslice)

Time slice = 1

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	3	2
P4	9	1

Average Waiting time
= (7 + 6 + 3 + 1) / 4
= 4.25

Average Response Time
= (0 + 0 + 1 + 1) / 4
= 1/2

#Context Switches = 11

Arrival	**P1**		**P2**	**P3**						**P4**				
schedule	P1		P2	P1	P3	P2	P1	P3	P2	P1	P4	P2	P1	P1
FIFO			P1	P3 P2	P2 P1	P1 P3	P3 P2	P2 P1	P1	P4 P2	P2 P1	P1		

More context switches but quicker response times

Example (larger timeslice)

Time slice = 5

Process	**Arrival Time**	**Burst Time**
P1	0	7
P2	2	4
P3	3	2
P4	9	1

Average Waiting time
= (7 + 3 + 6 + 2) / 4
= 4.25

Average Response Time
= (0 + 3 + 6 + 2) / 4
= 2.75

#Context Switches = 4

Arrival	**P1**		**P2**	**P3**						**P4**				
schedule	P1					P2				P3		P4		
FIFO			P2	P2 P3	P2 P3	P3 P1	P3 P1	P3 P1	P3 P1	P4 P1	P4 P1	P1		

Lesser context switches but looks more like FCFS (bad response time)

Round Robin Scheduling

- Advantages
  - Fair (Each process gets a fair chance to run on the CPU)
  - Low average wait time, when burst times vary
  - Faster response time
- Disadvantages
  - Increased context switching
    - Context switches are overheads!!!
  - High average wait time, when burst times have equal lengths

xv6 Scheduler Policy

Decided by the Scheduling Policy

The xv6 schedule Policy
--- **Strawman Scheduler**

- organize processes in a list
- pick the first one that is runnable
- put suspended task the end of the list

Far from ideal!!

- only round robin scheduling policy
- does not support priorities

```
scheduler(void)
{
  struct proc *p;

  for(;;){
    // Enable interrupts on this processor.
    sti();

    // Loop over process table looking for process to run.
    acquire(&ptable.lock);
    for(p = ptable.proc; p < &ptable.proc[NPROC]; p++){
      if(p->state != RUNNABLE)
        continue;

      // Switch to chosen process.  It is the process's job
      // to release ptable.lock and then reacquire it
      // before jumping back to us.
      proc = p;
      switchuvm(p);
      p->state = RUNNING;
      swtch(&cpu->scheduler, proc->context);
      switchkvm();

      // Process is done running for now.
      // It should have changed its p->state before coming back.
      proc = 0;
    }
    release(&ptable.lock);

  }
}
```

Priority Based Scheduling Algorithms

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Relook at Round Robin Scheduling

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	3	2
P4	9	1

Time slice = 1

Process P2 is a critical process while process P1, P3, and P4 are less critical

Process P2 is delayed considerably

Arrival	**P1**		**P2**	**P3**						**P4**				
schedule	P1		P2	P1	P3	P2	P1	P3	P2	P1	P4	P2	P1	P1

Priorities

Process	Arrival Time	Burst Time
P1	0	7
P2	2	4
P3	3	2
P4	9	1

Time slice = 1

Process P2 is a critical process while process P1, P3, and P4 are less critical

We need a higher priority for P2, compared to the other processes

This leads to priority based scheduling algorithms

Arrival	**P1**		**P2**	**P3**						**P4**				
schedule	P1		P2				P1							

Starvation

Process	Arrival Time	Burst Time
P1	0	8
P2	2	4
P3	3	2
P4	9	1

Time slice = 1

Low priority process may never get a chance to execute.

P4 is a low priority process

Arrival	**P1**		**P2**	**P3**						**P4**				
schedule	P1		P2				P1							

Priority based Scheduling

- Priority based Scheduling
  - Each process is assigned a priority
    - A priority is a number in a range (for instance between 0 and 255)
    - A small number would mean high priority while a large number would mean low priority
  - Scheduling policy : pick the process in the ready queue having the highest priority
  - Advantage : mechanism to provide relative importance to processes
  - Disadvantage : could lead to starvation of low priority processes

Dealing with Starvation

- Scheduler adjusts priority of processes to ensure that they all eventually execute
- Several techniques possible. For example,
  - Every process is given a base priority
  - After every time slot increment the priority of all other process
    - This ensures that even a low priority process will eventually execute
  - After a process executes, its priority is reset

Priorities are of two types

- Static priority : typically set at start of execution
  - If not set by user, there is a default value (base priority)
- Dynamic priority : scheduler can change the process priority during execution in order to achieve scheduling goals
  - eg1. decrease priority of a process to give another process a chance to execute
  - eg.2. increase priority for I/O bound processes

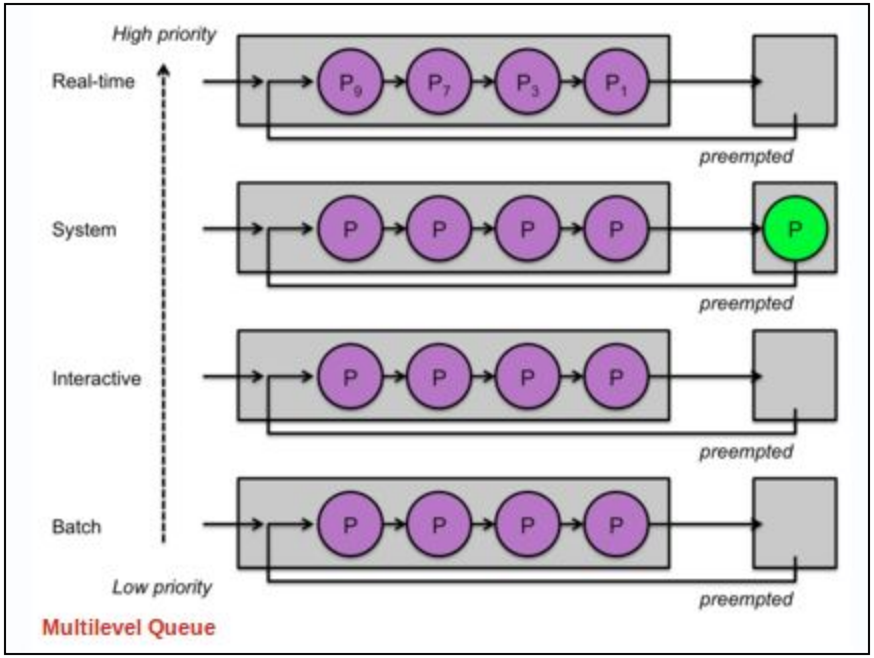
Priority based Scheduling with large number of processes

- Several processes get assigned the same base priority
  - Scheduling begins to behave more like round robin

Process	Arrival Time	Burst Time	Priority
P1	0	8	1
P2	2	4	1
P3	3	2	1
P4	9	1	1

Multilevel Queues

- Processes assigned to a priority classes
- Each class has its own ready queue
- Scheduler picks the highest priority queue (class) which has at least one ready process
- Selection of a process within the class could have its own policy
  - Typically round robin (but can be changed)
  - High priority classes can implement first come first serve in order to ensure quick response time for critical tasks

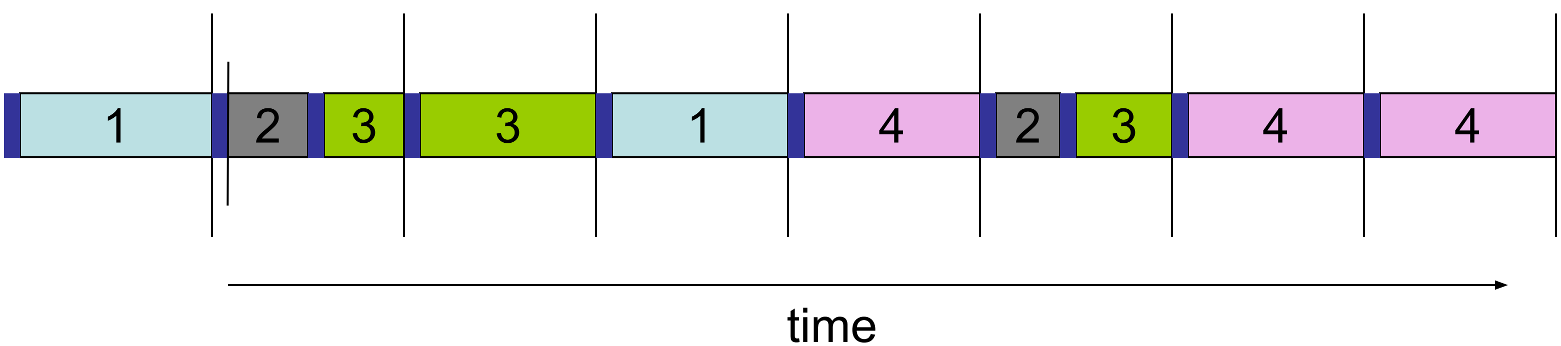


More on Multilevel Queues

- Scheduler can adjust time slice based on the queue class picked
  - I/O bound process can be assigned to higher priority classes with longer time slice
  - CPU bound processes can be assigned to lower priority classes with shorter time slices
- Disadvantage :
  - Class of a process must be assigned apriori
    (not the most efficient way to do things!)

Multilevel **feedback** Queues

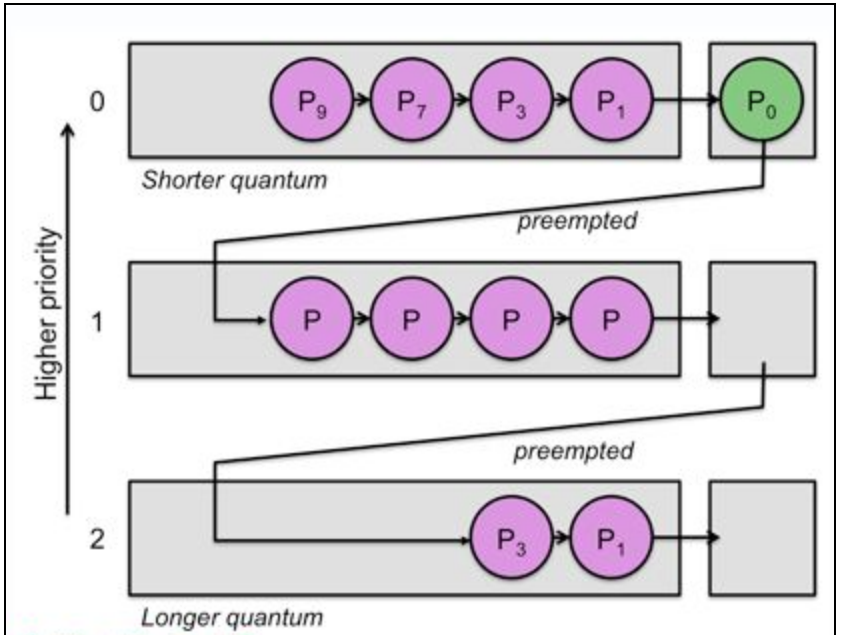
- Process dynamically moves between priority classes based on its CPU/ IO activity
- Basic observation
  - CPU bound process' likely to complete its entire timeslice
  - IO bound process' may not complete the entire time slice



Process 1 and 4 likely CPU bound
Process 2 likely IO bound

Multilevel feedback Queues (basic Idea)

- All processes start in the highest priority class
- If it finishes its time slice (likely CPU bound)
  - Move to the next lower priority class
- If it does not finish its time slice (likely IO bound)
  - Keep it on the same priority class
- As with any other priority based scheduling scheme, starvation needs to be dealt with



Multilevel Feedback Queue

Summary of Multi Level Queues

- Multiple Queues at various levels
- Static Priority, base priority
- Dynamic priority set based on some heuristics
  - IO bound processes should have a higher priority than CPU bound processes
- Timeslice changed dynamically based on heuristics
  - IO bound processes should get a longer timeslice than CPU bound processes
- Starvation dealt with
  - Every process, even the lowest priority process should execute.

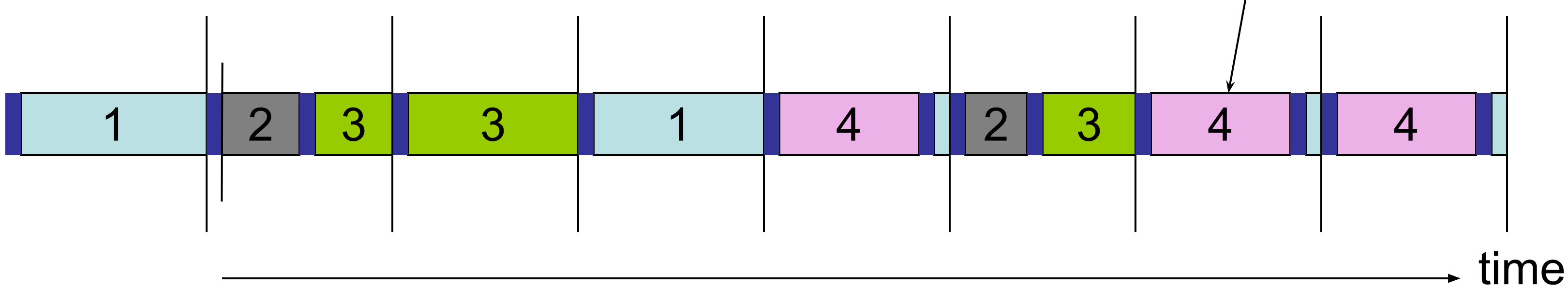
Gaming the System

- A compute intensive process can trick the scheduler and remain in the high priority queue (class)

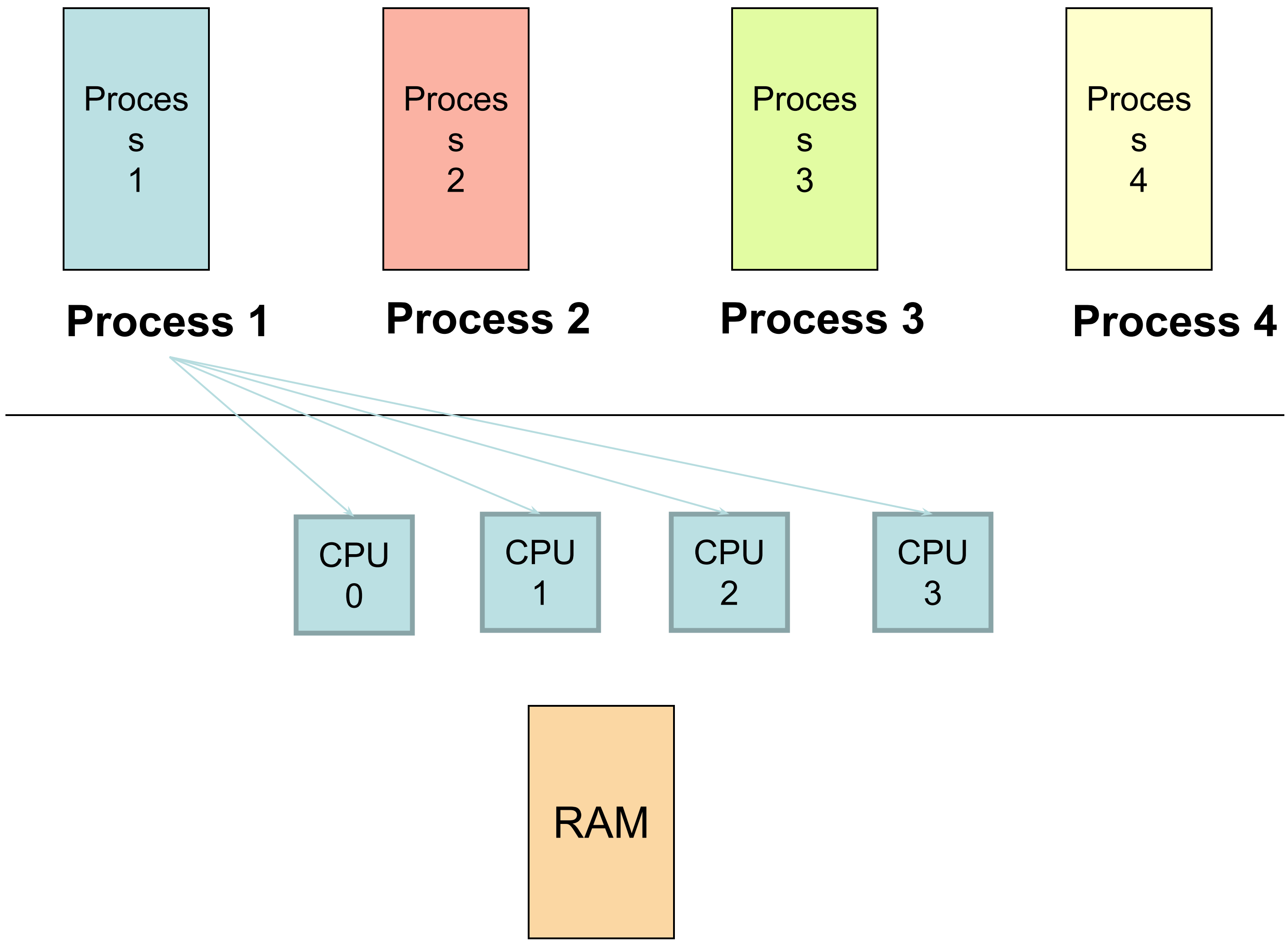
Sleep will force a context switch

```
while(1){
    do some work for most of the time slice
    sleep(till the end of the time slice)
}
```

Process 4 is gaming the system



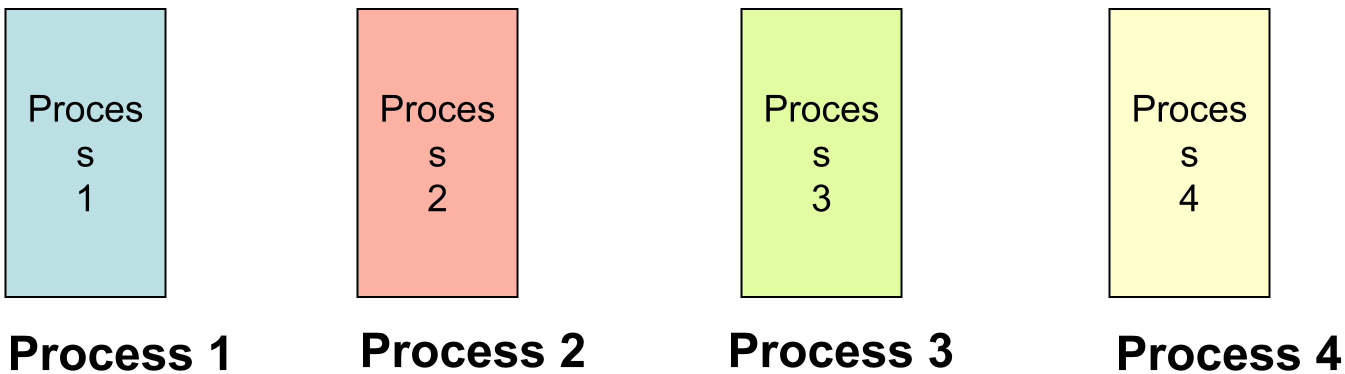
Multiprocessor Scheduling

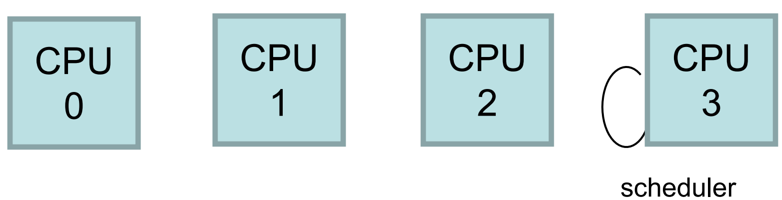


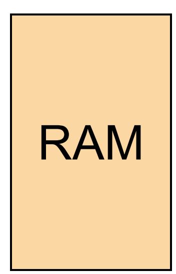
Process Migration

- As a result of symmetrical multiprocessing
  - A process may execute in a processor in one timeslice and another processor in the next time slice
  - This leads to process migration
    - Migration is expensive, it requires all memories to be repopulated
- Processor affinity
  - Process has a bitmask that tells what processors it can run on
    - Two types of processor affinity
      - Hard affinity – strict affinity to specific processors
      - Soft affinity

Multiprocessor Scheduling with a single scheduler

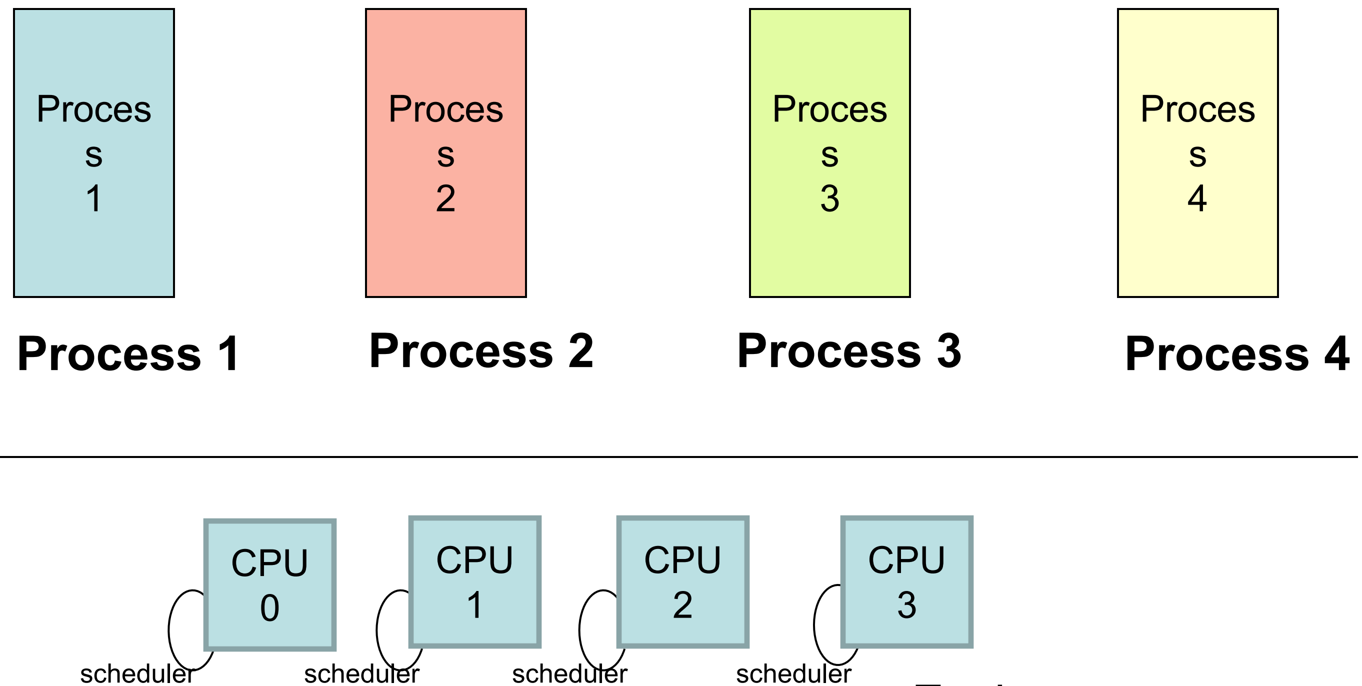




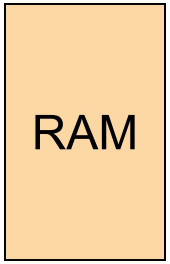


Strawman approach!!
One processor decides for everyone

Multiprocessor Scheduling (Symmetical Scheduling)



Two variants,
- Global queues
- Per CPU queues



Each processor runs a scheduler independently to select the process to execute

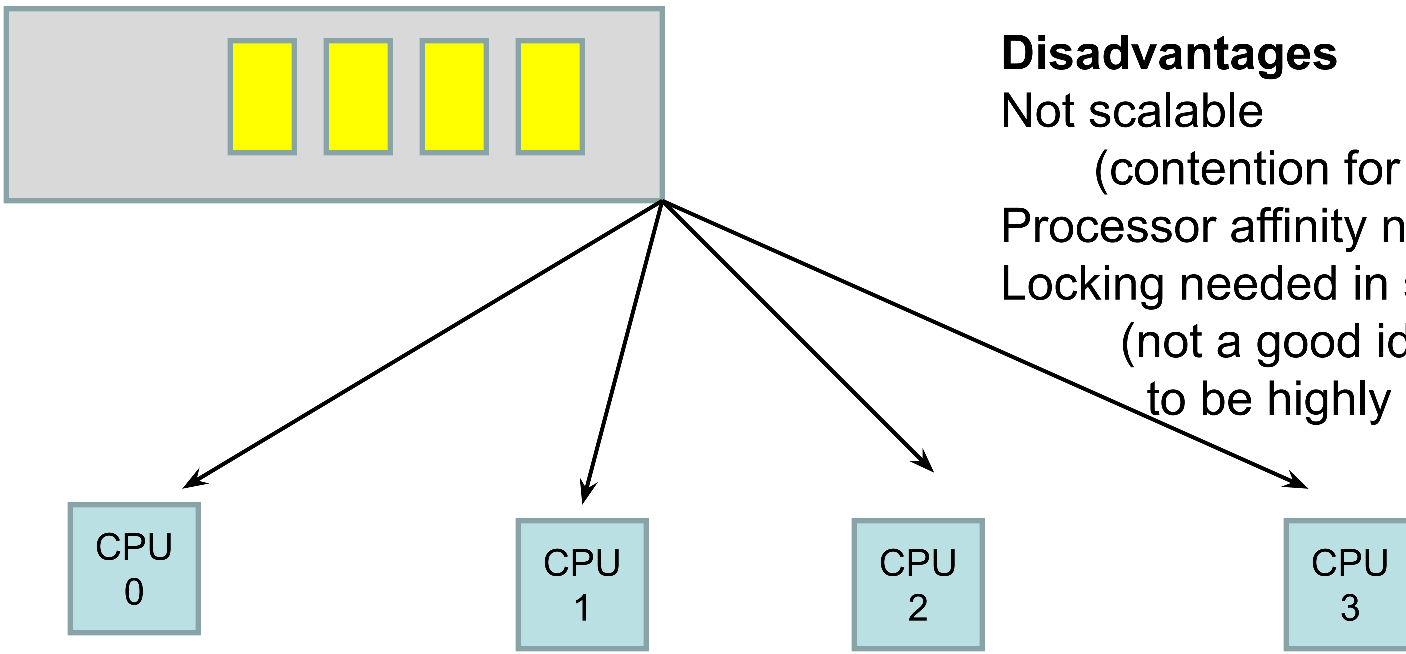
Requires locking to access the queues

Symmetrical Scheduling (with global queues)

Advantages
Good CPU Utilization
Fair to all processes

Disadvantages
Not scalable
(contention for the global queue)
Processor affinity not easily achieved
Locking needed in scheduler
(not a good idea. Schedulers need to be highly efficient)

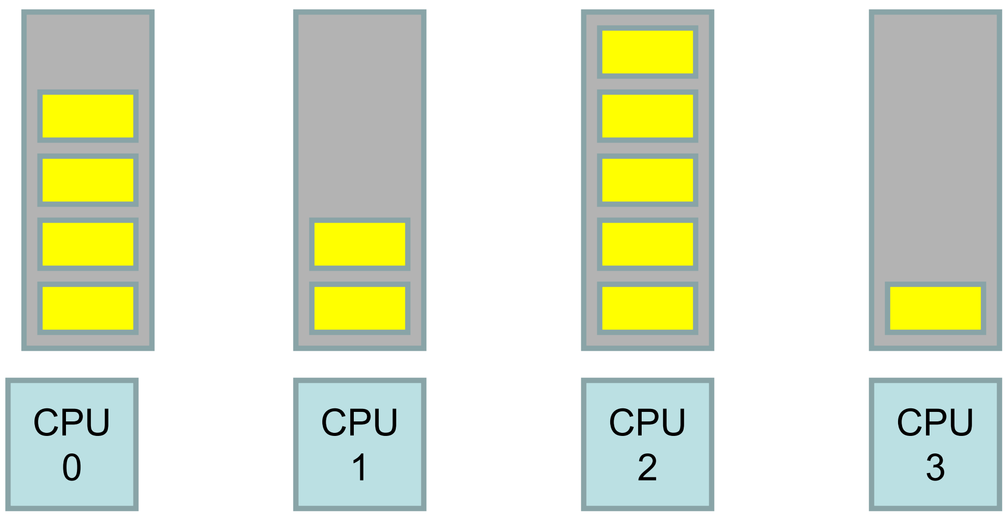
Global queues of runnable processes



Used in Linux 2.4, xv6

Symmetrical Scheduling (with per CPU queues)

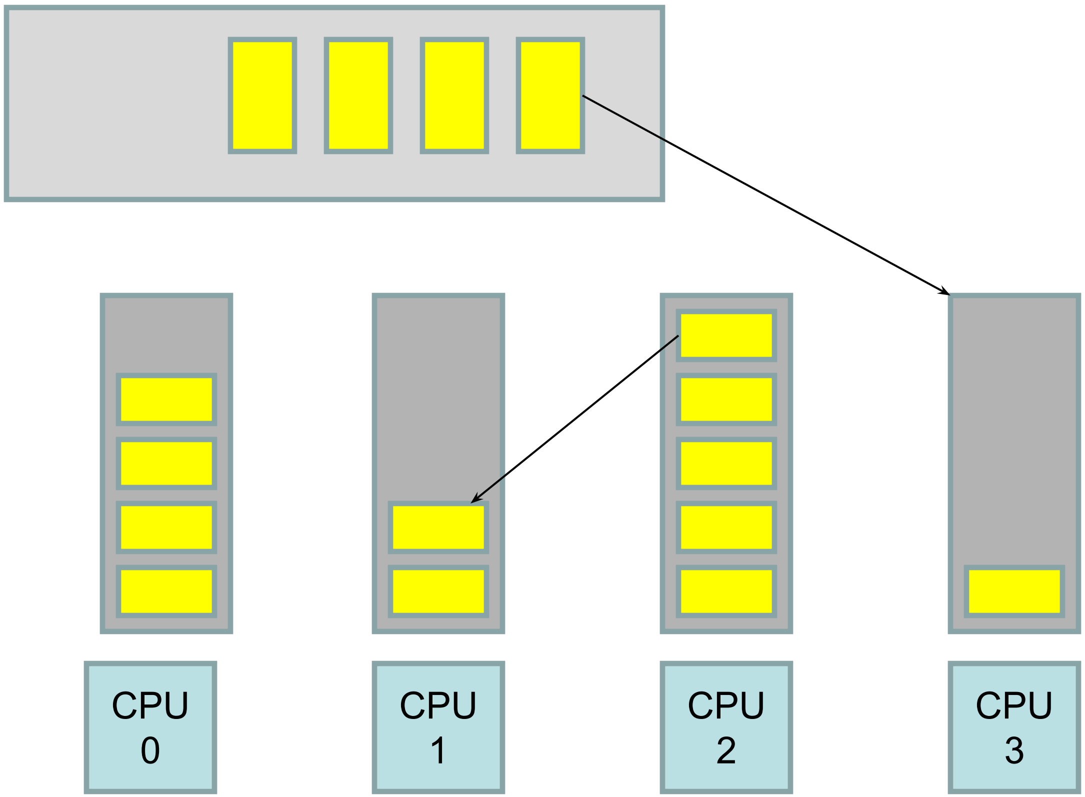
- Static partition of processes across CPUs



Advantages
Easy to implement
Scalable (no contention)
Locality

Disadvantages
Load imbalance

Hybrid Approach



- Use local and global queues
- Load balancing across queues feasible
- Locality achieved by processor affinity wrt the local queues
- Similar approach followed in Linux 2.6

Load Balancing

- On SMP systems, one processor may be overworked, while another underworked
- Load balancing attempts to keep the workload evenly distributed across all processors
- Two techniques
  - Push Migration : A special task periodically monitors load of all processors, and redistributes work when it finds an imbalance
  - Pull Migration : Idle processors pull a waiting task from a busy processor

Scheduling in Linux

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Process Types

- Real time
  - Deadlines that have to be met
  - Should never be blocked by a low priority task
- Normal Processes
  - Interactive
    - Constantly interact with their users, therefore spend a lot of time waiting for key presses and mouse operations.
    - When input is received, the process must wake up quickly (delay must be between 50 to 150 ms)
  - Batch
    - Does not require any user interaction, often runs in the background.

Process Types

- Real time
  - Deadlines that have to be met
  - Should never be blocked by a low

Once a process is specified real time, it is always considered a real time process

- Normal Processes
  - Interactive
    - Constantly interact with their users, therefore spend a lot of time waiting for key presses and mouse operations.
    - When input is received, the process must wake up quickly (delay must be between 50 to 150 ms)
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Process Types

- Real time
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- Normal Processes
  - Interactive
    - Constantly interact with their users
      key presses and mouse operations
    - When input is received, the proces
      between 50 to 150 ms)
  - Batch
    - Do not require any user interaction,

A process may act as an interactive process for some time and then become a batch process.

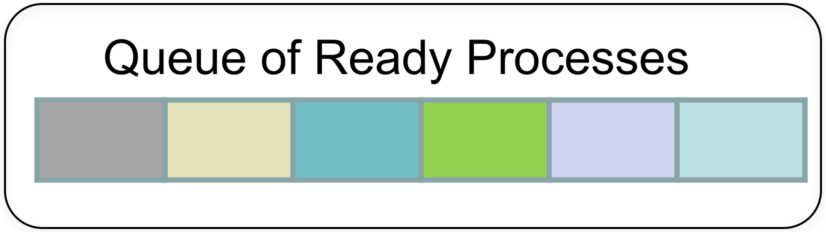
Linux uses sophisticated heuristics based on past behavior of the process to decide whether a given process should be considered interactive or batch

History (Schedulers for Normal Processors)

- O(n) scheduler
  - Linux 2.4 to 2.6
- O(1) scheduler
  - Linux 2.6 to 2.6.22
- CFS scheduler
  - Linux 2.6.23 onwards

O(n) Scheduler

- At every context switch
  - Scan the list of runnable processes
  - Compute priorities
  - Select the best process to run



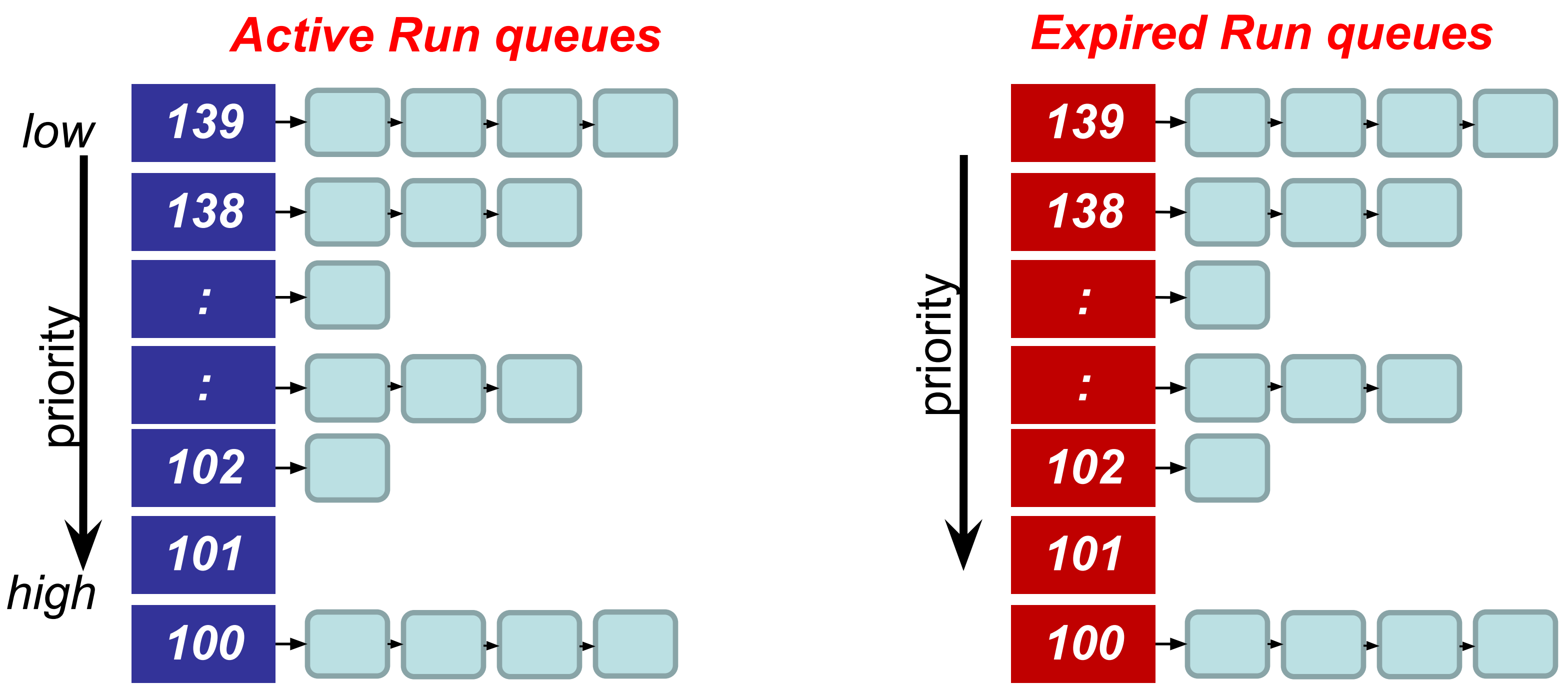
- O(n), when n is the number of runnable processes … not scalable!!
  - Scalability issues observed when Java was introduced (JVM spawns many tasks)
- Used a global run-queue in SMP systems
  - Again, not scalable!!

O(1) scheduler

- Constant time required to pick the next process to execute
  - easily scales to large number of processes
- Processes divided into 2 types
  - Real time
    - Priorities from 0 to 99
  - Normal processes
    - Interactive
    - Batch
    - Priorities from 100 to 139 (100 highest, 139 lowest priority)

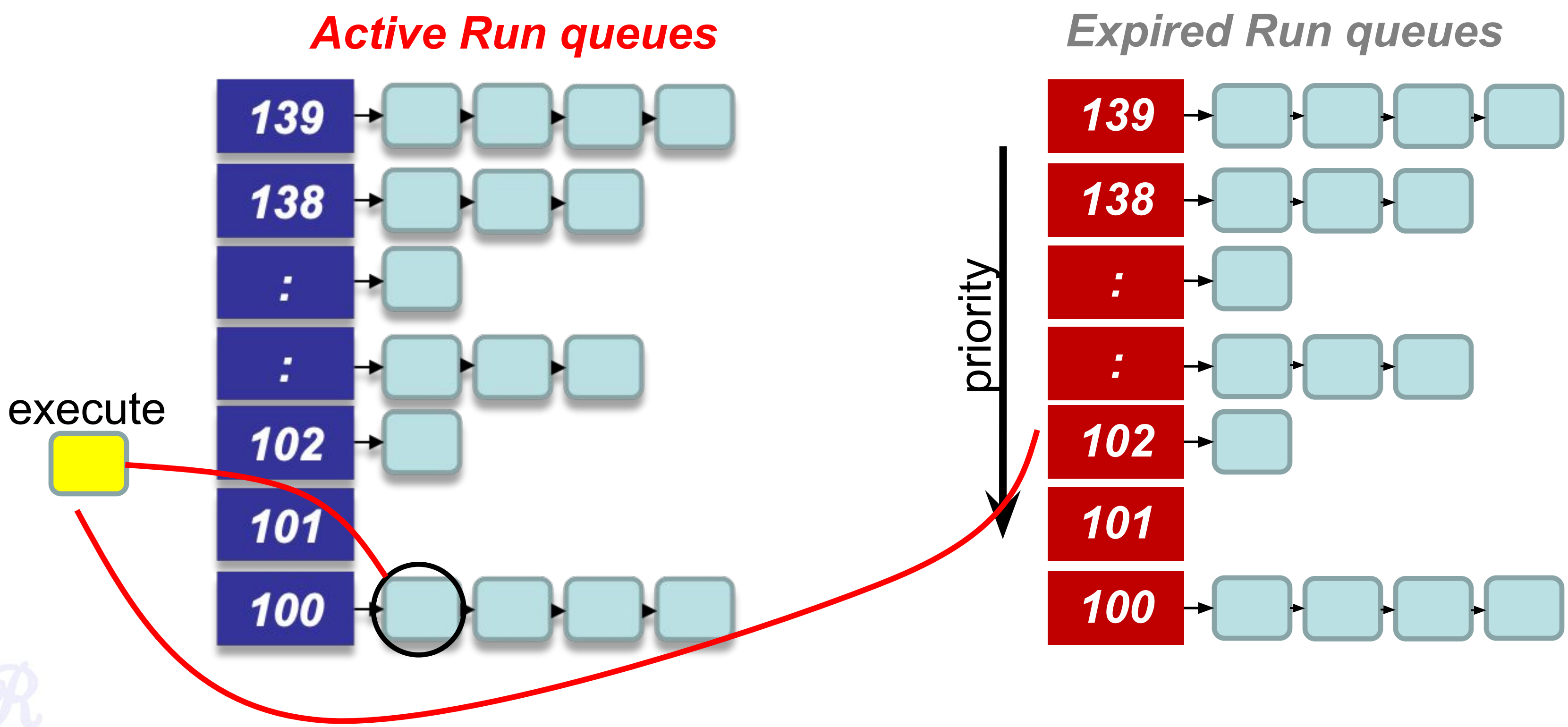
Scheduling Normal Processes

- Two ready queues in each CPU
  - Each queue has 40 priority classes (100 – 139)
  - 100 has highest priority, 139 has lowest priority



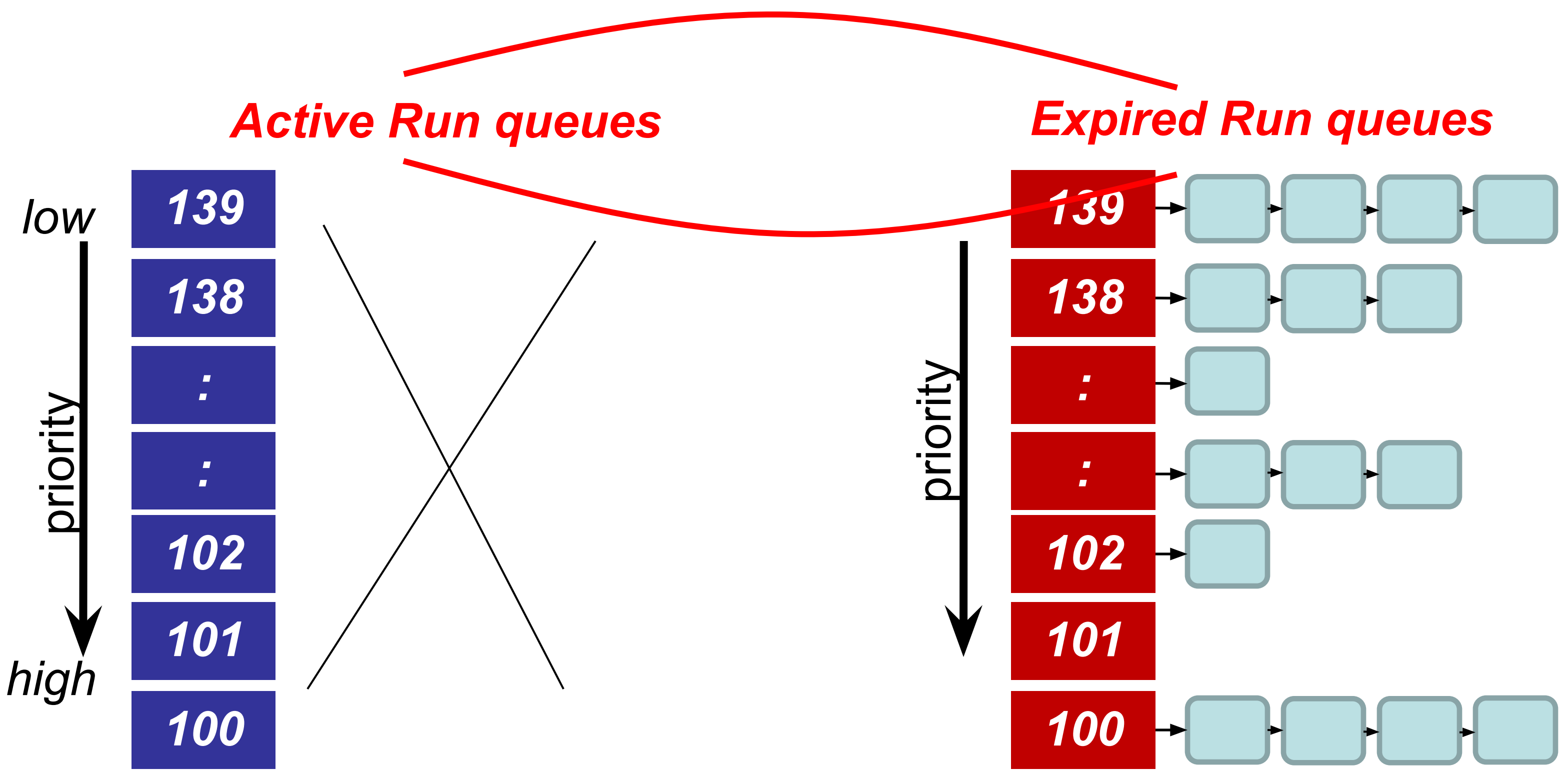
The Scheduling Policy

- Pick the first task from the lowest numbered run queue
- When done put task in the appropriate queue in the expired run queue



The Scheduling Policy

- Once active run queues are complete
  - Make expired run queues active and vice versa



contant time?

- There are 2 steps in the scheduling
  1. Find the lowest numbered queue with at least 1 task
  2. Choose the first task from that queue

- step 2 is obviously constant time
- Is step 1 contant time?
  - Store bitmap of run queues with non-zero entries
  - Use special instruction '*find-first-bit-set*'
    - *bsfl* on intel

More on Priorities

- 0 to 99 meant for real time processes
- 100 is the highest priority for a normal process
- 139 is the lowest priority
- Static Priorities
  - 120 is the base priority (default)
  - **nice :** command line to change default priority of a process

    $nice –n N ./a.out
  - N is a value from +19 to -20;
    - most selfish ‘-20’; (I want to go first)
    - most generous ‘+19’; (I will go last)

Based on a heuristic

Dynamic Priority

- To distinguish between batch and interactive processes
- Uses a 'bonus', which changes based on a heuristic

dynamic priority = MAX(100, MIN(static priority – bonus + 5), 139))

Has a value between 0 and 10

If bonus < 5, implies less interaction with the user
thus more of a CPU bound process.
The dynamic priority is therefore decreased (toward 139)

If bonus > 5, implies more interaction with the user
thus more of an interactive process.
The dynamic priority is increased (toward 100).

Dynamic Priority (setting the bonus)

- To distinguish between batch and interactive processes
- Based on average sleep time
  - An I/O bound process will sleep more therefore should get a higher priority
  - A CPU bound process will sleep less, therefore should get lower priority

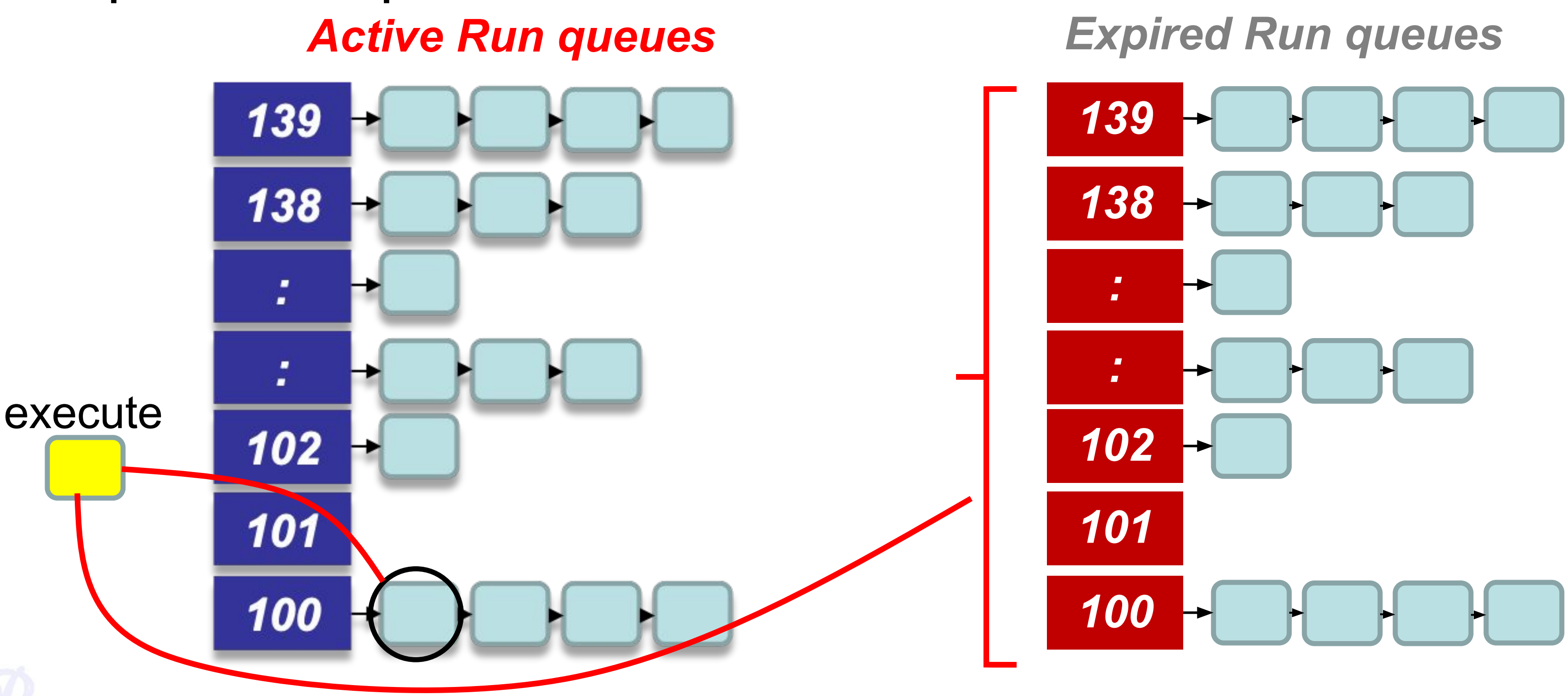
dynamic priority = MAX(100, MIN(static priority – bonus + 5), 139))

heuristic

Average sleep time	Bonus
Greater than or equal to 0 but smaller than 100 ms	0
Greater than or equal to 100 ms but smaller than 200 ms	1
Greater than or equal to 200 ms but smaller than 300 ms	2
Greater than or equal to 300 ms but smaller than 400 ms	3
Greater than or equal to 400 ms but smaller than 500 ms	4
Greater than or equal to 500 ms but smaller than 600 ms	5
Greater than or equal to 600 ms but smaller than 700 ms	6
Greater than or equal to 700 ms but smaller than 800 ms	7
Greater than or equal to 800 ms but smaller than 900 ms	8
Greater than or equal to 900 ms but smaller than 1000 ms	9
1 second	10

Dynamic Priority and Run Queues

- Dynamic priority used to determine which run queue to put the task
- No matter how 'nice' you are, you still need to wait on run queues --- prevents starvation



Setting the Timeslice

- Interactive processes have high priorities.
  - But likely to not complete their timeslice
  - Give it the largest timeslice to ensure that it completes its burst without being preempted. More heuristics

```
If priority < 120
    time slice = (140 – priority) * 20    milliseconds
else
    time slice = (140 – priority) * 5   milliseconds
```

Priority:	Static Pri	Niceness	Quantum
Highest	100	-20	800 ms
High	110	-10	600 ms
Normal	120	0	100 ms
Low	130	10	50 ms
Lowest	139	19	5 ms

Summarizing the O(1) Scheduler

- **Queues:** Multi level feed back queues with 40 priority classes
- **Base Priority:** Base priority set to 120 by default; modifiable by users using nice.
- **Dynamic Priority:** Dynamic priority set by heuristics based on process' sleep time
- **Dynamic timeslices:** Time slice interval for each process is set based on the dynamic priority
- **Starvation:** is dealt with by the two queues

Limitations of O(1) Scheduler

- Too complex heuristics to distinguish between interactive and non-interactive processes
- Dependence between timeslice and priority
- Priority and timeslice values not uniform

Completely Fair Scheduling (CFS)

- The Linux scheduler since 2.6.23
- By Ingo Molnar
  - based on the Rotating Staircase Deadline Scheduler (RSDL) by Con Kolivas.
  - Incorporated in the Linux kernel since 2007
- No heuristics.
- Elegant handling of I/O and CPU bound processes.

Completely Fair Scheduling (CFS)

Ideal Fair Scheduling

Process	burst time
A	8ms
B	4ms
C	16ms
D	4ms

Divide processor time equally among processes

Ideal Fairness : If there are N processes in the system, each process should have got (100/N)% of the CPU time

Ideal Fairness

A	1	2	3	4	6	8							
B	1	2	3	4									
C	1	2	3	4	6	8	12	16					
D	1	2	3	4									

4ms slice

execution with respect to time

Ideal Fair Scheduling

Process	burst time
A	8ms
B	4ms
C	16ms
D	4ms

Divide processor time equally among processes

Ideal Fairness : If there are N processes in the system, each process should have got (100/N)% of the CPU time

Ideal Fairness

Each process gets
4/4 = 1ms of the processor time

A	1	2	3	4	6	8							
B	1	2	3	4									
C	1	2	3	4	6	8	12	16					
D	1	2	3	4									

4ms slice

execution with respect to time

Ideal Fair Scheduling

Process	burst time
A	8ms
B	4ms
C	16ms
D	4ms

Divide processor time equally among processes

Ideal Fairness : If there are N processes in the system, each process should have got (100/N)% of the CPU time

Ideal Fairness

Each process gets
4/2 = 2ms of the processor time

A	1	2	3	4	6	8							
B	1	2	3	4									
C	1	2	3	4	6	8	12	16					
D	1	2	3	4									

4ms slice

execution with respect to time

Ideal Fair Scheduling

Process	burst time
A	8ms
B	4ms
C	16ms
D	4ms

Divide processor time equally among processes

Ideal Fairness : If there are N processes in the system, each process should have got (100/N)% of the CPU time

Ideal Fairness

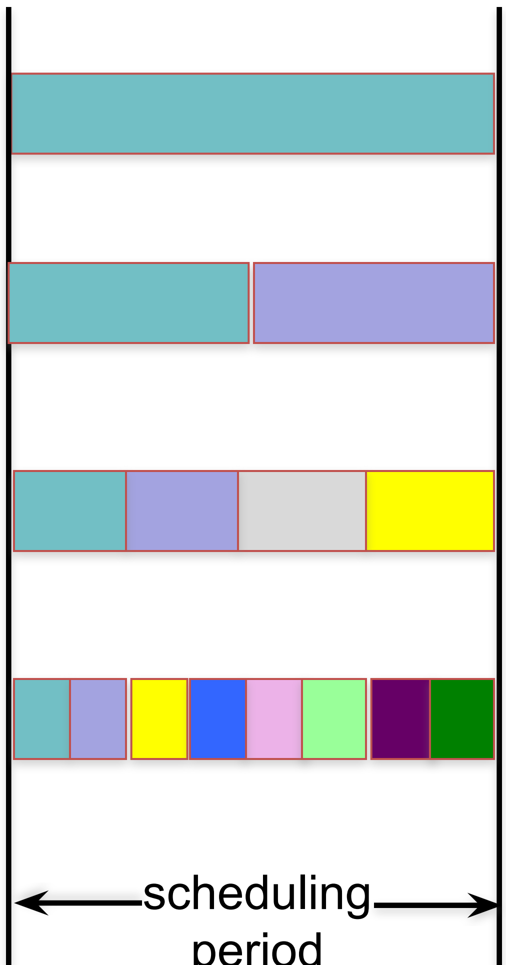
A	1	2	3	4	6	8							
B	1	2	3	4									
C	1	2	3	4	6	8	12	16					
D	1	2	3	4									

The single process gets the entire 4ms of the processor time

4ms period

execution with respect to time

Not so Ideal Fair Scheduling



1 process in the ready queue

2 processes in the ready queue

4 processes in the ready queue

8 processes in the ready queue

sched_min_granularity_min
granularity of each epoch (eg. 4ms)
sched_latency_ns
epoch duration (eg. 20ms)

Not so Ideal Fair Scheduling

sched_min_granularity_ns
min granularity of each epoch (eg. 4ms)
sched_latency_ns
epoch duration (eg. 20ms)

The scheduler checks if the following inequality holds

nr_running > (sched_latency_ns)/(sched_min_granularity_ns)

, where nr_running is the number of running tasks

If inequality is satisfied, then there are too many tasks in the system and scheduler period needs to be increased

*period = sched_min_granularity_ns * nr_running*

If inequality is not satisfied, then

peirod = sched_latency_ns

Configuring at runtime

Reading

#cat /proc/sys/kernel/sched_latency_ns

#cat /proc/sys/kernel/sched_min_granularity_ns

Writing

#echo VALUE > /proc/sys/kernel/sched_latency_ns

Virtual Runtimes
(keeping track of execution time)

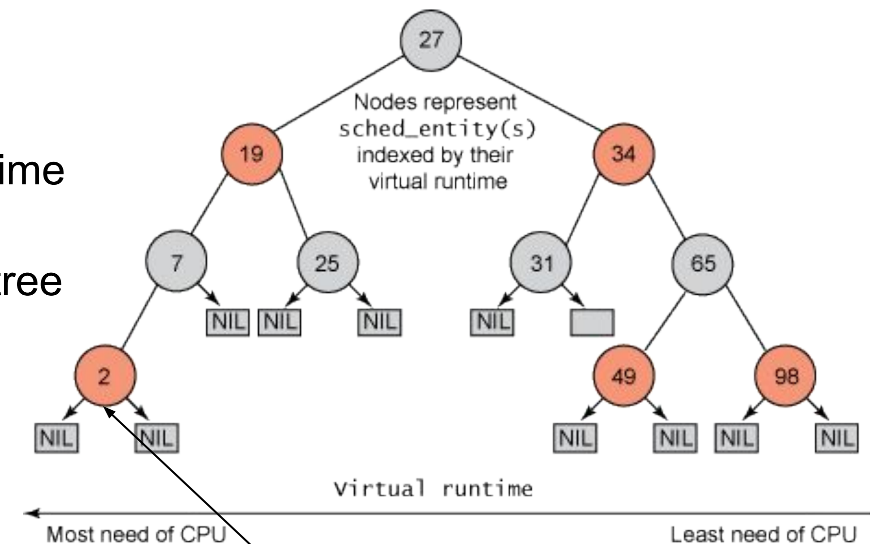
- With each runnable process is included a virtual runtime (vruntime)
  - At every scheduling point, if process has run for t ms, then (vruntime += t)
  - vruntime for a process therefore monotonically increases

The CFS Idea

- When timer interrupt occurs
  - Choose the task with the lowest vruntime (min_vruntime)
  - Compute its dynamic timeslice
  - Program the high resolution timer with this timeslice
- The process begins to execute in the CPU
- When interrupt occurs again
  - Context switch if there is another task with a smaller runtime

Picking the Next Task to Run

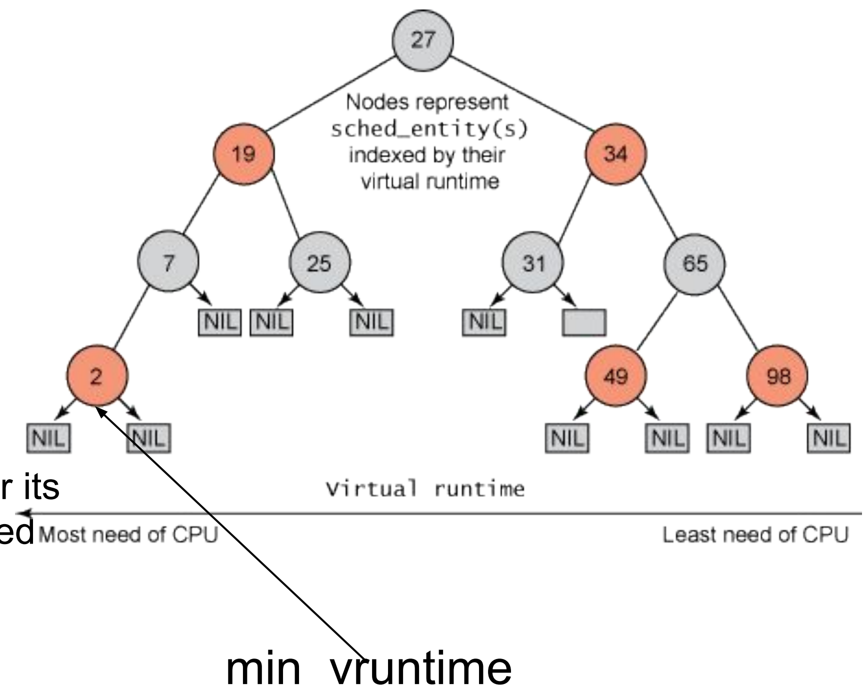
- CFS uses a red-black tree.
  - Each node in the tree represents a runnable task
  - Nodes ordered according to their vruntime
  - Nodes on the left have lower vruntime compared to nodes on the right of the tree
  - The left most node is the task with the least vruntime
    - This is cached in min_vruntime



min_vruntime

Picking the Next Task to Run

- At a context switch,
  - Pick the left most node of the tree
    - This has the lowest runtime.
    - It is cached in min_vruntime. Therefore accessed in O(1)
  - If the previous process is runnable, it is inserted into the tree depending on its new vruntime. Done in O(log(n))
    - Tasks move from left to right of tree after its execution completes… starvation avoided



Why Red Black Tree?

- Self Balancing
  - No path in the tree will be twice as long as any other path
- All operations are O(log n)
  - Thus inserting / deleting tasks from the tree is quick and efficient

Priorities and CFS

- Priority (due to nice values) used to weigh the vruntime

- if process has run for t ms, then

  vruntime += t * (weight based on nice of process)

- A lower priority implies time moves at a faster rate compared to that of a high priority task

I/O and CPU bound processes

- What we need,
  - I/O bound should get higher priority and get a longer time to execute compared to CPU bound
  - CFS achieves this efficiently
    - I/O bound processes have small CPU bursts therefore will have a low vruntime. They would appear towards the left of the tree…. Thus are given higher priorities
    - I/O bound processes will typically have larger time slices, because they have smaller vruntime

New Process

- Gets added to the RB-tree
- Starts with an initial value of min_vruntime..
- This ensures that it gets to execute quickly

Thank You