Operating System Principles: Scheduling

CS 111

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Operating System Principles

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Outline

- What is scheduling?
  - What are our scheduling goals?
- What resources should we schedule?
- Example scheduling algorithms and their implications

What Is Scheduling?

- An operating system often has choices about what to do next
- In particular:
  - For a resource that can serve one client at a time
  - When there are multiple potential clients
  - Who gets to use the resource next?
  - And for how long?
- Making those decisions is scheduling

OS Scheduling Examples

- What job to run next on an idle core?
  - How long should we let it run?
- In what order to handle a set of block requests for a flash drive?
- If multiple messages are to be sent over the network, in what order should they be sent?
- We’ll primarily consider scheduling processes

How Do We Decide How To Schedule?

- Generally, we choose goals we wish to achieve
- And design a scheduling algorithm that is likely to achieve those goals
- Different scheduling algorithms try to optimize different quantities
- So changing our scheduling algorithm can drastically change system behavior

The Process Queue

- The OS typically keeps a queue of processes that are ready to run
  - Ordered by whichever one should run next
  - Which depends on the scheduling algorithm used
- When time comes to schedule a new process, grab the first one on the process queue
- Processes that are not ready to run either:
  - Aren’t in that queue
  - Or are at the end
  - Or are ignored by scheduler

Potential Scheduling Goals

- Maximize throughput
  - Get as much work done as possible
- Minimize average waiting time
  - Try to avoid delaying too many for too long
- Ensure some degree of fairness
  - E.g., minimize worst case waiting time
- Meet explicit priority goals
  - Scheduled items tagged with a relative priority
- Real time scheduling
  - Scheduled items tagged with a deadline to be met

Different Kinds of Systems, Different Scheduling Goals

- How should we schedule our cores?
- Time sharing
  - Fast response time to interactive programs
  - Each user gets an equal share of the CPU
- Batch
  - Maximize total system throughput
  - Delays of individual processes are unimportant
- Real-time
  - Critical operations must happen on time
  - Non-critical operations may not happen at all
- Service Level Agreement (SLA)
  - Make sure all agreements are met
  - Various agreements may differ in details

Scheduling: Policy and Mechanism

- The scheduler will move jobs onto and off of a processor core (*dispatching*)
  - Requiring various mechanics to do so
  - Part of the scheduling mechanism
- How dispatching is done should not depend on the policy used to decide who to dispatch
- Desirable to separate the choice of who runs (policy) from the dispatching mechanism
  - Also desirable that OS process queue structure not be policy-dependent

Preemptive Vs. Non-Preemptive Scheduling

- When we schedule a piece of work, we could let it use the resource until it finishes
- Or we could interrupt it part way through
  - Allowing other pieces of work to run instead
- If scheduled work always runs to completion, the scheduler is non-preemptive
- If the scheduler temporarily halts running work to run something else, it's preemptive

Pros and Cons of Non-Preemptive Scheduling

+ Low scheduling overhead
+ Tends to produce high throughput
+ Conceptually very simple
– Poor response time for processes
– Bugs can cause machine to freeze up
  – If process contains infinite loop, e.g.
– Poor fairness (by most definitions)
– May make real time and priority scheduling difficult

Pros and Cons of Pre-emptive Scheduling

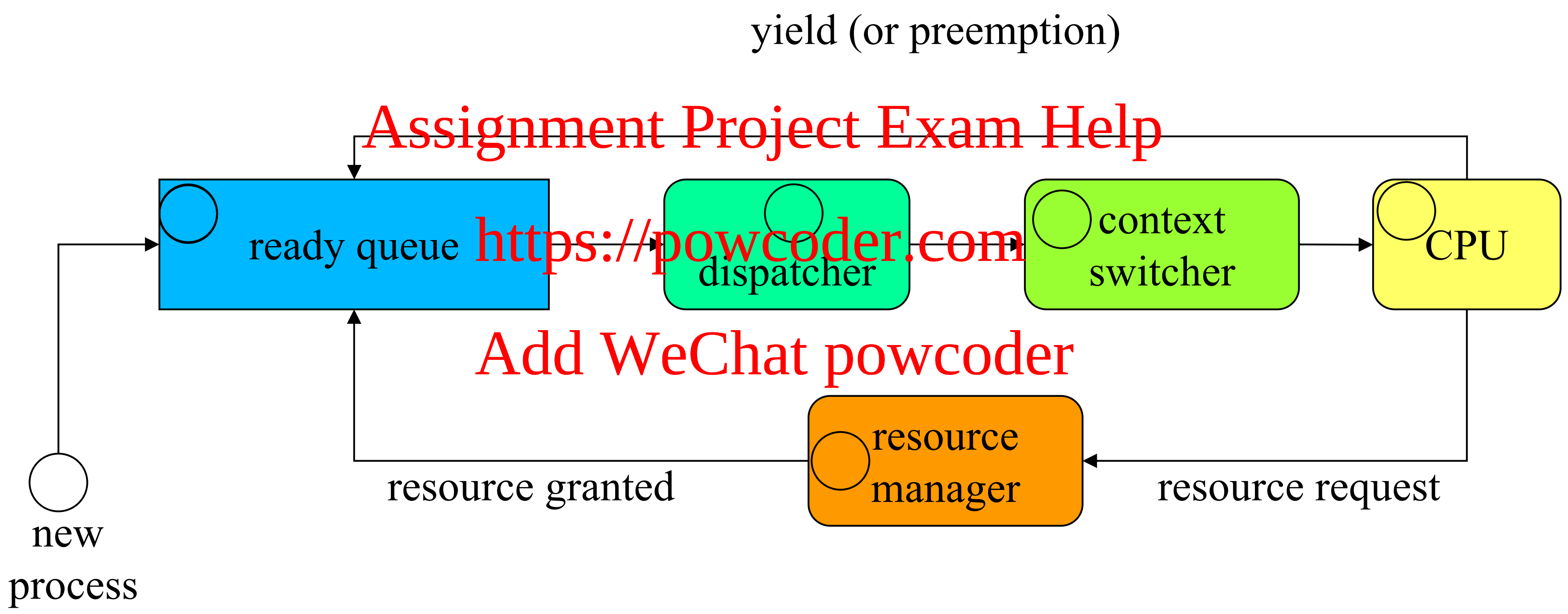
+ Can give good response time
+ Can produce very fair usage

+ Good for real-time and priority scheduling

– More complex

– Requires ability to cleanly halt process and save its state
– May not get good throughput
– Possibly higher overhead

Scheduling the CPU



Scheduling and Performance

- How you schedule important system activities has a major effect on performance
- Performance has different aspects
  - You may not be able to optimize for all of them
- Scheduling performance has very different characteristic under light vs. heavy load
- Important to understand the performance basics regarding scheduling

General Comments on Performance

- Performance goals should be quantitative and measurable
  - If we want "goodness" we must be able to quantify it
  - You cannot optimize what you do not measure
- Metrics ... the way & units in which we measure
  - Choose a characteristic to be measured
    - It must correlate well with goodness/badness of service
  - Find a unit to quantify that characteristic
    - It must a unit that can actually be measured
  - Define a process for measuring the characteristic
- That's a brief description
  - But actually measuring performance is complex

How Should We Quantify Scheduler Performance?

- Candidate metric: throughput (processes/second)
  - But different processes need different run times
  - Process completion time not controlled by scheduler
- Candidate metric: delay (milliseconds)
  - But specifically what delays should we measure?
    - Time to finish a job (turnaround time)?
    - Time to get some response?
  - Some delays are not the scheduler's fault
    - Time to complete a service request
    - Time to wait for a busy resource

Software can't optimize what it doesn't control.

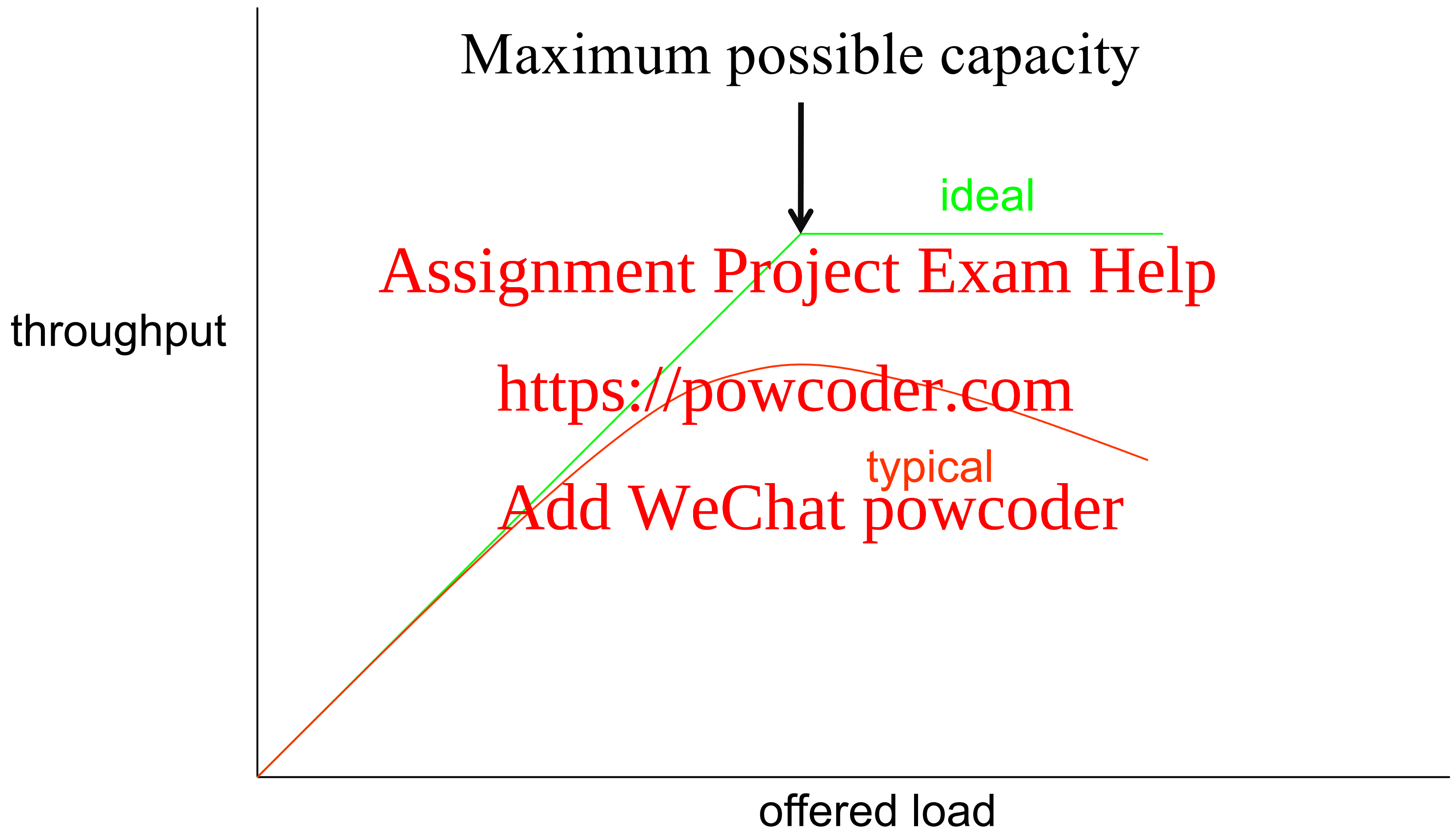
Other Scheduling Metrics

- Mean time to completion (seconds)
  - For a particular job mix (benchmark)
- Throughput (operations per second)
  - For a particular activity or job mix (benchmark)
- Mean response time (milliseconds)
  - Time spent on the ready queue
- Overall "goodness"
  - Requires a customer-specific weighting function
  - Often stated in Service Level Agreements (SLAs)

An Example – Measuring CPU Scheduling

- Process execution can be divided into phases
  - Time spent running
    - The process controls how long it needs to run
  - Time spent waiting for resources or completions
    - Resource managers control how long these take
  - Time spent waiting to be run when ready
    - This time is controlled by the scheduler
- Proposed metric:
  - Time that "ready" processes spend waiting for the CPU

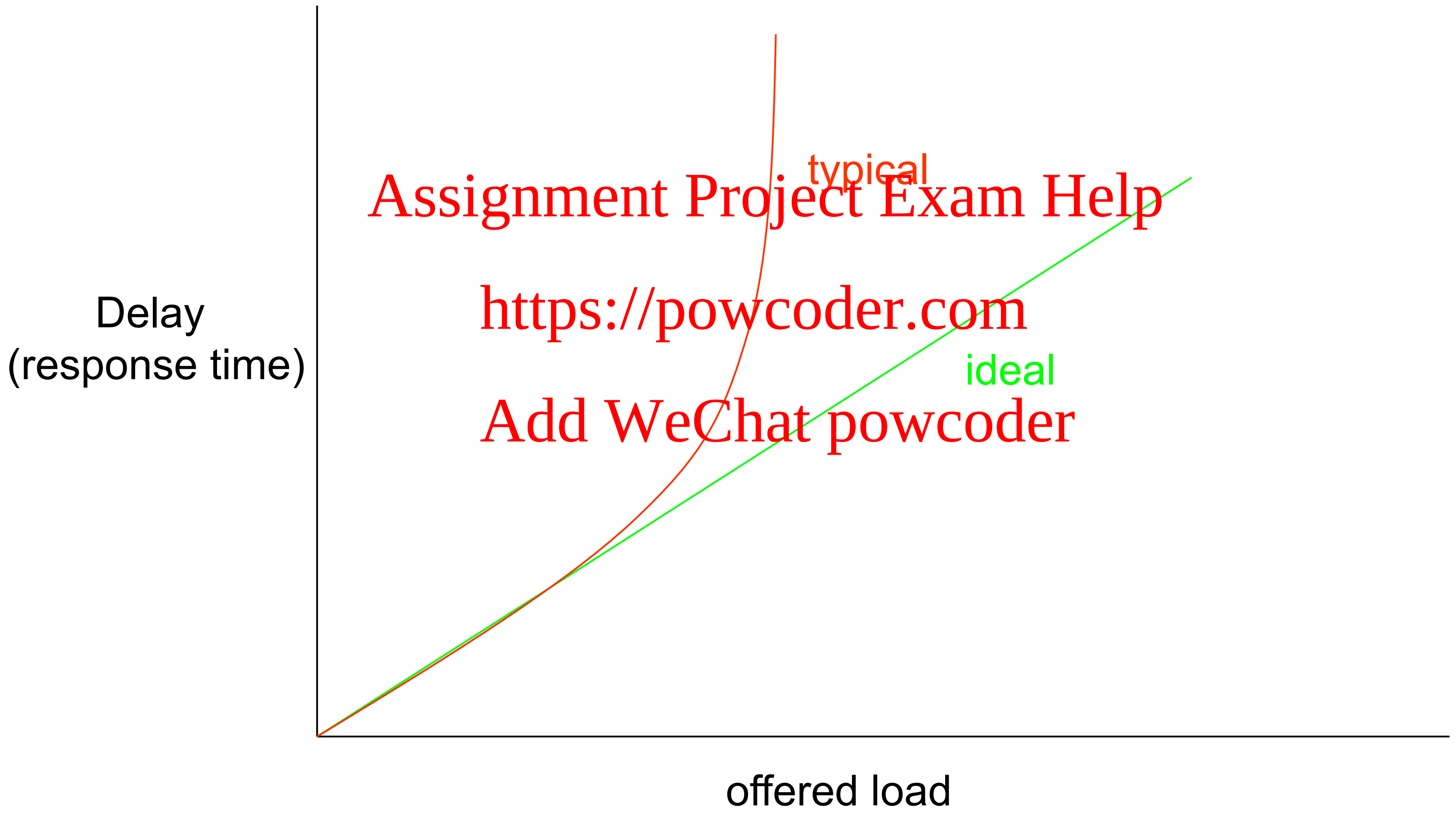
Typical Throughput vs. Load Curve



Why Don't We Achieve Ideal Throughput?

- Scheduling is not free
  - It takes time to dispatch a process (overhead)
  - More dispatches means more overhead (lost time)
  - Less time (per second) is available to run processes
- How to minimize the performance gap
  - Reduce the overhead per dispatch
  - Minimize the number of dispatches (per second)
- This phenomenon is seen in many areas besides process scheduling

Typical Response Time vs. Load Curve



Why Does Response Time Explode?

- Real systems have finite limits
  - Such as queue size
- When limits exceeded, requests are typically dropped
  - Which is an infinite response time, for them
  - There may be automatic retries (e.g., TCP), but they could be dropped, too
- If load arrives a lot faster than it is serviced, lots of stuff gets dropped
- Unless you're careful, overheads explode during periods of heavy load

Graceful Degradation

- When is a system "overloaded"?
  - When it is no longer able to meet its service goals
- What can we do when overloaded?
  - Continue service, but with degraded performance
  - Maintain performance by rejecting work
  - Resume normal service when load drops to normal
- What should we <u>not</u> do when overloaded?
  - Allow throughput to drop to zero (i.e., stop doing work)
  - Allow response time to grow without limit

Non-Preemptive Scheduling

- Scheduled process runs until it yields CPU
- Works well for simple systems
  - Small numbers of processes
  - With natural producer consumer relationships
- Good for maximizing throughput
- Depends on each process to voluntarily yield
  - A piggy process can starve others
  - A buggy process can lock up the entire system

Non-Preemptive Scheduling Algorithms

- First come first served
- Shortest job next
  - We won't cover this in detail in lecture
  - It's in the readings
- Real time schedulers

First Come First Served

- The simplest of all scheduling algorithms
- Run first process on ready queue
  - Until it completes or yields
- Then run next process on queue
  - Until it completes or yields
- Highly variable delays
  - Depends on process implementations
- All processes will eventually be served

First Come First Served Example

Dispatch Order		0, 1, 2, 3, 4	
Process	Duration	Start Time	End Time
0	350	0	350
1	125	350	475
2	475	475	950
3	250	950	1200
4	75	1200	1275
Total	1275		
Average wait		595	

Note: Average is worse than total/5 because four other processes had to wait for the slow-poke who ran first.

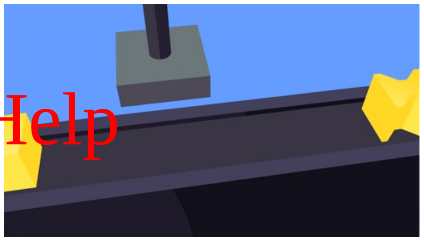
When Would First Come First Served Work Well?

- FCFS scheduling is very simple
- It may deliver very poor response time
- Thus it makes the most sense:

1. When response time is not important (e.g., batch)
2. Where minimizing overhead more important than any single job's completion time (e.g., expensive HW)
3. In embedded (e.g., telephone or set-top box) systems
   - Where computations are brief
   - And/or exist in natural producer/consumer relationships

Real Time Schedulers

- For certain systems, some things must happen at particular times



  - E.g., industrial control systems
  - If you don't rivet the widget before the conveyer belt moves on, you have a worthless widget
- These systems must schedule on the basis of real-time deadlines
- Can be either *hard* or *soft*

Hard Real Time Schedulers

- The system absolutely must meet its deadlines
- By definition, system fails if a deadline is not met
  - E.g., controlling a nuclear power plant . . .

- How can we ensure no missed deadlines?
- Typically by very, very careful analysis
  - Make sure no possible schedule causes a deadline to be missed
  - By working it out ahead of time
  - Then scheduler rigorously enforces deadlines

Ensuring Hard Deadlines

- Must have deep understanding of the code used in each job
  - You know exactly how long it will take
- Vital to avoid non-deterministic things
  - Even if the non-deterministic mechanism usually speeds things up
  - You're screwed if it ever slows them down
- Typically means you do things like turn off interrupts
- And scheduler is non-preemptive
- Typically you set up a pre-defined schedule
  - No run time decisions

Soft Real Time Schedulers

- Highly desirable to meet your deadlines
- But some (or any) of them can occasionally be missed
- Goal of scheduler is to avoid missing deadlines
  - With the understanding that you miss a few
- May have different classes of deadlines
  - Some “harder” than others
- Need not require quite as much analysis

Soft Real Time Schedulers and Non-Preemption

- Not as vital that tasks run to completion to meet their deadline
  - Also not as predictable, since you probably did less careful analysis
- In particular, a new task with an earlier deadline might arrive
- If you don't pre-empt, you might not be able to meet that deadline

What If You Don't Meet a Deadline?

- Depends on the particular type of system
- Might just drop the job whose deadline you missed
- Might allow system to fall behind
- Might drop some other job in the future
- At any rate, it will be well defined in each particular system

What Algorithms Do You Use For Soft Real Time?

- Most common is Earliest Deadline First
- Each job has a deadline associated with it
  - Based on a common clock
- Keep the job queue sorted by those deadlines
- Whenever one job completes, pick the first one off the queue
- Prune the queue to remove missed deadlines
- Goal: Minimize *total lateness*

Preemptive Scheduling

- Again in the context of CPU scheduling
- A thread or process is chosen to run
- It runs until either it yields
- Or the OS decides to interrupt it
- At which point some other process/thread runs
- Typically, the interrupted process/thread is restarted later

Implications of Forcing Preemption

- A process can be forced to yield at any time
  - If a more important process becomes ready
    - Perhaps as a result of an I/O completion interrupt
  - If running process's importance is lowered
    - Perhaps as a result of having run for too long
- Interrupted process might not be in a "clean" state
  - Which could complicate saving and restoring its state
- Enables enforced "fair share" scheduling
- Introduces gratuitous context switches
  - Not required by the dynamics of processes
- Creates potential resource sharing problems

Implementing Preemption

- Need a way to get control away from process
  - E.g., process makes a sys call, or clock interrupt
- Consult scheduler before returning to process
  - Has any ready process had its priority raised?
  - Has any process been awakened?
  - Has current process had its priority lowered?
- Scheduler finds highest priority ready process
  - If current process, return as usual
  - If not, yield on behalf of current process and switch to higher priority process

Clock Interrupts

- Modern processors contain a clock
- A peripheral device
  - With limited powers
- Can generate an interrupt at a fixed time interval
- Which temporarily halts any running process
- Good way to ensure that a runaway process doesn't keep control forever
- Key technology for preemptive scheduling

Round Robin Scheduling Algorithm

- Goal - fair share scheduling
  - All processes offered equal shares of CPU
  - All processes experience similar queue delays
- All processes are assigned a nominal time slice
  - Usually the same sized slice for all
- Each process is scheduled in turn
  - Runs until it blocks, or its time slice expires
  - Then put at the end of the process queue
- Then the next process is run
- Eventually, each process reaches front of queue

Properties of Round Robin Scheduling

- All processes get relatively quick chance to do some computation
  - At the cost of not finishing any process as quickly
  - A big win for interactive processes
- Far more context switches
  - Which can be expensive
- Runaway processes do relatively little harm
  - Only take 1/nth of the overall cycles

Round Robin and I/O Interrupts

- Processes get halted by round robin scheduling if their time slice expires
- If they block for I/O (or anything else) on their own, the scheduler doesn't halt them
  - They "halt themselves"
- Thus, some percentage of the time round robin acts no differently than FIFO
  - When I/O occurs in a process and it blocks

Round Robin Example

Assume a 50 msec time slice (or *quantum*)

Process	Length	1st	2nd	3d	4th	5th	6th	7th	8th	Finish	Switches
0	350	**0**	**250**	**475**	**650**	**800**	**950**	**1050**	▨	1100	7
1	125	**50**	**300**	**525**	▨	▨	▨	▨	▨	550	3
2	475	**100**	**350**	**550**	**700**	**850**	**1000**	**1100**	**1250**	1275	10
3	250	**150**	**400**	**600**	**750**	**900**	▨	▨	▨	900	5
4	75	**200**	**450**	▨	▨	▨	▨	▨	▨	475	2
										1275	**27**

Average waiting time: 100 msec

First process completed: 475 msec

Comparing Round Robin to FIFO

- Context switches: 27 vs. 5 for FIFO
  - Clearly more expensive
- First job completed: 475 msec vs. 350 for FIFO
  - Can take longer to complete first process
- Average waiting time: 100 msec vs. 595 for FIFO
  - For first opportunity to compute
  - Clearly more responsive

Choosing a Time Slice

- Performance of a preemptive scheduler depends heavily on how long the time slice is
- Long time slices avoid too many context switches
  - Which waste cycles
  - So better throughput and utilization
- Short time slices provide better response time to processes
- How to balance?

Costs of a Context Switch

- Entering the OS
  - Taking interrupt, saving registers, calling scheduler
- Cycles to choose who to run
  - The scheduler/dispatcher does work to choose
- Moving OS context to the new process
  - Switch stack, non-resident process description
- Switching process address spaces
  - Map-out old process, map-in new process
- Losing instruction and data caches
  - Greatly slowing down the next hundred instructions

Probably the most important cost nowadays

Priority Scheduling Algorithms

- Sometimes processes aren’t all equally important
- We might want to preferentially run the more important processes first
- How would our scheduling algorithm work then?
- Assign each job a priority number
- Run according to priority number

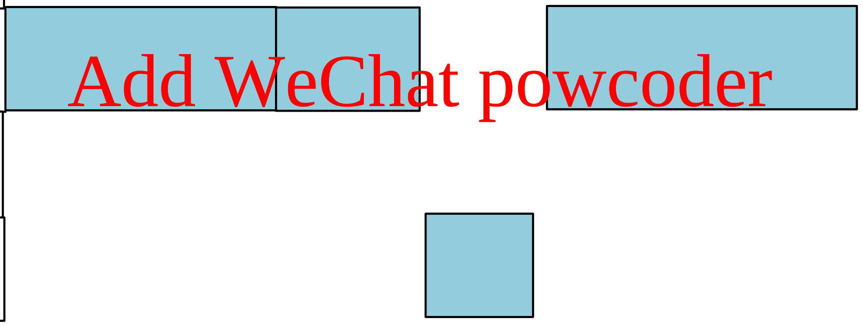
Priority and Preemption

- If non-preemptive, priority scheduling is just about ordering processes
- Much like shortest job first, but ordered by priority instead
- But what if scheduling is preemptive?
- In that case, when new process is created, it might preempt running process
  - If its priority is higher

Priority Scheduling Example

550 **Time**

Process	Priority	Length
0	10	350
1	30	125
2	40	475
3	20	250
4	50	75



Process 4 completes

So we go back to process 2

Process 3's priority is lower than running process

Process 4's priority is higher than running process

Problems With Priority Scheduling

- Possible *starvation*
- Can a low priority process ever run?
- If not, is that really the effect we wanted?
- May make more sense to adjust priorities
  - Processes that have run for a long time have priority temporarily lowered
  - Processes that have not been able to run have priority temporarily raised

Hard Priorities Vs. Soft Priorities

- What does a priority mean?
- That the higher priority has absolute precedence over the lower?
  - *Hard priorities*
  - That's what the example showed
- That the higher priority should get a larger share of the resource than the lower?
  - *Soft priorities*

Priority Scheduling in Linux

- A soft priority system
- Each process in Linux has a priority
  - Called a *nice* value
  - A soft priority describing share of CPU that a process should get
- Commands can be run to change process priorities
- Anyone can request lower priority for his processes
- Only privileged user can request higher

Priority Scheduling in Windows

- 32 different priority levels
  - Half for regular tasks, half for soft real time
  - Real time scheduling requires special privileges
  - Using a multi-queue approach
- Users can choose from 5 of these priority levels
- Kernel adjusts priorities based on process behavior
  - Goal of improving responsiveness

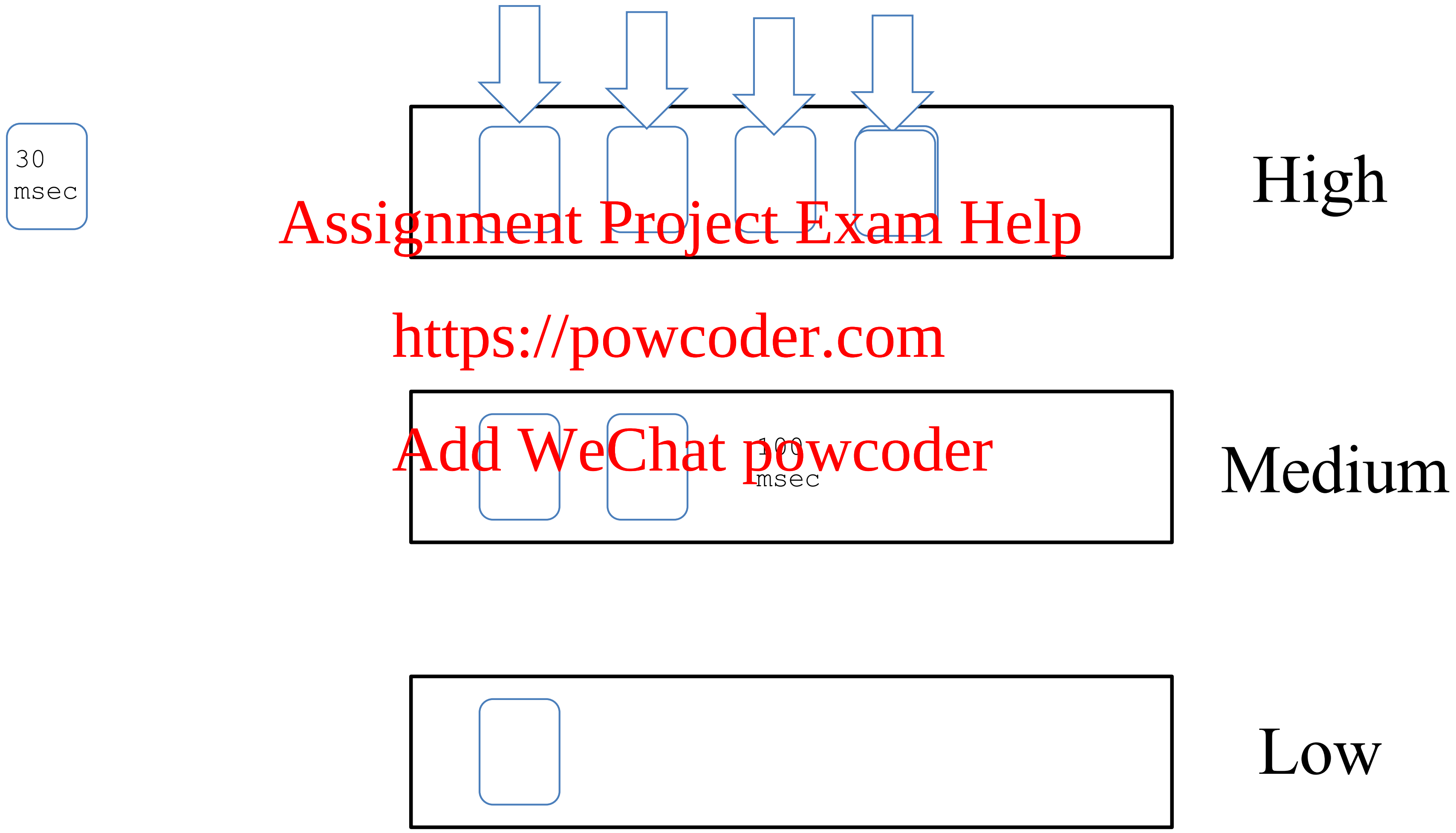
Multi-Level Feedback Queue (MLFQ) Scheduling

- One time slice length may not fit all processes
- Create multiple ready queues
  - Short quantum (foreground) tasks that finish quickly
    - Short but high priority time slices
    - To optimize response time
  - Long quantum (background) tasks that run longer
    - Longer but low priority time slices
    - To minimize overhead
- Round robin within a queue

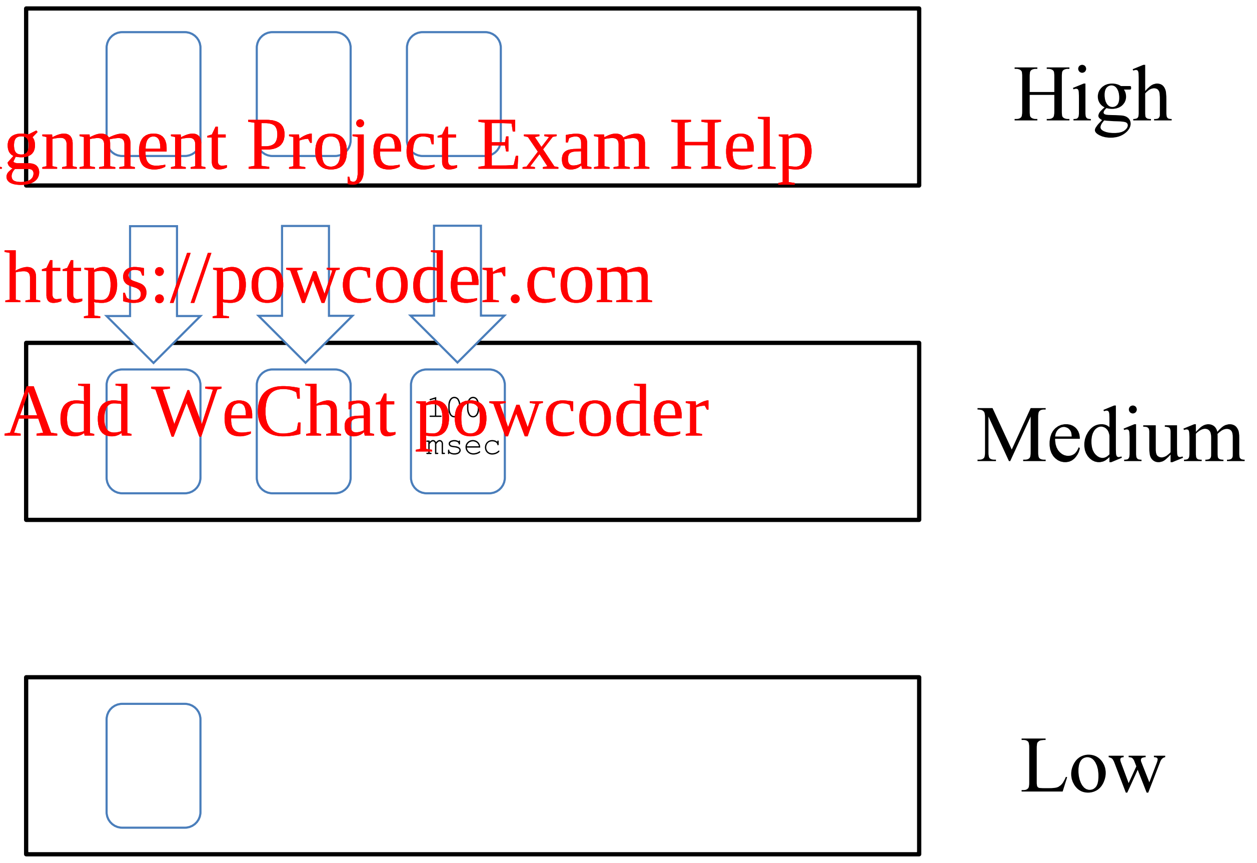
How Do I Know What Queue To Put New Process Into?

- If it's in the wrong queue, its scheduling discipline causes it problems
- Start all processes in short quantum (high priority) queue
  - Give it a standard allocation of CPU
  - Every time it runs, reduce its allocation
  - Move to longer quantum (lower priority) queue after it uses its allocation
- Periodically move all processes to a higher priority queue
  - To avoid starvation

MLFQ At Work



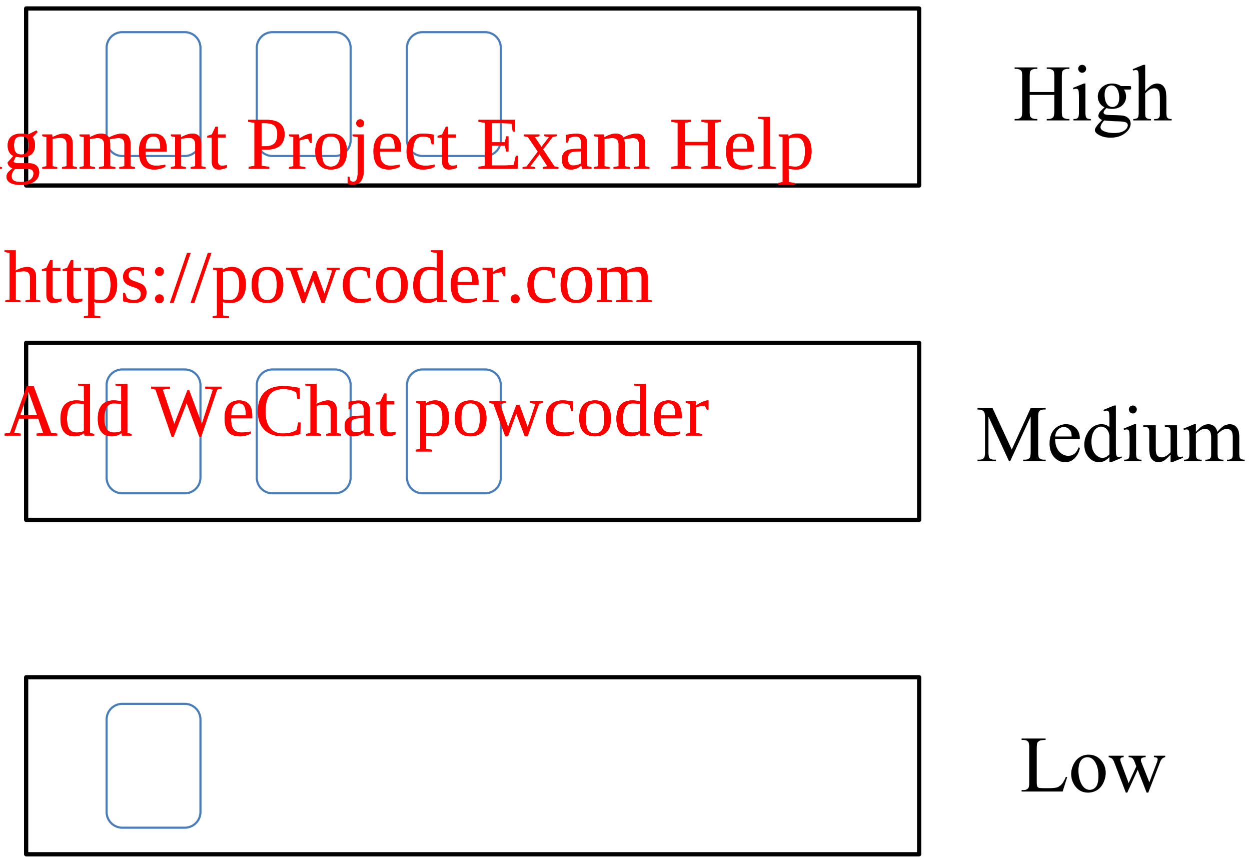
MLFQ Continuing



What About Fairness?

Periodically promote everyone

Resetting time slices accordingly



What Benefits Do We Expect From MLFQ?

- Acceptable response time for interactive jobs
  - Or other jobs with regular external inputs
  - It won't be too long before they're scheduled
  - But they won't waste CPU running for a long time
- Efficient but fair CPU use for non-interactive jobs
  - They run for a long time slice without interruption
  - If they're starved, eventually they get a priority boost
- Dynamic and automatic adjustment of scheduling based on actual behavior of jobs