Scheduling
CS 111
Operating Systems
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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 disk drive?
- If multiple messages are to be sent over the network, in what order should they be sent?

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

- 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

Preemptive Vs. Non-Preemptive Scheduling

- When we schedule a piece of work, we could let it use the resource until it finishes
- Could use virtualization to interrupt 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 jobs to run something else, it's preemptive
- Cooperative scheduling – when process blocks or voluntarily releases, schedule someone else

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.
– Not good fairness (by most definitions)
– May make real time and priority scheduling difficult

Pros and Cons of Pre-emptive Scheduling

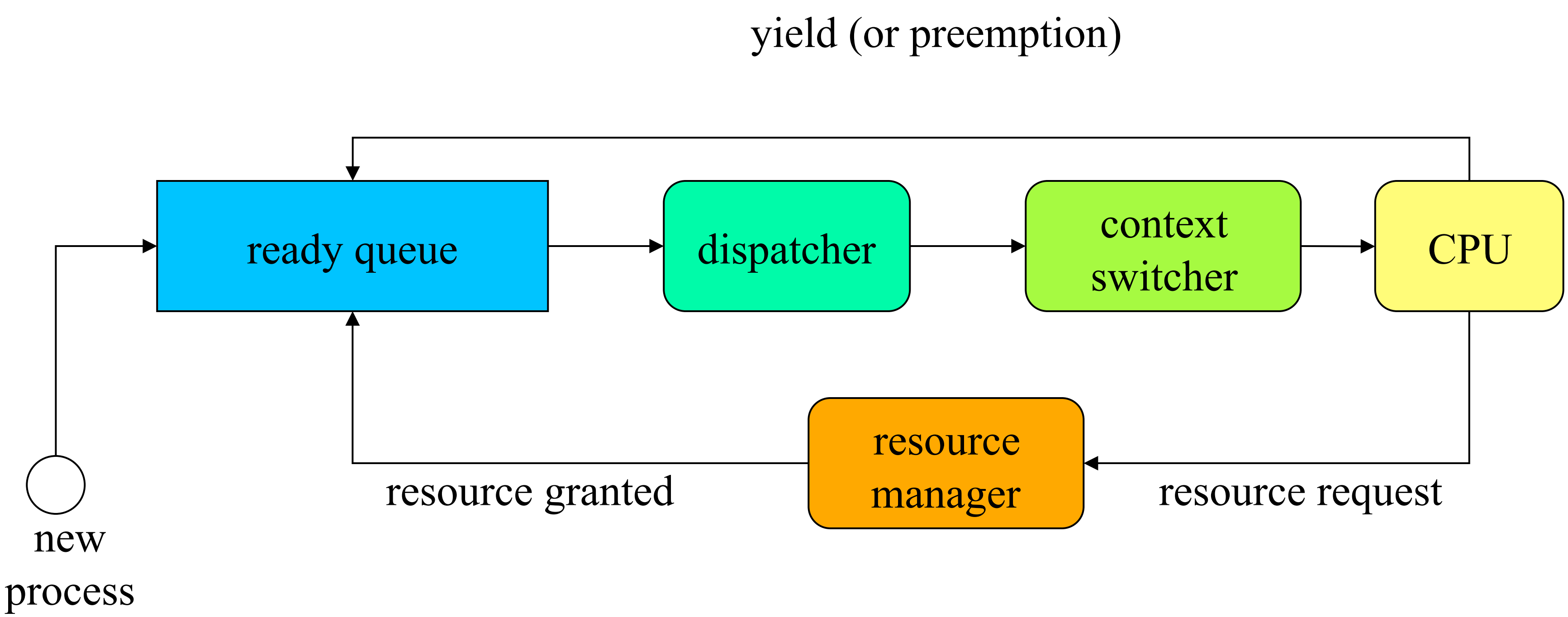
+ Can give good response time
+ Can produce very fair usage
+ Works well with real-time and priority scheduling

– More complex
– Requires ability to cleanly halt process and save its state
– May not get good throughput

Scheduling: Policy and Mechanism

- The scheduler will move jobs into and out of a processor (*dispatching*)
  - Requiring various mechanics to do so
- 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

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 both
- Scheduling performance has very different characteristic under light vs. heavy load
- Important to understand the performance basics regarding scheduling

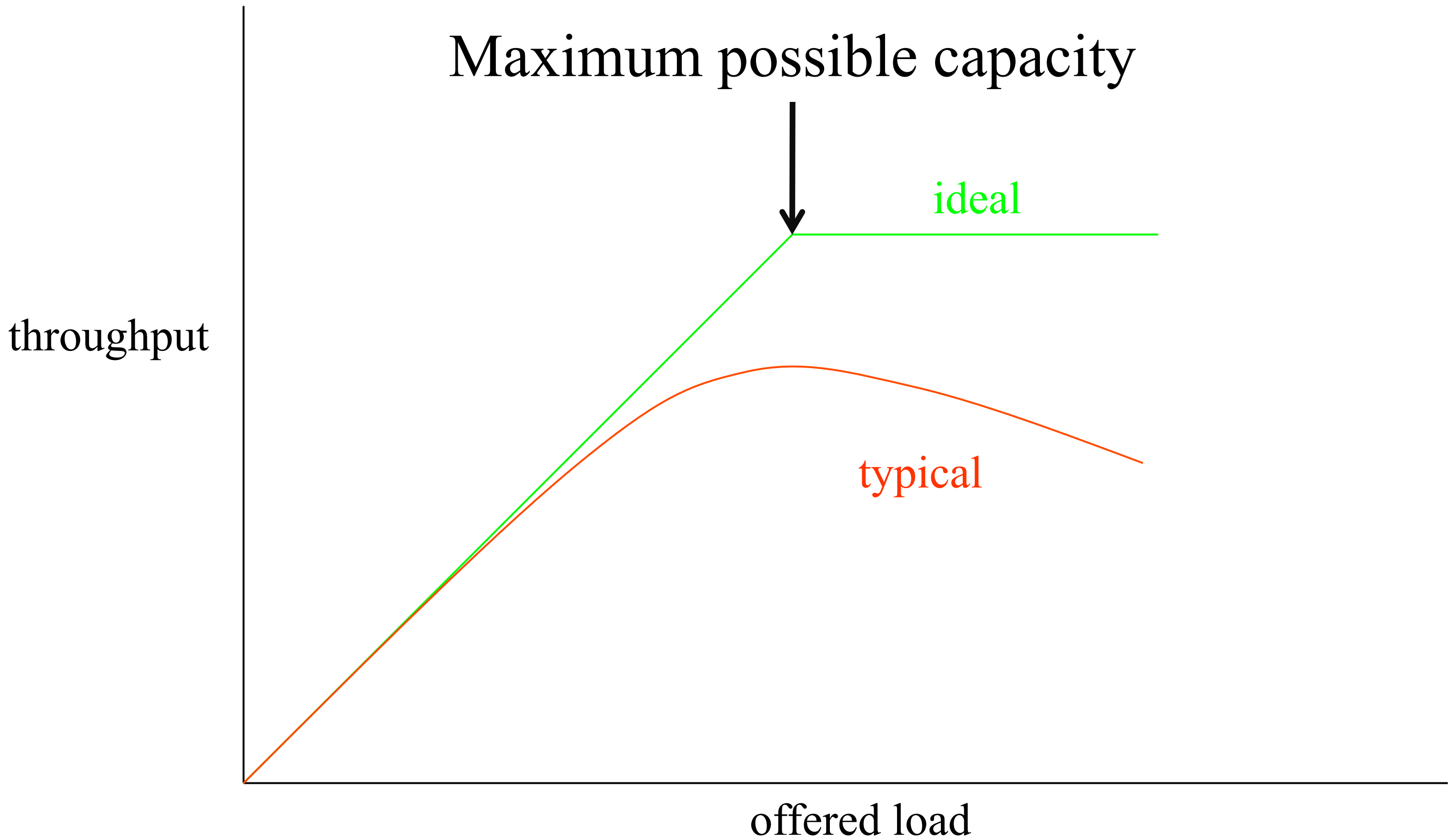
Quantifying Scheduler Performance

- 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?
  - Some delays are not the scheduler's fault
    - Time to complete a service request
    - Time to wait for a busy resource
- Different parties care about these metrics

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
    - This time is controlled by the scheduler
- Proposed metric:
  - Time that "ready" processes spend waiting for the CPU

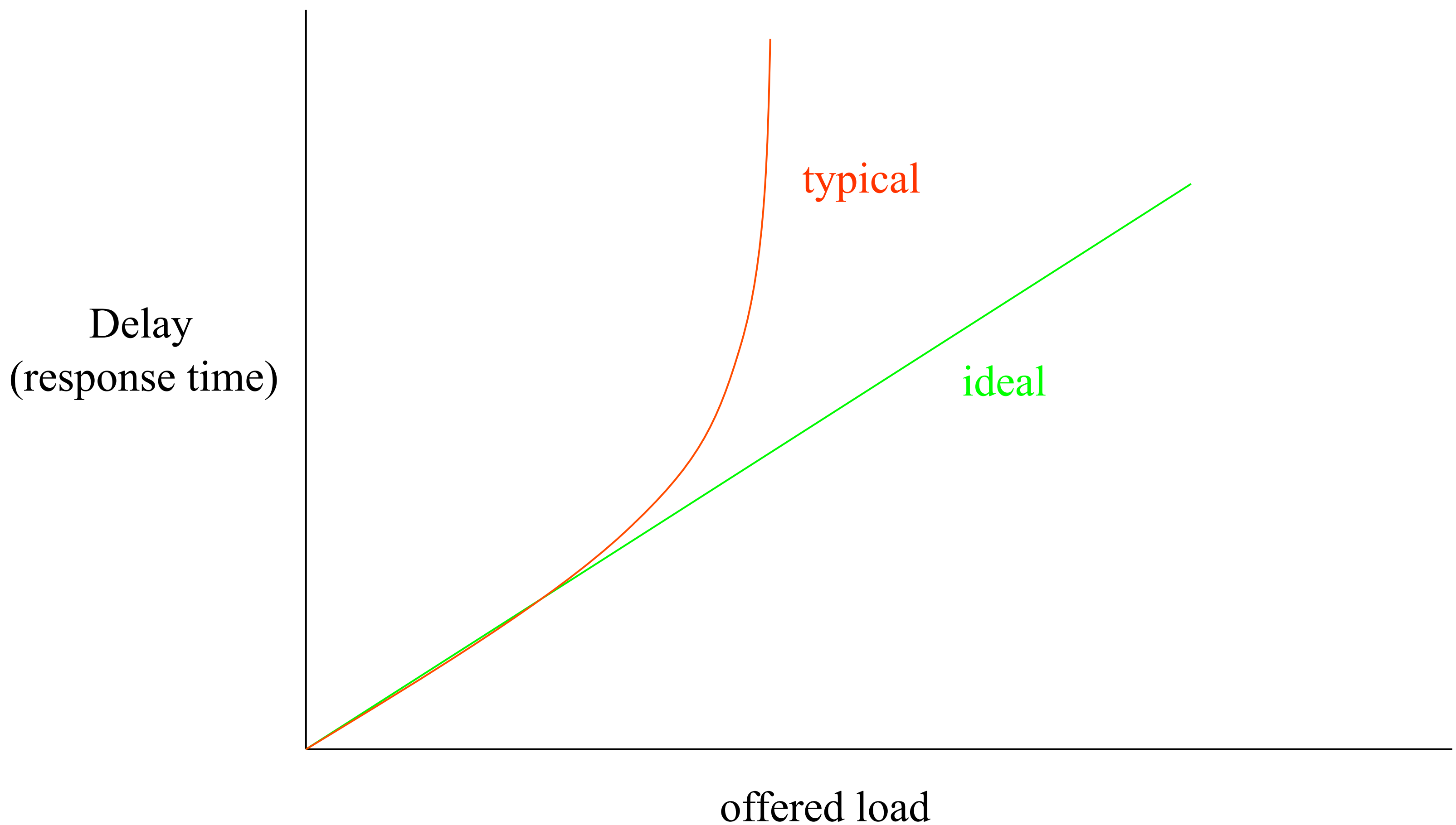
Typical Throughput vs. Load Curve



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 those limits are 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 careful, overheads during heavy load explode
- Effects like receive livelock can also hurt

Graceful Degradation

- When is a system "overloaded"?
  - When it is no longer able to meet 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

- Consider in the context of CPU 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

When Should a Process Yield?

- When it knows it's not going to make progress
  - E.g., while waiting for I/O
  - Better to let someone else make progress than sit in a pointless wait loop
- After it has had its "fair share" of time
  - Which is hard to define
  - Since it may depend on the state of everything else in the system
- Can't expect application programmers to do sophisticated things to decide

Scheduling Other Resources Non-Preemptively

- Schedulers aren't just for the CPU or cores
- They also schedule use of other system resources
  - Disks
  - Networks
  - At low level, busses
- Is non-preemptive best for each such resource?
- Which algorithms we will discuss make sense for each?

Non-Preemptive Scheduling Algorithms

- First come first served
- Shortest job next
- 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. In batch systems, where response time is not important
  2. In embedded (e.g. telephone or set-top box) systems where computations are brief and/or exist in natural producer/consumer relationships

Shortest Job First

- Find the shortest task on ready queue
  - Run it until it completes or yields
- Find the next shortest task on ready queue
  - Run it until it completes or yields
- Yields minimum average queuing delay
  - This can be very good for interactive response time
  - But it penalizes longer jobs

Shortest Job First Example

Dispatch Order			4,1,3,0,2		
Process	Duration		Start Time		End Time
4	75		0		75
1	125		75		200
3	250		200		450
0	350		450		800
2	475		800		1275
Total	1275				
Average wait			305		

Note: Even though total time remained unchanged, reordering the processes significantly reduced the average wait time.

Is Shortest Job First Practical?

- How can we know how long a job is going to run?
  - Processes predict for themselves?
  - The system predicts for them?
- How fair is SJF scheduling?
  - The smaller jobs will always be run first
  - New small jobs cut in line, ahead of older longer jobs
  - Will the long jobs ever run?
    - Only if short jobs stop arriving ... which could be never
- This is called *starvation*
  - It is caused by discriminatory scheduling

What If the Prediction is Wrong?

- Regardless of who made it
- In non-preemptive system, we have little choice:
  - Continue running the process until it yields
- If prediction is wrong, the purpose of Shortest-Job-First scheduling is defeated
  - Response time suffers as a result
- Few computer systems attempt to use Shortest-Job-First scheduling
  - But grocery stores and banks do use it
    - 10-item-or-less registers
    - Simple deposit & check cashing windows

Is Starvation Really That Bad?

- If optimizing for response time, it may make sense to preferentially schedule shorter jobs
  - The long jobs are “inappropriate” for this type of system
  - And inconvenience many other jobs
- If a job is inappropriate for our system, perhaps we should refuse to run it
  - But making it wait for an indefinitely long period of time doesn’t sound like reasonable behavior
  - Especially without feedback to job’s submitter

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, 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 follows 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 timings
  - 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

How Does a Hard Real Time System Schedule?

- There is usually a very carefully pre-defined schedule
- No actual decisions made at run time
- It's all been worked out ahead of time
- Not necessarily using any particular algorithm
- The designers may have just tinkered around to make everything "fit"

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 might
- 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
- Perhaps prune the queue to remove jobs whose deadlines were missed
- Minimizes total lateness

Example of a Soft Real Time Scheduler

- A video playing device
- Frames arrive
  - From disk or network or wherever
- Ideally, each frame should be rendered "on time"
  - To achieve highest user-perceived quality
- If you can't render a frame on time, might be better to skip it entirely
  - Rather than fall further behind

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 higher priority process becomes ready
    - Perhaps as a result of an I/O completion interrupt
  - If running process's priority 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 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 and 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 $1/n^{th}$ 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
- 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*)

Dispatch Order: 0, 1, 2, 3, 4, 0, 1, 2, . . .											
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						525	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 Example to Non-Preemptive Examples

- Context switches: 27 vs. 5 (for both FIFO and SJF)
  - Clearly more expensive
- First job completed: 475 msec vs.
  - 75 (shortest job first)
  - 350 (FIFO)
  - Clearly takes longer to complete some process
- Average waiting time: 100 msec vs.
  - 350 (shortest job first)
  - 595 (FIFO)
  - For first opportunity to compute
  - Clearly more responsive

Choosing a Time Slice

- Performance of a preemptive scheduler depends heavily on how long 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

Characterizing Costs of a Time Slice Choice

- What % of CPU use does a process get?
- Depends on workload
  - More processes in queue = fewer slices/second
- CPU share = time_slice * slices/second
  - 2% = 20ms/sec = 2ms/slice * 10 slices/sec
  - 2% = 20ms/sec = 5ms/slice * 4 slices/sec
- Natural rescheduling interval
  - When a typical process blocks for resources or I/O
  - Ideally, fair-share would be based on this period
  - Only time-slice-end if process runs too long

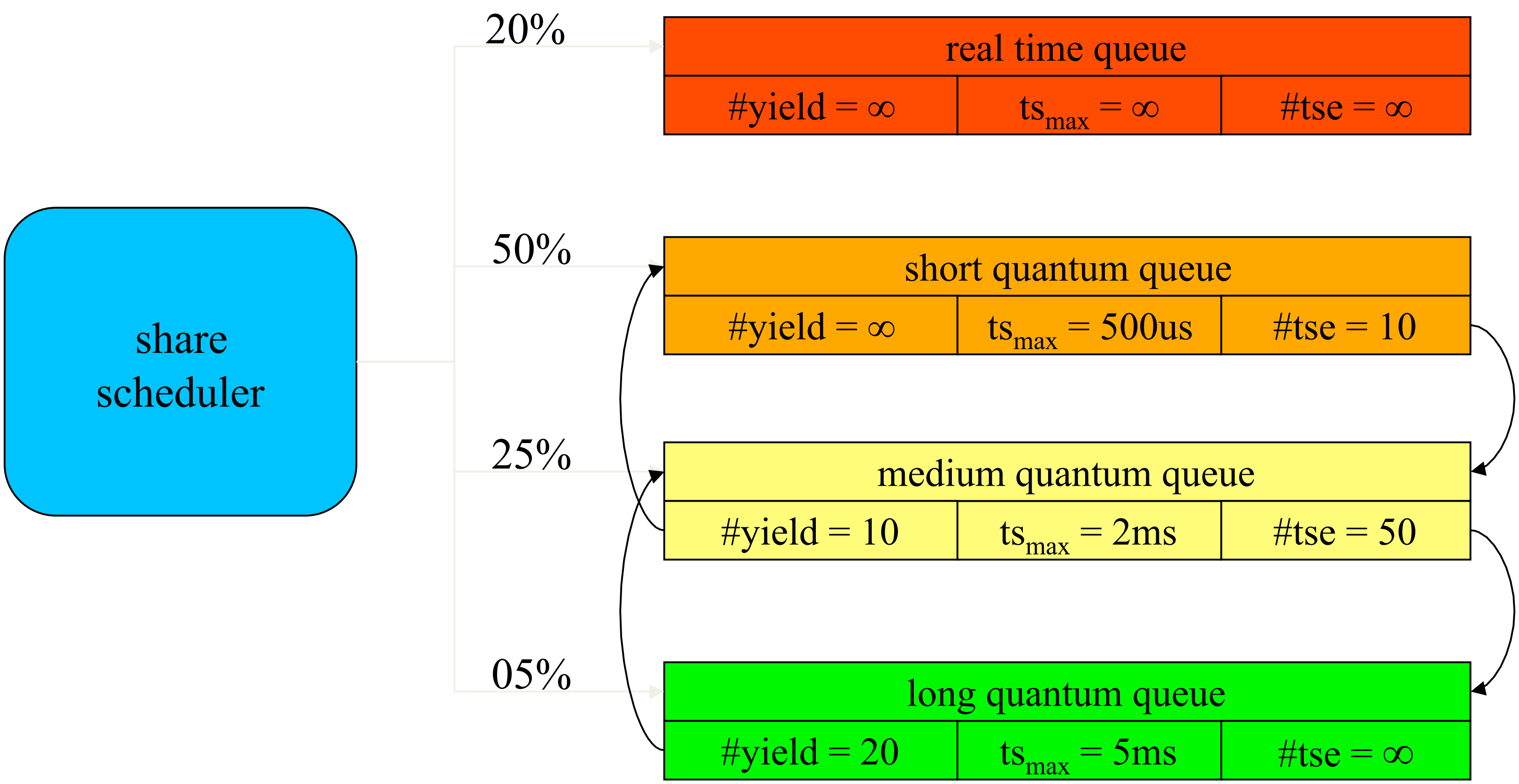
Multi-queue Scheduling

- One time slice length may not fit all processes
- Create multiple ready queues
  - Short quantum (foreground) tasks that finish quickly
    - Short but frequent time slices, optimize response time
  - Long quantum (background) tasks that run longer
    - Longer but infrequent time slices, minimize overhead
  - Different queues may get different shares of the CPU

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

- Start all processes in short quantum queue
  - Move downwards if too many time-slice ends
  - Move back upwards if too few time slice ends
  - Processes dynamically find the right queue
- If you also have real time tasks, you know what belongs there
  - Start them in real time queue and don't move them

Multiple Queue Scheduling



Priority Scheduling Algorithm

- 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

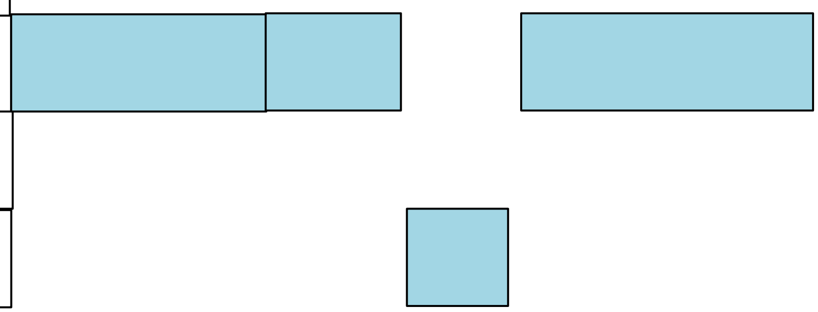
Priority and Preemption

- 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

Priority Scheduling in Linux

- 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