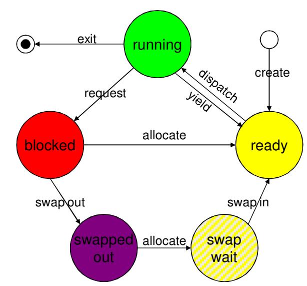
Processes, Execution, and State

3F. Execution State Model
4A. Introduction to Scheduling
4B. Non-Preemptive Scheduling
4C. Preemptive Scheduling
4D. Adaptive Scheduling
4E. Scheduling and Performance
4F. Real-Time Scheduling
9F. Performance under Load

execution states with swapping



un-dispatching a running process

- somehow we enter the operating system
  - e.g. via a yield system call or a clock interrupt
- state of the process has already been preserved
  - user mode PC, PS and registers are already saved on stack
  - supervisor mode registers are also saved on (the supervisor mode) stack
  - descriptions of address space. and pointers to code, data and stack segments, and all other resources are already stored in the process descriptor
- yield CPU – call scheduler to select next process

(re-)dispatching a process

- decision to switch is made in supv mode
  - after state of current process has been saved
  - the scheduler has been called to yield the CPU
- select the next process to be run
  - get pointer to its process descriptor(s)
- locate and restore its saved state
  - restore code, data, stack segments
  - restore saved registers, PS, and finally the PC
- and we are now executing in a new process

Blocking and Unblocking Processes

- Process needs an unavailable resource
  - data that has not yet been read in from disk
  - a message that has not yet been sent
  - a lock that has not yet been released
- Must be blocked until resource is available
  - change process state to blocked
- Un-block when resource becomes available
  - change process state to ready

Blocking and unblocking processes

- blocked/unblocked are merely notes to scheduler
  - blocked processes are not eligible to be dispatched
- anyone can set them, anyone can change them
- this usually happens in a resource manager
  - when process needs an unavailable resource
    - change process's scheduling state to "blocked"
    - call the scheduler and yield the CPU
  - when the required resource becomes available
    - change process's scheduling state to "ready"
    - notify scheduler that a change has occurred

Primary and Secondary Storage

- primary = main (executable) memory
  - primary storage is expensive and very limited
  - only processes in primary storage can be run
- secondary = non-executable (e.g. Disk)
  - blocked processes can be moved to secondary storage
  - swap out code, data, stack and non-resident context
  - make room in primary for other "ready" processes
- returning to primary memory
  - process is copied back when it becomes unblocked

Why we swap

- Make the best use of limited memory
  - a process can only execute if it is in memory
  - max # of processes limited by memory size
  - if it isn't READY, it doesn't need to be in memory
- Improve CPU utilization
  - when there are no READY processes, CPU is idle
  - idle CPU time is wasted, reduced throughput
  - we need READY processes in memory
- Swapping takes time and consumes I/O
  - so we want to do it as little as possible

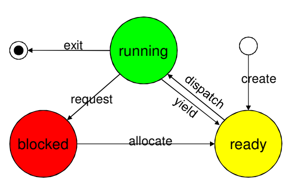
Swapping Out

- Process' state is in main memory
  - code and data segments
  - non-resident process descriptor
- Copy them out to secondary storage
  - if we are lucky, some may still be there
- Update resident process descriptor
  - process is no longer in memory
  - pointer to location on 2ndary storage device
- Freed memory available for other processes

Swapping Back In

- Re-Allocate memory to contain process
  - code and data segments, non-resident process descriptor
- Read that data back from secondary storage
- Change process state back to Ready
- What about the state of the computations
  - saved registers are on the stack
  - user-mode stack is in the saved data segments
  - supervisor-mode stack is in non-resident descriptor
- This involves a lot of time and I/O

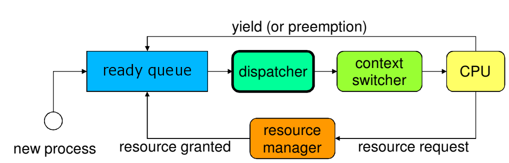
Three State Scheduling Model



- a process may block to await
  - completion of a requested I/O operation
  - availability of an requested resource
  - some external event
- or a process can simply yield

What is CPU Scheduling?

- Choosing which *ready* process to run next
- Goals:
  - keeping the CPU productively occupied
  - meeting the user's performance expectations



Goals and Metrics

- goals should be quantitative and measurable
  - if something is important, it must be 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
    - it must be a characteristic we can measure or compute
  - find a unit to quantify that characteristic
  - define a process for measuring the characteristic

CPU Scheduling: Proposed Metrics

- candidate metric: time to completion (seconds)
  - different processes require different run times
- candidate metric: throughput (procs/second)
  - same problem, not different processes
- candidate metric: response time (milliseconds)
  - some delays are not the scheduler's fault
    - time to complete a service request, wait for a resource
- candidate metric: fairness (standard deviation)
  - per user, per process, are all equally important

Rectified 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

Different Kinds of Systems have Different Scheduling Goals

- Time sharing
  - Fast response time to interactive programs
  - Each user gets an equal share of the CPU
  - Execution favors higher priority processes
- 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

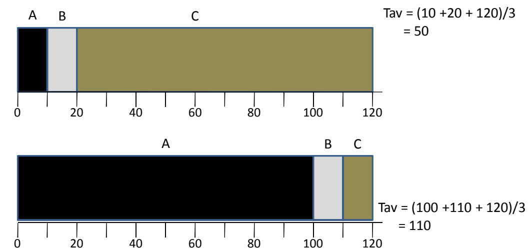
Non-Preepmtive Scheduling

- scheduled process runs until it yields CPU
  - may yield specifically to another process
  - may merely yield to "next" process
- works well for simple systems
  - small numbers of processes
  - with natural producer consumer relationships
- depends on each process to voluntarily yield
  - a piggy process can starve others
  - a buggy process can lock up the entire system

Non-Preemptive: First-In-First-Out

- Algorithm:
  - run first process in queue until it blocks or yields
- Advantages:
  - very simple to implement
  - seems intuitively fair
  - all process will eventually be served
- Problems:
  - highly variable response time (delays)
  - a long task can force many others to wait (convoy)

Example: First In First Out



Non-Preemptive: Shortest Job First

- Algorithm:
  - all processes declare their expected run time
  - run the shortest until it blocks or yields
- Advantages:
  - likely to yield the fastest response time
- Problems:
  - some processes may face unbounded wait times
    - Is this fair? Is this even “correct” scheduling?
  - ability to correctly estimate required run time

Starvation

- <u>unbounded</u> waiting times
  - not merely a CPU scheduling issue
  - it can happen with any controlled resource
- caused by case-by-case discrimination
  - where it is possible to lose every time
- ways to prevent
  - strict (FIFO) queuing of requests
    - credit for time spent waiting is equivalent
    - ensure that individual queues cannot be starved
  - input metering to limit queue lengths

Non-Preemptive: Priority

- Algorithm:
  - all processes are given a priority
  - run the highest priority until it blocks or yields
- Advantages:
  - users control assignment of priorities
  - can optimize per-customer “goodness” function
- Problems:
  - still subject to (less arbitrary) starvation
  - per-process may not be fine enough control

Preemptive Scheduling

- 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
- Advantages
  - enables enforced "fair share" scheduling
- Problems
  - introduces gratuitous context switches
  - creates potential resource sharing problems

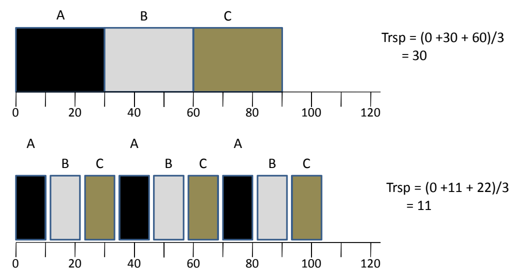
Forcing Processes to Yield

- need to take CPU away from process
  - e.g. process makes a system call, or clock interrupt
- consult scheduler before returning to process
  - if any ready process has had priority raised
  - if any process has been awakened
  - if current process has had priority lowered
- scheduler finds highest priority ready process
  - if current process, return as usual
  - if not, yield on behalf of the current process

Preemptive: Round-Robin

- Algorithm
  - processes are run in (circular) queue order
  - each process is given a nominal time-slice
  - timer interrupts process if time-slice expires
- Advantages
  - greatly reduced time from *ready* to *running*
  - intuitively fair
- Problems
  - some processes will need many time-slices
  - extra interrupts/context-switches add overhead

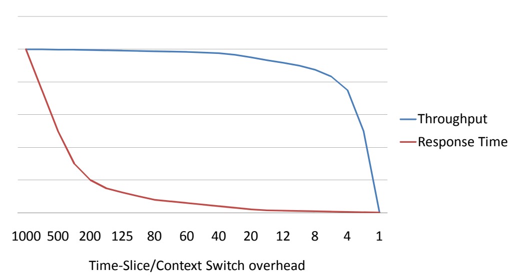
Example: Round-Robbin



Costs of an extra 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 process descriptor, kernel stack
- switching process address spaces
  - map-out old process, map-in new process
- losing hard-earned L1 and L2 cache contents

Response Time/Throughput Trade-off



So which approach is best?

- preemptive has better response time
  - but what should we choose for our time-slice?
- non-preemptive has lower overhead
  - but how should we order our the processes?
- there is no one "best" algorithm
  - performance depends on the specific job mix
  - goodness is measured relative to specific goals
- a good scheduler must be <u>adaptive</u>
  - responding automatically to changing loads
  - configurable to meet different requirements

The "Natural" Time-Slice

- CPU share = time_slice x slices/second

  2% = 20ms/sec   2ms/slice x 10 slices/sec

  2% = 20ms/sec   5ms/slice x 4 slices/sec
- context switches are far from free
  - they waste otherwise useful cycles
  - they introduce delay into useful computations
- natural rescheduling interval
  - when a process blocks for resources or I/O
  - optimal time-slice would be based on this period

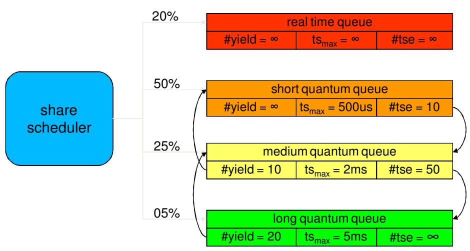
Dynamic Multi-Queue Scheduling

- natural time-slice is different for each process
  - create multiple ready queues
  - some with short time-slices that run more often
  - some with long time-slices that run infrequently
  - different queues may get different CPU shares
- Advantages:
  - response time very similar to Round-Robin
  - relatively few gratuitous preemptions
- Problem:
  - how do we know where a process belongs

Dynamic Equilibrium

- Natural equilibria are seldom calibrated
- Usually the net result of
  - competing processes
  - negative feedback
- Once set in place these processes
  - are self calibrating
  - automatically adapt to changing circumstances
- The tuning is in rate and feedback constants
  - avoid over-correction, ensure convergence

Dynamic Multi-Queue Scheduling



Mechanism/Policy Separation

- simple built-in scheduler mechanisms
  - always run the highest priority process
  - formulae to compute priority and time slice length
- controlled by user specifiable policy
  - per process (inheritable) parameters
    - initial, relative, minimum, maximum priorities
    - queue in which process should be started (or resumed)
    - these can be set based on user ID, or program being run
  - per queue parameters
    - maximum time slice length and number of time slices
    - priority change per unit of run time and wait time
    - CPU share (absolute or relative to other queues)

Real Time Schedulers

- Some things <u>must</u> happen at <u>particular times</u>
  - if you can't process the next sound sample in time, there will be a gap in the music
  - if you don't rivet the widget before the conveyer belt moves, you have a manufacturing error
  - if you can't adjust the spoilers quickly enough, the space shuttle goes out of control
- Real Time scheduling has deadlines
  - they can be either *soft* or *hard*

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 careful design-time analysis
  - prove no possible schedule misses a deadline
  - scheduling order may be hard-coded

Ensuring Hard Deadlines

- Requires deep understanding of all code
  - we know exactly how long it will take in every case
- Avoid complex operations w/non-deterministic times
  - e.g. interrupts, garbage collection
- Predictability is more important than speed
  - non-preemptive, fixed execution order
  - no run time decisions

Soft Real Time Schedulers

- Highly desirable to meet your deadlines
  - some (or any) can occasionally be missed
- Goal of scheduler is to avoid missing deadlines
  - with the understanding that you might
  - sometimes called “best effort”
- May have different classes of deadlines
  - some “harder” than others
- May have more dynamic/variable traffic
  - rendering up-front analysis impractical

Soft Real Time and Preemption

- All tasks need not always run to completion
  - we are allowed to miss some deadlines
- A high priority near-deadline task may arrive
  - it should preempt a lower priority task
- What if we miss (or cannot make) a deadline?
  - we fall behind, run it as soon as possible?
  - skip this invocation, we will catch it next time?
  - kill the task that missed its deadline?

  This is a policy question, let the programmer decide

Soft Real-Time Algorithms?

- Most common is Earliest Deadline First
  - each job has a deadline associated with it
  - keep the job queue sorted by those deadlines
  - always run the first job on the queue
- Minimizes *total lateness*
- Possible refinements
  - skip jobs that are already late
  - drop low priority jobs when system is overloaded

Example of a Soft Real Time Scheduler

- A video playing device
- Frames arrive (e.g. from disk or network)
- Each frame should be rendered “on time”
  - to achieve highest user-perceived quality
- If a frame is late, skip it
  - rather than fall further behind

CPU Scheduling is not Enough

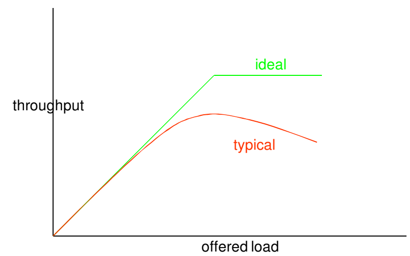
- CPU scheduler chooses a *ready* process
- memory scheduling
  - a process on secondary storage is not *ready*
- resource allocation
  - a process waiting for a resource is not *ready*
- I/O scheduling
  - a process waiting for I/O is not *ready*
- cache management
  - if process data is not cached, it will need more I/O

Charles Dickens on System Performance

"Annual income, twenty pounds;
annual expenditure, nineteen, nineteen, six;
Result … happiness.
Annual income, twenty pounds;
annual expenditure, twenty pounds ought & six;
Result … misery!"

Wilkins Micawber, David Copperfield

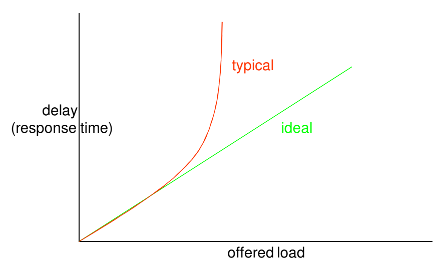
Performance: Throughput vs Load



(why throughput falls off)

- dispatching processes 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)
    - allow longer time slices per task
    - increase the number of servers (e.g. CPUs)
- this phenomenon will be seen in many areas

Performance: response time vs load



(why response time grows w/o limit)

- response time is function of server & load
  - how long it takes to complete one request
  - how long the waiting line is
- length of the line is function of server & load
  - how long it takes to complete one request
  - the average inter-request arrival interval
- if requests arrive faster than they are serviced
  - the length of the waiting list grows
  - and the response time grows with it

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 acceptable performance by rejecting work
  - resume normal service when load drops to normal
- what can we not do when overloaded?
  - allow throughput to drop to zero (stop doing work)
  - allow response time to grow without limit

Assignments

- Projects
  - try to get P1A working before lab session
  - move on to (more difficult) P1B ASAP
- Reading
  - Arpaci C12-14, 17 memory & allocation algorithms
  - Garbage Collection

Supplementary Slides

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

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 use virtualization techniques to 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 jobs to run something else, it's preemptive

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 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

Fairness as a Scheduling Metric

- Maybe we want to make sure all processes are treated fairly
- In what dimension?
  - Fairness in delay? Which one?
  - Fairness in time spent processing?
- Many metrics can be used in Jain's fairness equation:

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

CPU Scheduling is not Enough

- CPU scheduler chooses a *ready* process
- memory scheduling
  - a process on secondary storage is not *ready*
- resource allocation
  - a process waiting for a resource is not *ready*
- I/O scheduling
  - a process waiting for I/O is not *ready*
- cache management
  - if process data is not cached, it will need more I/O

Greek to English dictionary

- many of these are often used in queuing theory
  - λ lambda request arrival rate (e.g. 200/second)
  - μ mu request service rate (e.g. 400/second)
  - τ tau time to complete operation (e.g. 5ms)
  - $\tau(p_i)$ time process i will need to complete
  - ρ rho load factor (λ/μ, e.g. 50% of capacity)
- when ($\lambda > \mu$) or ($\rho > 1$)
  - requests arriving faster than they can be serviced
  - the system is <u>over-loaded</u>

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

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

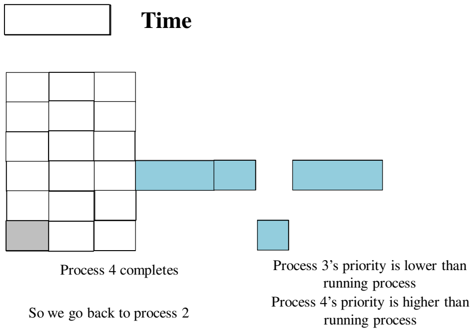
Priority Scheduling Algorithm

- 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



Problems With Priority Scheduling

- Possible starvation
- Can a low priority process <u>ever</u> 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

- 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

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 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

Graceful Degradataion

- System overloads will happen
  - random fluctuations in traffic
  - load bursts from unanticipated events
  - additional work associated with errors
- What to do when the system is overloaded?
  - offer slower service to all clients?
  - allow deadlines to get later and later?
  - offer on-time service to fewer clients?
- We must choose (or allow clients to do so)

Discussion Slides