Operating Systems

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Scheduling

Myungjin Lee
myungjin.lee@ed.ac.uk

Scheduling

- In discussing processes and threads, we talked about context switching
  - an interrupt occurs (device completion, timer interrupt)
  - a thread causes a trap or exception
  - may need to choose a different thread/process to run
- We glossed over the choice of which process or thread is chosen to be run next
  - “some thread from the ready queue”
- This decision is called scheduling
  - scheduling is a policy
  - context switching is a mechanism

Classes of Schedulers

- Batch
  - Throughput / utilization oriented
  - Example: audit inter-bank funds transfers each night, Pixar rendering, Hadoop/MapReduce jobs
- Interactive
  - Response time oriented
- Real time
  - Deadline driven
  - Example: embedded systems (cars, airplanes, etc.)
- Parallel
  - Speedup-driven
  - Example: “space-shared” use of a 1000-processor machine for large simulations

We’ll be talking primarily about interactive schedulers

Multiple levels of scheduling decisions

- Long term
  - Should a new "job" be "initiated," or should it be held?
    - typical of batch systems
    - what might cause you to make a "hold" decision?
- Medium term
  - Should a running program be temporarily marked as non-runnable (e.g., swapped out)?
- Short term
  - Which thread should be given the CPU next? For how long?
  - Which I/O operation should be sent to the disk next?
  - On a multiprocessor:
    - should we attempt to coordinate the running of threads from the same address space in some way?
    - should we worry about cache state (processor affinity)?

Scheduling Goals I: Performance

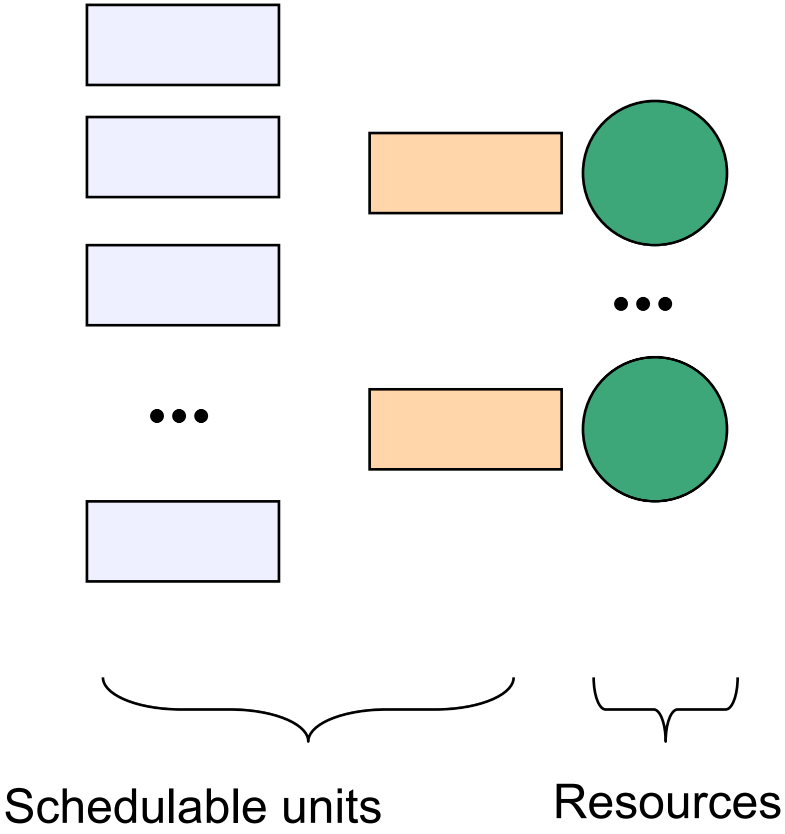
- Many possible metrics / performance goals (which sometimes conflict)
  - maximize CPU utilization
  - maximize throughput (`requests completed / s`)
  - minimize average response time (`average time from submission of request to completion of response`)
  - minimize average waiting time (`average time from submission of request to start of execution`)
  - minimize energy (`joules per instruction`) subject to some constraint (`e.g., frames/second`)

Scheduling Goals II: Fairness

- No single, compelling definition of “fair”
  - How to measure fairness?
    - Equal CPU consumption? (over what time scale?)
  - Fair per-user? per-process? per-thread?
  - What if one process is CPU bound and one is I/O bound?

- Sometimes the goal is to be unfair:
  - Explicitly favor some particular class of requests (priority system), but…
  - avoid starvation (be sure everyone gets at least some service)

The basic situation



Scheduling:

- Who to assign each resource to
- When to re-evaluate your decisions

When to assign?

- Pre-emptive vs. non-preemptive schedulers
  - Non-preemptive
    - once you give somebody the green light, they've got it until they relinquish it
      - an I/O operation
      - allocation of memory in a system without swapping
  - Preemptive
    - you can re-visit a decision
      - setting the timer allows you to preempt the CPU from a thread even if it doesn't relinquish it voluntarily
      - in any modern system, if you mark a program as non-runnable, its memory resources will eventually be re-allocated to others
    - Re-assignment always involves some overhead
      - Overhead doesn't contribute to the goal of any scheduler

- We'll assume "work conserving" policies
  - Never leave a resource idle when someone wants it
    - Why even mention this? When might it be useful to do something else?

Before we look at specific policies

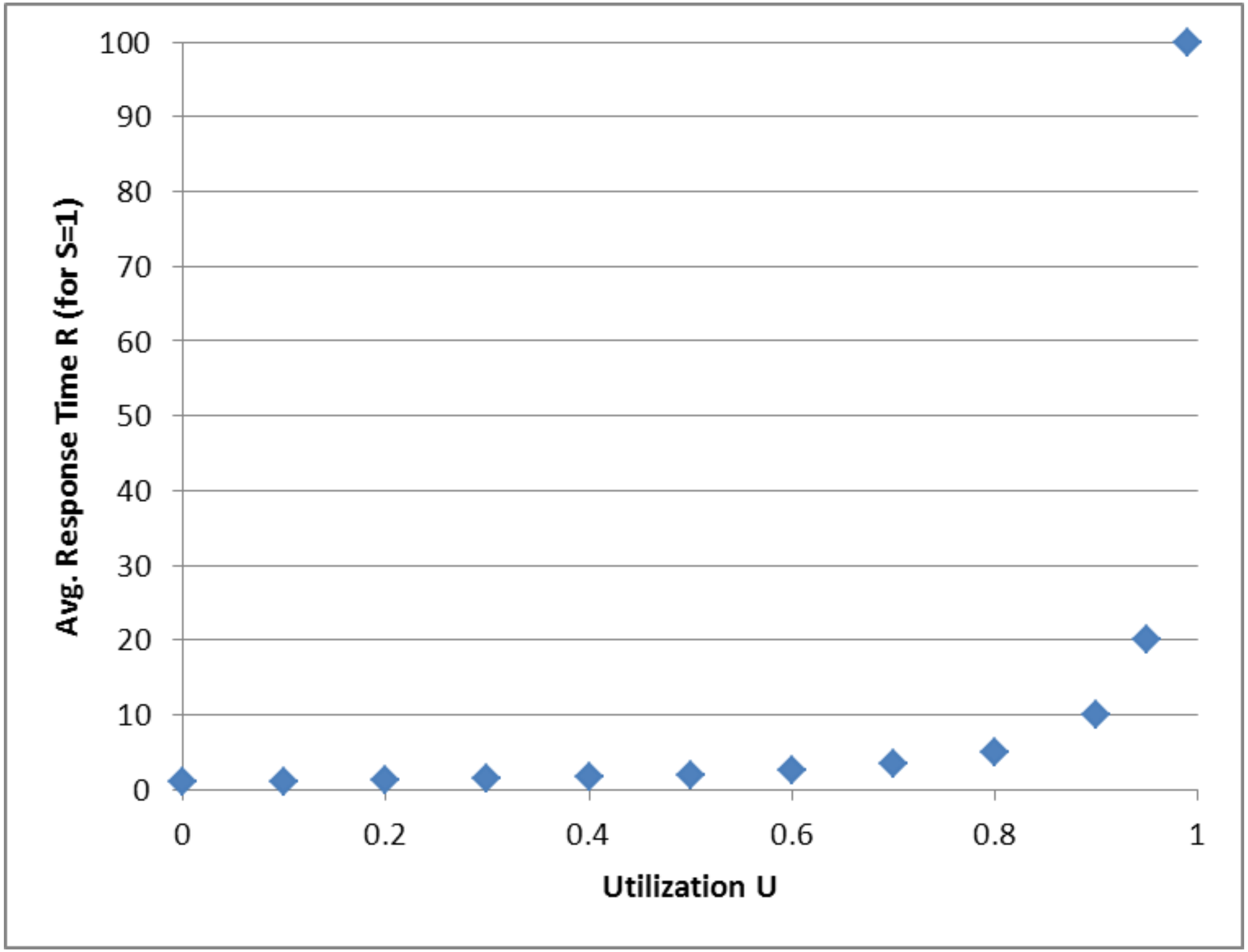
- There are some simple but useful “laws” to know about …

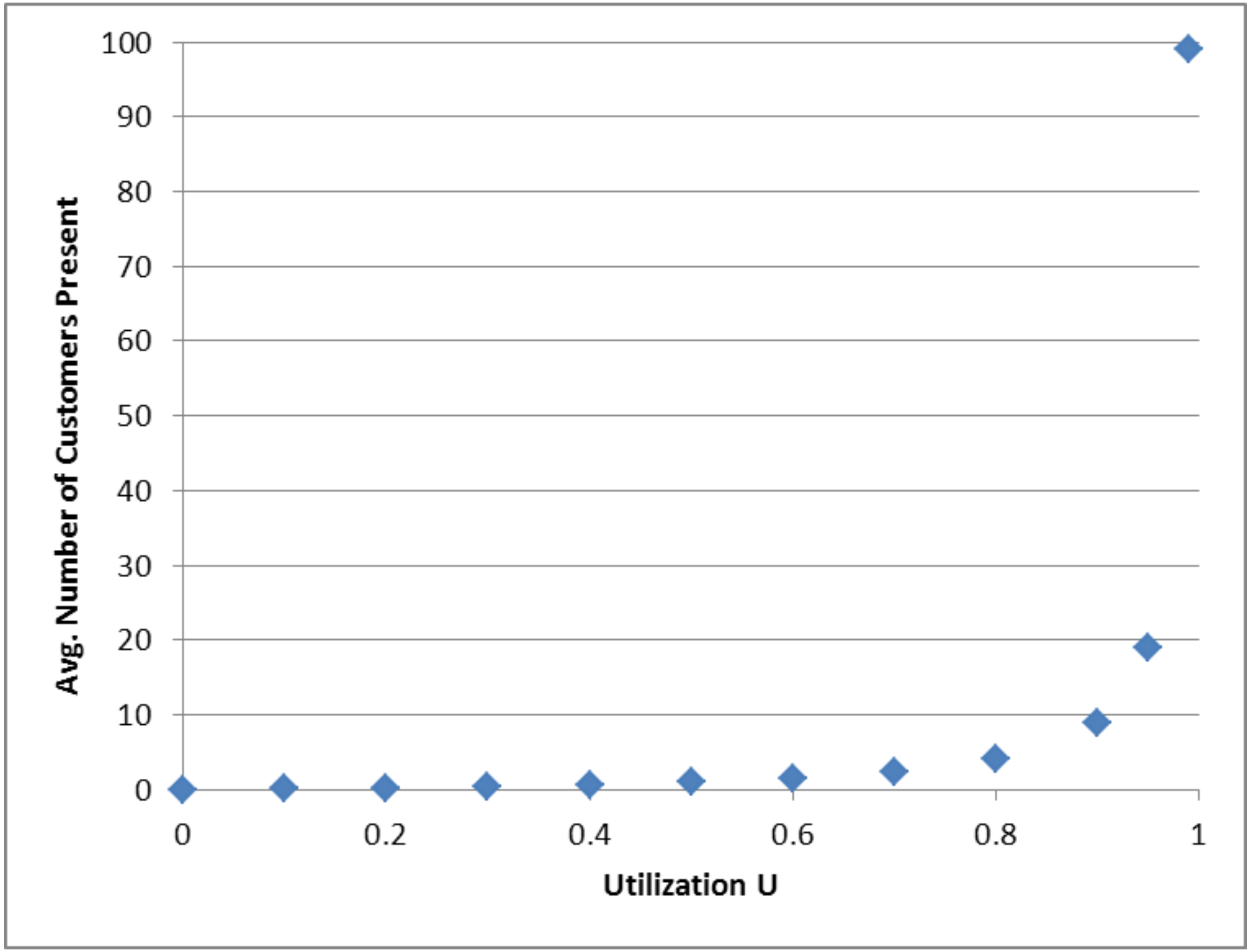
- The Utilization Law: U = X * S
  - Where U is utilization, X is throughput (requests per second), and S is average service time
    - Obviously true
    - This means that utilization is constant, independent of the schedule, so long as the workload can be processed

- Little's Law: N = X * R
  - Where N is average number in system, X is throughput, and R is average response time (average time in system)
    - This means that better average response time implies fewer in system, and vice versa
  - Proof:
    - Let W denote the total time-in-system accumulated by all customers during a time interval of length T
    - The average number of requests in the system N = W / T
    - If C customers complete during that time period, then the average contribution of each completing request R = W / C
    - Algebraically, W/T = C/T * W/C.
    - Thus, N = X * R

(Not quite a law – requires some assumptions)

- Response Time at a single server under FCFS scheduling: $R = S / (1-U)$
  - Clearly, when a customer arrives, her response time will be the service time of everyone ahead of her in line, plus her own service time: $R = S * (1+A)$
    - Assumes everyone has the same average service time
  - Assume that the number you see ahead of you at your instant of arrival is the long-term average number in line; so $R = S * (1+N)$
  - By Little's Law, $N = X * R$
  - So $R = S * (1 + X*R) = S + S*X*R = S / (1 – X*S)$
  - By the Utilization Law, $U = X*S$
  - So $R = S / (1-U)$
  - And since $N = X*R$, $N = U / (1-U)$


Avg. Response Time R (for S=1)
100
90
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
Utilization U



100
90
80
70
60
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
Avg. Number of Customers Present
Utilization U

- Kleinrock's Conservation Law for priority scheduling:

$$\sum_p U_p * R_p = \text{constant}$$

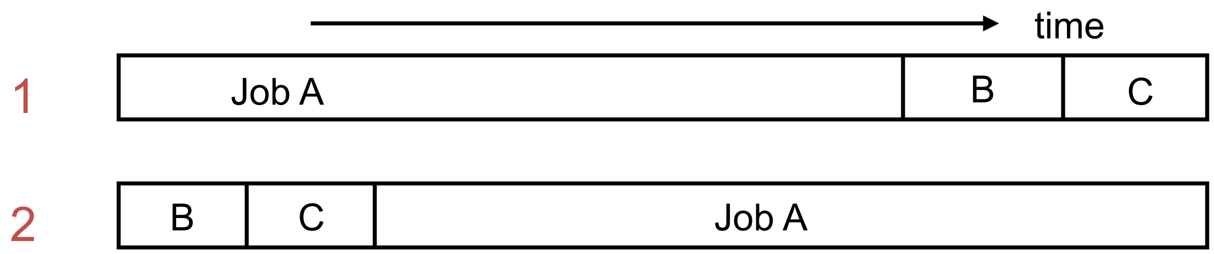
  - Where U_p is the utilization by priority level p and R_p is the time in system of priority level p
    - This means you can't improve the response time of one class of task by increasing its priority, without hurting the response time of at least one other class

Algorithm #1: FCFS/FIFO

- First-come first-served / First-in first-out (FCFS/FIFO)
  - schedule in the order that they arrive
  - “real-world” scheduling of people in (single) lines
    - supermarkets, McD’s, Starbucks …
  - jobs treated equally, no starvation
    - In what sense is this “fair”?

- Sounds perfect!
  - in the real world, when does FCFS/FIFO work well?
    - even then, what’s it’s limitation?
  - and when does it work badly?

FCFS/FIFO example



- Suppose the duration of A is 5, and the durations of B and C are each 1
  - average response time for schedule 1 (assuming A, B, and C all arrive at about time 0) is (5+6+7)/3 = 18/3 = 6
  - average response time for schedule 2 is (1+2+7)/3 = 10/3 = 3.3
  - consider also "elongation factor" – a "perceptual" measure:
    - Schedule 1: A is 5/5, B is 6/1, C is 7/1 (worst is 7, ave is 4.7)
    - Schedule 2: A is 7/5, B is 1/1, C is 2/1 (worst is 2, ave is 1.5)

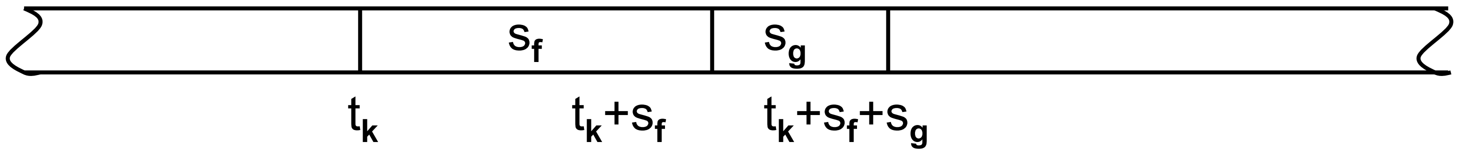
FCFS/FIFO drawbacks

- Average response time can be lousy
  - small requests wait behind big ones
- May lead to poor utilization of other resources
  - if you send me on my way, I can go keep another resource busy
  - FCFS may result in poor overlap of CPU and I/O activity
    - E.g., a CPU-intensive job prevents an I/O-intensive job from doing a small bit of computation, thus preventing it from going back and keeping the I/O subsystem busy
- Note: The more copies of the resource there are to be scheduled, the less dramatic the impact of occasional very large jobs (so long as there is a single waiting line)
  - E.g., many cores vs. one core

Algorithm #2: SPT/SJF

- Shortest processing time first / Shortest job first (SPT/SJF)
  - choose the request with the smallest service requirement
- *Provably optimal* with respect to average response time
  - Why do we care about “provably optimal”?

SPT/SJF optimality – The interchange argument



- In any schedule that is not SPT/SJF, there is some adjacent pair of requests f and g where the service time (duration) of f, s_f, exceeds that of g, s_g
- The total contribution to average response time of f and g is $2t_k+2s_f+s_g$
- If you interchange f and g, their total contribution will be $2t_k+2s_g+s_f$, which is smaller because $s_g < s_f$
- If the variability among request durations is zero, how does FCFS compare to SPT for average response time?

SPT/SJF drawbacks

- It’s non-preemptive
  - So?
- … but there’s a preemptive version – SRPT (Shortest Remaining Processing Time first) – that accommodates arrivals (rather than assuming all requests are initially available)

- Sounds perfect!
  - what about starvation?
  - can you know the processing time of a request?
  - can you guess/approximate? How?

Algorithm #3: RR

- Round Robin scheduling (RR)
  - Use preemption to offset lack of information about execution times
    - I don't know which one should run first, so let's run them all!
  - ready queue is treated as a circular FIFO queue
  - each request is given a time slice, called a quantum
    - request executes for duration of quantum, or until it blocks
      - what signifies the end of a quantum?
    - time-division multiplexing (time-slicing)
  - great for timesharing
    - no starvation

- Sounds perfect!
  - how is RR an improvement over FCFS?
  - how is RR an improvement over SPT?
  - how is RR an approximation to SPT?

RR drawbacks

- What if all jobs are exactly the same length?
  – What would the pessimal schedule be (with average response time as the measure)?
- What do you set the quantum to be?
  – no value is “correct”
    - if small, then context switch often, incurring high overhead
    - if large, then response time degrades
- Treats all jobs equally
    - if I run 100 copies of SETI@home, it degrades your service
    - how might I fix this?

Algorithm #4: Priority

- Assign priorities to requests
  - choose request with highest priority to run next
    - if tie, use another scheduling algorithm to break (e.g., RR)
  - Goal: non-fairness (favor one group over another)

- Abstractly modeled (and usually implemented) as multiple "priority queues"
  - put a ready request on the queue associated with its priority

- Sounds perfect!

Priority drawbacks

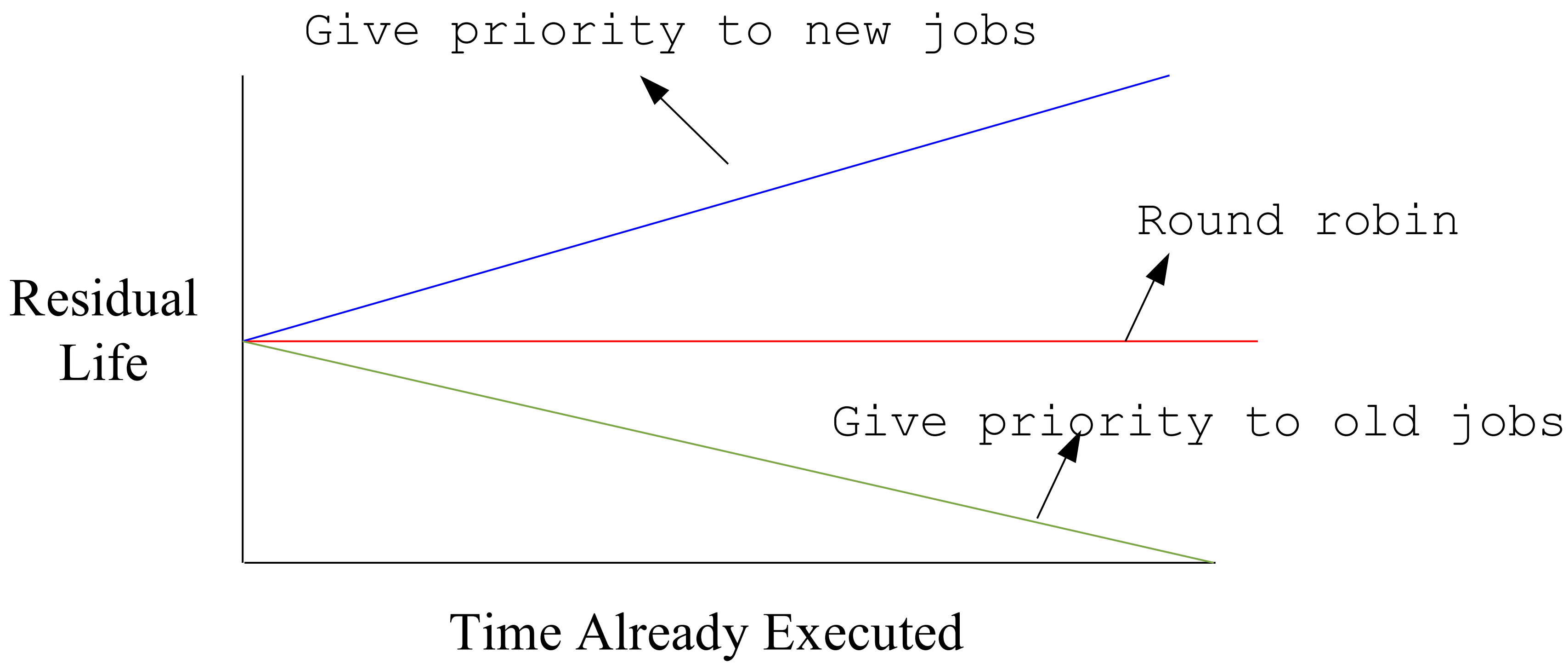
- How are you going to assign priorities?
- Starvation
  - if there is an endless supply of high priority jobs, no low-priority job will ever run
- Solution: “age” threads over time
  - increase priority as a function of accumulated wait time
  - decrease priority as a function of accumulated processing time
  - many ugly heuristics have been explored in this space

Program behavior and scheduling

- An analogy:
  - Say you're at the airport waiting for a flight
  - There are two identical ATMs:
    - ATM 1 has 3 people in line
    - ATM 2 has 6 people in line
  - You get into the line for ATM 1
  - ATM 2's line shrinks to 4 people
  - Why might you now switch lines, preferring 5th in line for ATM 2 over 4th in line for ATM 1?

Residual Life

- Given that a job has already executed for X seconds, how much longer will it execute, on average, before completing?



Multi-level Feedback Queues (MLFQ)

- It's been observed that workloads tend to have increasing residual life – "if you don't finish quickly, you're probably a lifer"
- This is exploited in practice by using a policy that discriminates against the old (with apologies to the EEOC)
- MLFQ:
  – there is a hierarchy of queues
  – there is a priority ordering among the queues
  – new requests enter the highest priority queue
  – each queue is scheduled RR
  – requests move between queues based on execution history

UNIX scheduling

- Canonical scheduler is pretty much MLFQ
  - 3-4 classes spanning ~170 priority levels
    - timesharing: lowest 60 priorities
    - system: middle 40 priorities
    - real-time: highest 60 priorities
  - priority scheduling across queues, RR within
    - process with highest priority always run first
    - processes with same priority scheduled RR
  - processes dynamically change priority
    - increases over time if process blocks before end of quantum
    - decreases if process uses entire quantum
- Goals:
  - reward interactive behavior over CPU hogs
    - interactive jobs typically have short bursts of CPU

Summary

- Scheduling takes place at many levels
- It can make a huge difference in performance
  - this difference increases with the variability in service requirements
- Multiple goals, sometimes conflicting
- There are many “pure” algorithms, most with some drawbacks in practice – FCFS, SPT, RR, Priority
- Real systems use hybrids that exploit observed program behavior
- Scheduling is still important, and there are still new angles to be explored – particularly in large-scale datacenters for reasons of cost and energy

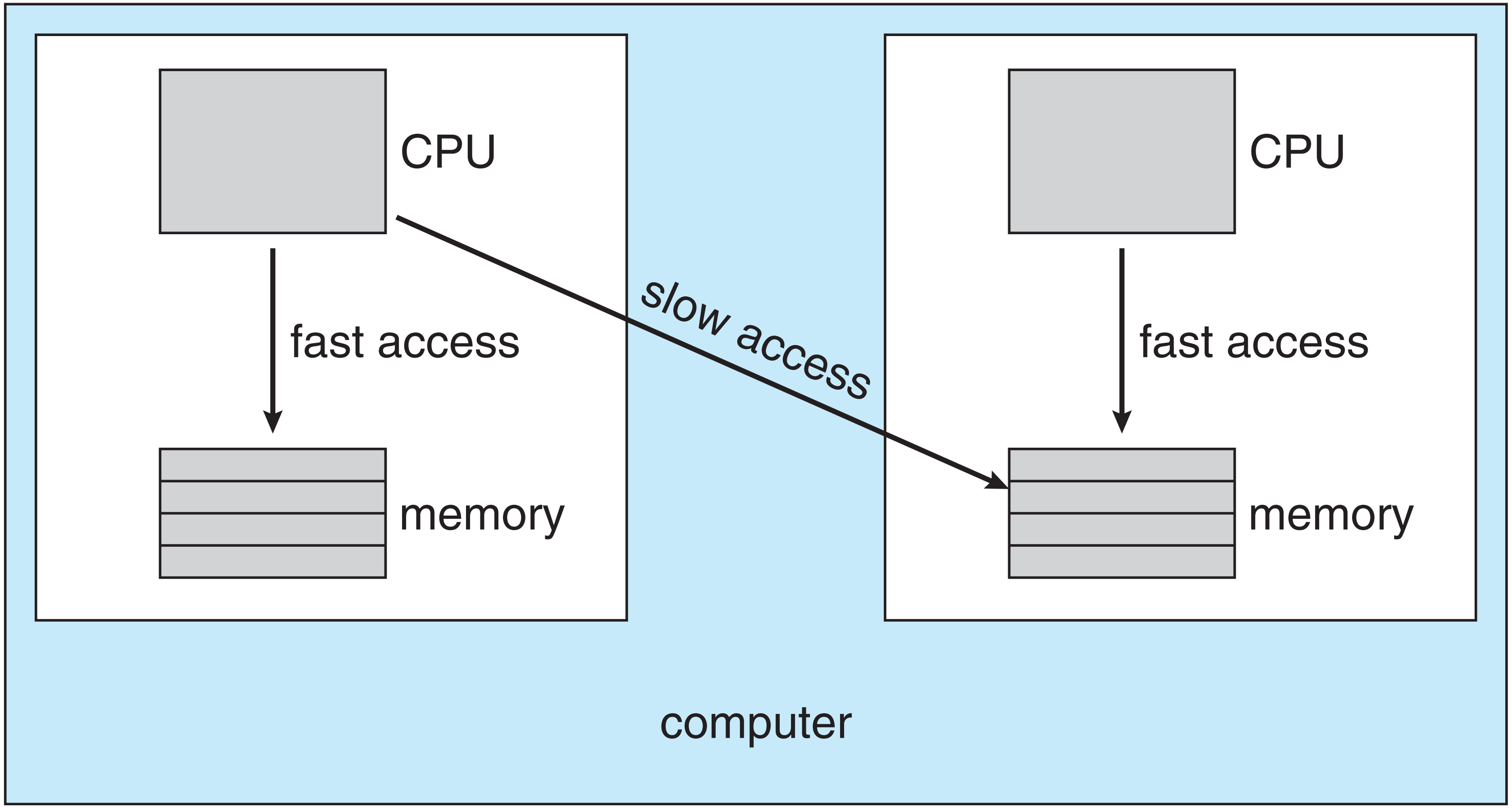
Multiprocessor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- Homogeneous processors within a multiprocessor
- Asymmetric multiprocessing – only one processor accesses the system data structures, alleviating the need for data sharing
- Symmetric multiprocessing (SMP) – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
  - Currently, most common
  - Windows, Linux, and MAC OS X support SMP

Multiprocessor Scheduling – Processor affinity

- Process has affinity for processor on which it is currently running
  - keep using the same processor to avoid having to repopulate cache
  - soft affinity: not guaranteed the same processor
  - hard affinity: process can specify a subset of processors
  - Variations including processor sets

NUMA and CPU Scheduling



NUMA: non-uniform memory access

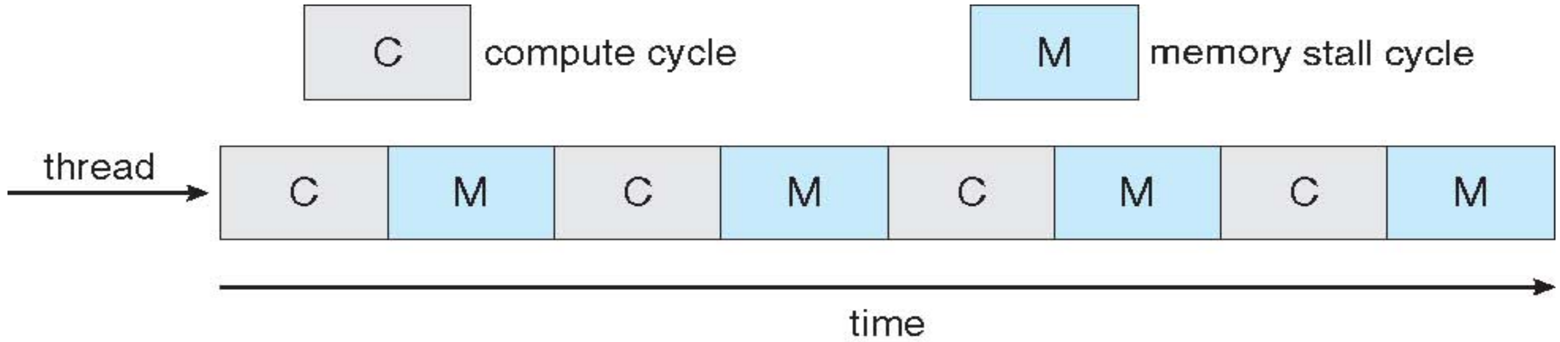
Multiprocessor Scheduling – Load Balancing

- If symmetric multiprocessing (SMP), need to keep all CPUs loaded for efficiency
- Load balancing attempts to keep workload evenly distributed
- Push migration – periodic task checks load on each processor, and if found pushes task from overloaded CPU to other CPUs
- Pull migration – idle processors pull waiting task from busy processor

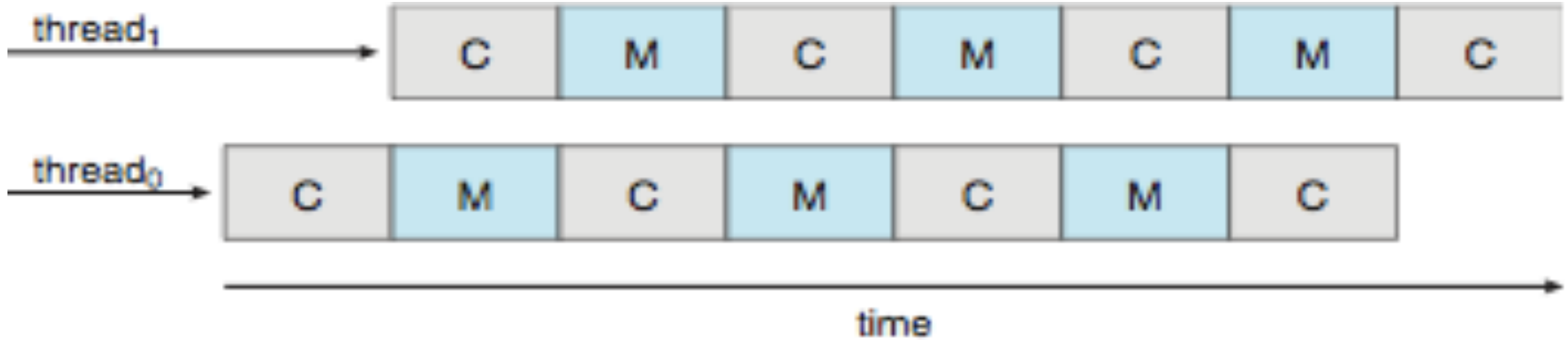
Multicore Processors

- Recent trend to place multiple processor cores on same physical chip
- Faster and consumes less power
- Multiple hardware threads per core also growing
  - Takes advantage of memory stall: progress can run another thread while memory retrieve happens

Multithreaded Multicore System



Single threaded processor core



Dual threaded processor core