15-410

"...Everything old is new again..."

Scheduling
Oct. 26, 2015

Dave Eckhardt

Roger Dannenberg

Outline

Chapter 5 (or Chapter 7): Scheduling

- **Scheduling-people/textbook terminology note**
  - **"Waiting time" means "time spent runnable but stuck in a scheduler queue"**
    - **Not "time waiting for the actual event to awaken you"!**
  - **"Task" means "something a scheduler schedules" (we say "thread" or sometimes "runnable")**

CPU-I/O Cycle

Process **view: 2 states**

- Running
- Blocked on I/O

Life Cycle:

- I/O (loading executable), CPU, I/O, CPU, .., CPU (`exit()`)

System **view**

- Running
- Blocked on I/O
- Runnable (i.e. Waiting) – not enough processors right now

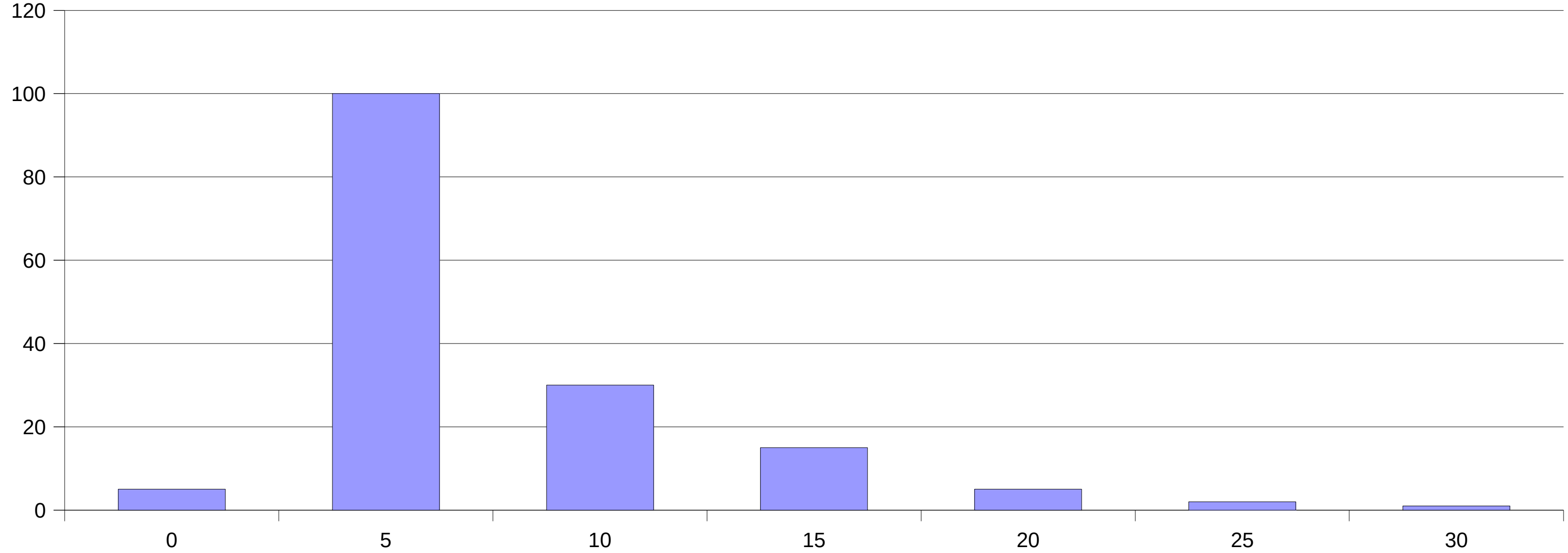
Running ⇒ blocked mostly depends on program

- How long do processes run before blocking?

CPU Burst Lengths

In general

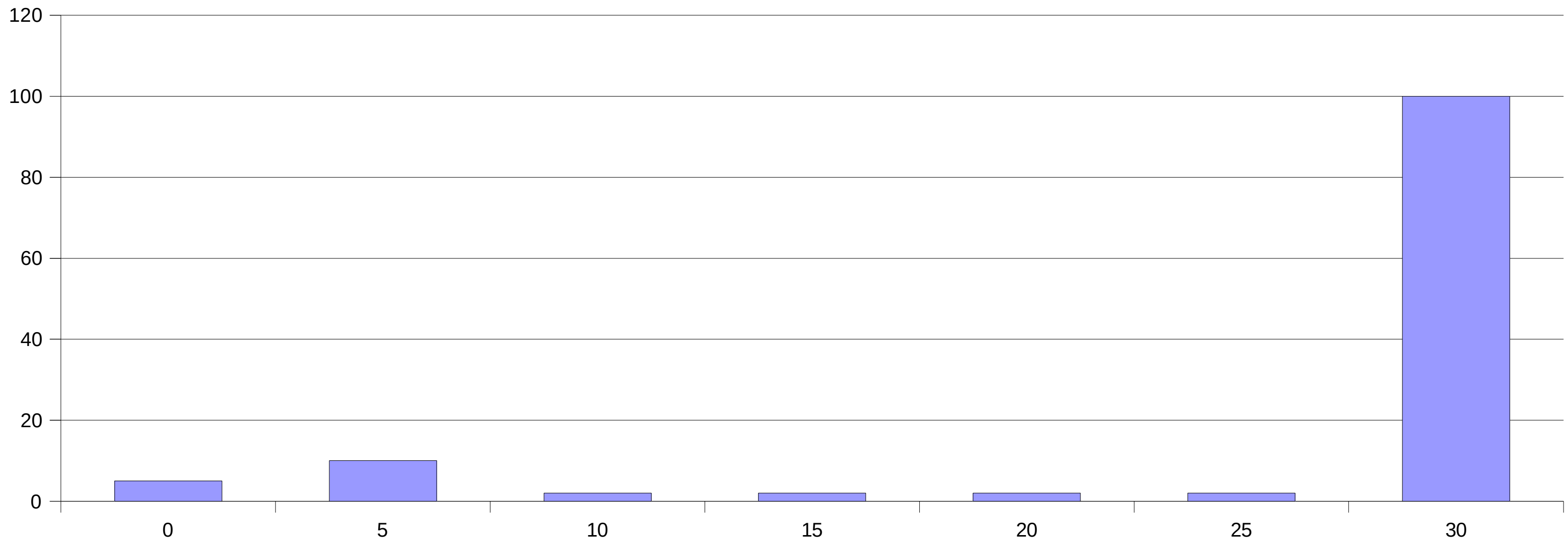
- Exponential fall-off in CPU burst length



CPU Burst Lengths

"CPU-bound" program

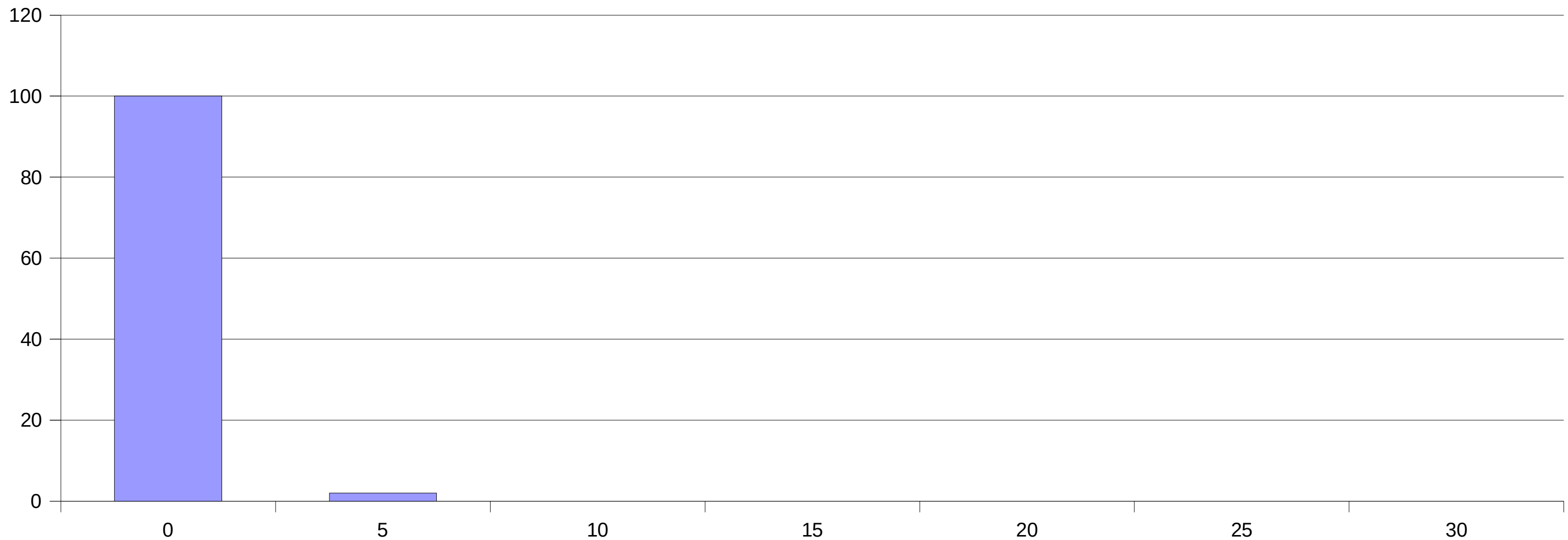
- Batch job
- Long CPU bursts



CPU Burst Lengths

"I/O-bound" program

- Copy, Data acquisition, ...
- *Tiny* CPU bursts between system calls



Why Scheduling?

What if we let a CPU-bound program run to completion?

- What happens to I/O-bound programs?

What if we run an I/O-bound program whenever it is runnable?

- What happens to CPU-bound programs?

Preemptive?

Four opportunities to schedule

- A running process blocks (I/O, page fault, wait(), ...)
- A running process exits
- A blocked process becomes runnable (I/O done)
- Other interrupt (clock)

Multitasking types

- Fully Preemptive: *All four cause scheduling*
- “Cooperative”: only first two

Preemptive *kernel*?

Preemptive multitasking

- All four cases cause context switch

Preemptive *kernel*

- All four cases cause context switch *in kernel mode*
- This is a goal of Project 3
  - System calls: interrupt disabling only when really necessary
  - Clock interrupts should suspend system call execution
    - So fork() should *appear* atomic, but not *execute* that way

CPU Scheduler

Invoked when CPU becomes idle and/or time passes

- Current task blocks
- Clock interrupt

Select next task

- *Quickly*
- PCB's in: FIFO, priority queue, tree, ...

Switch (using "dispatcher")

- Your term may vary

Dispatcher

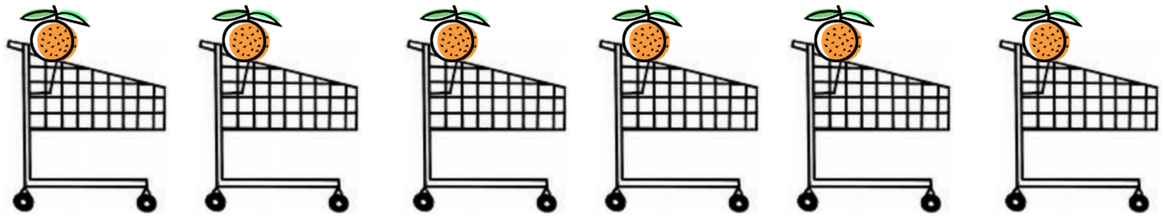
Set down running task

- Save register state
- Update CPU usage information
- Store PCB in “run queue”

Pick up designated task

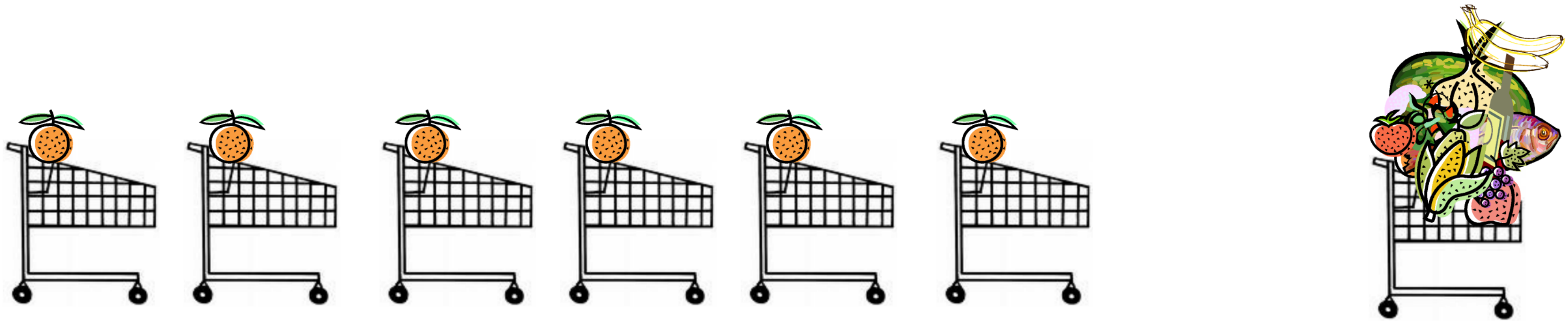
- Activate new task's memory
  - Protection, mapping
- Restore register state
- “Return” to whatever the task was previously doing

Consider…



Who goes first? Last?

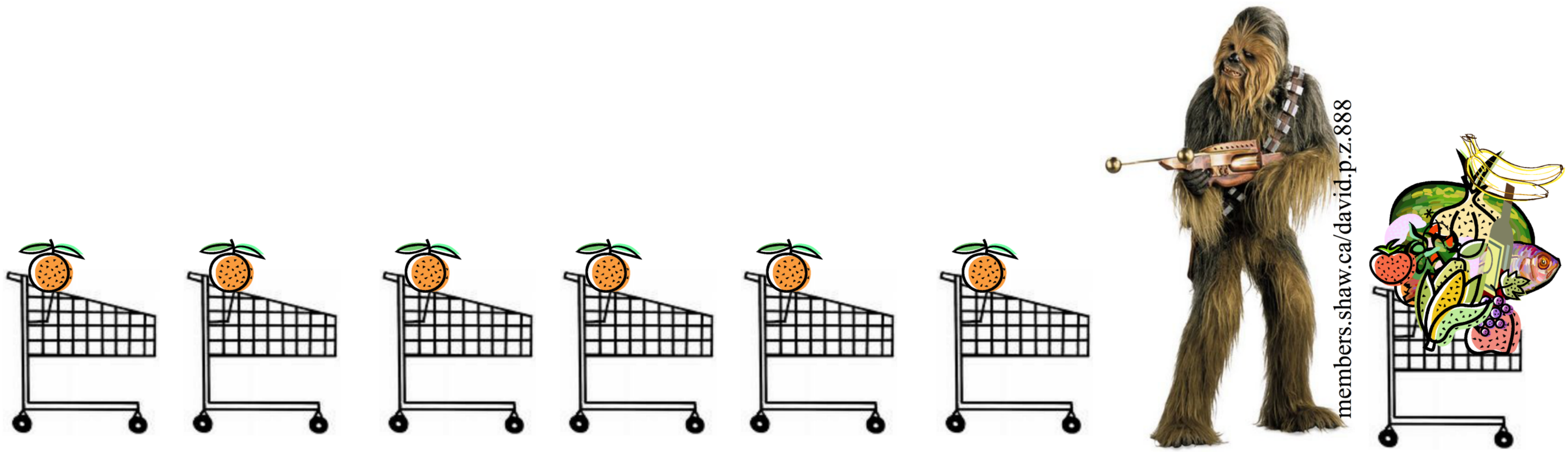
Consider…



Who goes first? Last?

Now who goes first? Last?

Consider…



Who goes first? Last?

Now who goes first? Last?

Does this change things?

Scheduling Criteria

System administrator view

- Maximize/trade off
  - CPU utilization ("busy-ness")
    - Was important when buying computers was expensive
    - Now heat and power often cost more than silicon
  - Throughput ("jobs per second")

Process view

- Minimize
  - Turnaround time (everything, fork() to exit())
  - Waiting time (runnable but not running)

User view (interactive processes)

- Minimize response time (input/output latency)
- *Predictable* response time ("Why is it slow today??")

Algorithms

Don't try these at home

- FCFS
- SJF
- Priority

Reasonable

- Round-Robin
- Multi-level (plus feedback)

Multiprocessor

- Load balancing
- Processor affinity

Real-time

FCFS- First Come, First Served

Basic idea

- Run task until it relinquishes CPU
- When runnable, place at end of FIFO queue

Waiting time *very* dependent on mix

- Some processes run briefly, some much longer

"Convoy effect"

- N tasks each make 1 I/O request, stall (e.g., file copy)
- 1 task executes very long CPU burst
  - All I/O tasks become runnable during this time
- Lather, rinse, repeat
  - Result: N "I/O-bound tasks" can't keep I/O devices busy!

SJF- Shortest Job First

Basic idea

- Choose task with shortest *next* CPU burst
- Will give up CPU soonest, be "nicest" to other tasks
- Provably "optimal"
  - Minimizes average waiting time across tasks
- ***Practically impossible*** (oh, well)
  - Could ***predict*** next burst length...
    - Text suggests averaging recent burst lengths
      - Does not present evaluation (Why not? Hmm...)

SJF- Shortest Job First

Basic idea

- Choose task with shortest *next* CPU burst
- Will give up CPU soonest, be "nicest" to other tasks
- Provably "optimal"
  - Minimizes average waiting time across tasks
- ***Practically impossible*** (oh, well)
  - Could ***predict*** next burst length...
    - Text suggests averaging recent burst lengths
      - Does not present evaluation (Why not? Hmm...)
    - Sometimes applications ***can*** state their remaining work
      - Harchol-Balter et al., "Size-Based Scheduling to Improve Web Performance", ACM TOCS 21:2, 5/2003

Priority

Basic idea

- Choose "most important" waiting task
  - (Nomenclature: does "high priority" mean `p=0` or `p=255`?)

Priority assignment

- Static: fixed property (engineered?)
- Dynamic: function of task behaviour

Big problem: *Starvation*

- "Most important" task gets to run often
- "Least important" task may *never* run
- Common hack: priority "ageing"

Round-Robin

Basic idea

- Run each task for a fixed “time quantum”
- When quantum expires, append to FIFO queue

“Fair”

- But not “provably optimal”

Choosing quantum length

- Infinite (until process does I/O) = FCFS
- Infinitesimal (1 instruction) = “Processor sharing”
  - A technical term used by theory folks
- Balance “fairness” vs. context-switch costs

True "Processor Sharing"

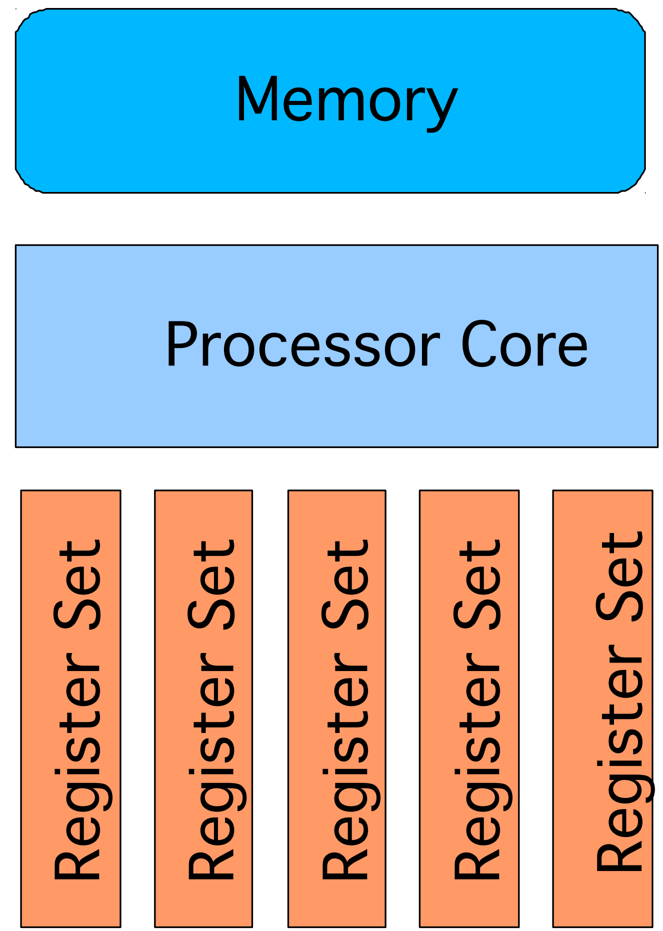
CDC Peripheral Processors

Memory latency

- ***Long***, fixed constant
- Every instruction has a memory operand

Solution: round robin

- Quantum = 1 instruction



True "Processor Sharing"

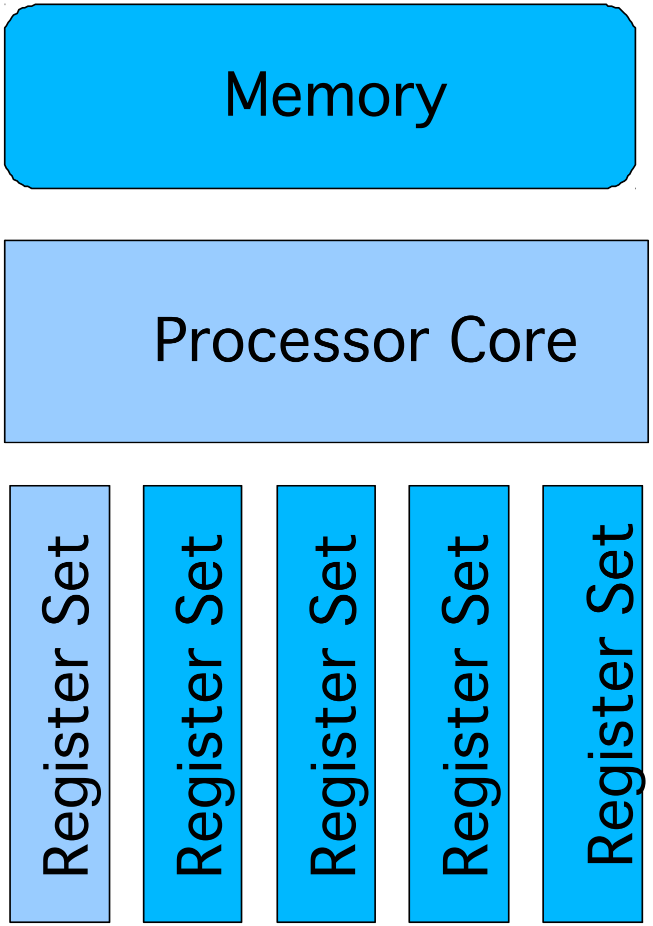
CDC Peripheral Processors

Memory latency

- *Long*, fixed constant
- Every instruction has a memory operand

Solution: round robin

- Quantum = 1 instruction
- One "process" running
- N-1 "processes" waiting on memory



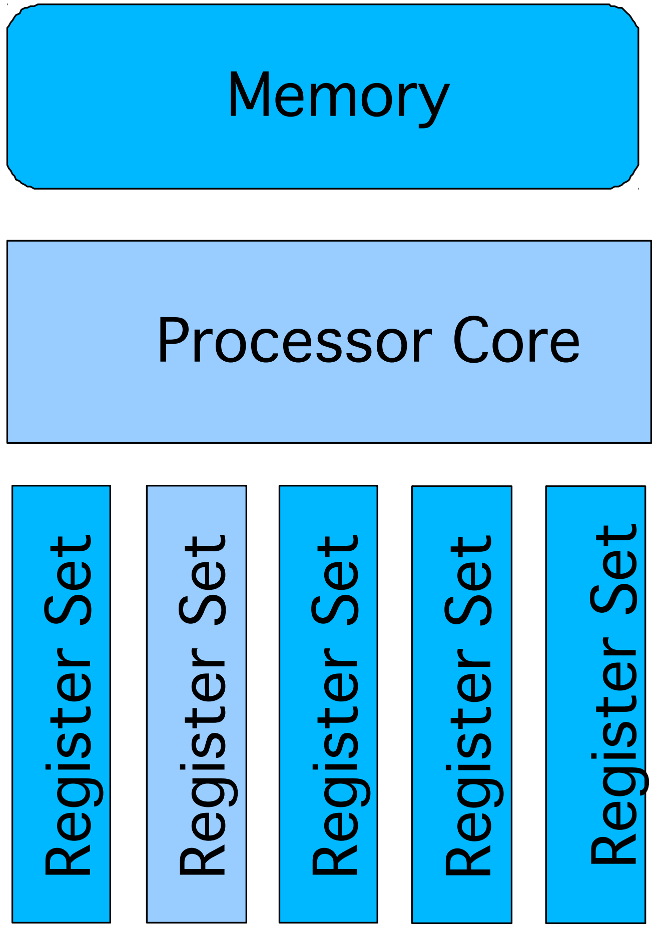
True "Processor Sharing"

Each instruction

- "Brief" computation
- One load or one store
  - Sleeps process N cycles

Steady state

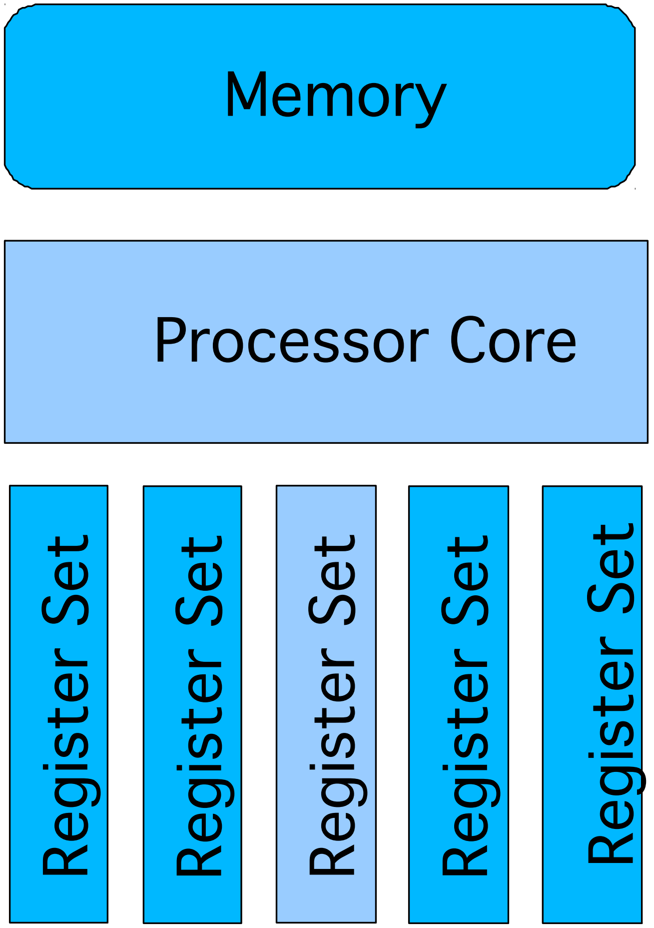
- Run when you're ready
- Ready when it's your turn



Everything Old Is New Again

Intel "hyperthreading"

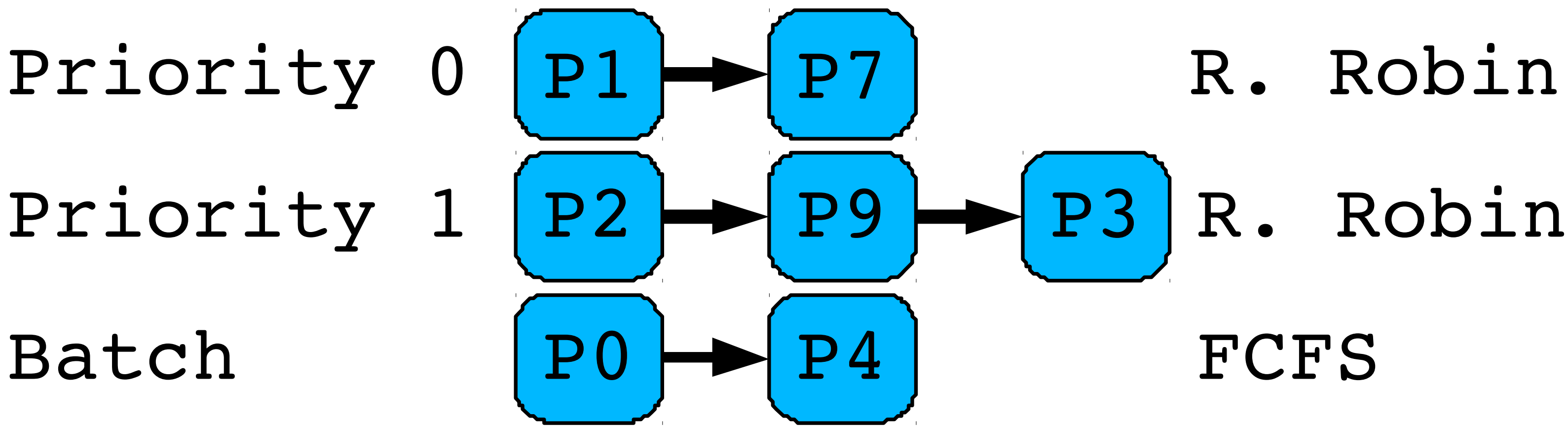
- N register sets
- M functional units
- Switch on long-running operations
- Sharing less regular
- Sharing illusion more lumpy
  - Good for some application *mixes*
  - *Awful* for others
  - "Hyperthreading Hurts Server Performance, Say Developers" - ZDNet UK, 2005-11-18



Multi-level Queue

N independent process queues

- One per priority
- Algorithm per-queue



Multi-level Queue

Inter-queue scheduling?

- **Strict priority**
  - **Pri 0 runs before Pri 1, Pri 1 runs before batch –** *every time*
- **Time slicing (e.g., weighted round-robin)**
  - **Pri 0 gets 2 slices**
  - **Pri 1 gets 1 slice**
  - **Batch gets 1 slice**

Multi-level *Feedback* Queue

N queues, different quanta

Block/sleep before quantum expires?

- Added to end of your queue ("good runnable")

Exhaust your quantum?

- Demoted to slower queue ("bad runnable!")
  - Lower priority, typically longer quantum

Can you be promoted back up?

- Maybe I/O promotes you
- Maybe you "age" upward

Popular "time-sharing" scheduler

Multiprocessor Scheduling

Common assumptions

- Homogeneous processors (same speed)
- Uniform memory access (UMA)

Goal: Load sharing / Load balancing

- "Easy": single global ready queue – no false idleness

Multiprocessor Scheduling

Common assumptions

- Homogeneous processors (same speed)
- Uniform memory access (UMA)

Goal: Load sharing / Load balancing

- "Easy": single global ready queue – no false idleness

But!

- Single global ready queue is a contention "hot spot"
- "Processor Affinity": some processor may be more desirable or necessary
  - Special I/O device
  - Fast thread switch
  - Resuming onto most-recent CPU may find some stuff still cached
  - $1/N^{th}$ of memory may be faster - "NUMA"

Scheduler Evaluation Approaches

“Deterministic modeling”

- aka “hand execution”

Queueing theory

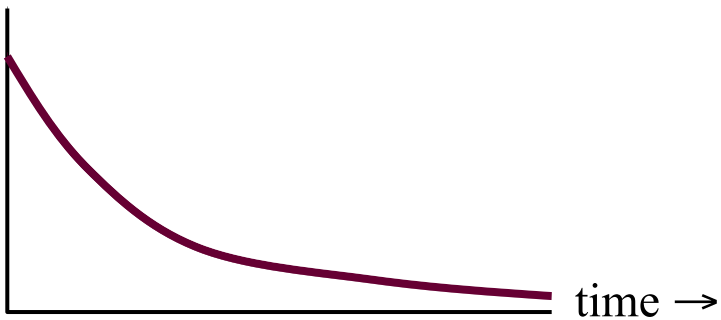
- Often gives fast and useful *approximations*
- Math gets big fast
- Math sensitive to assumptions
  - May be unrealistic (aka “wrong”)

Simulation

- Workload model or trace-driven
- GIGO hazard (either way)

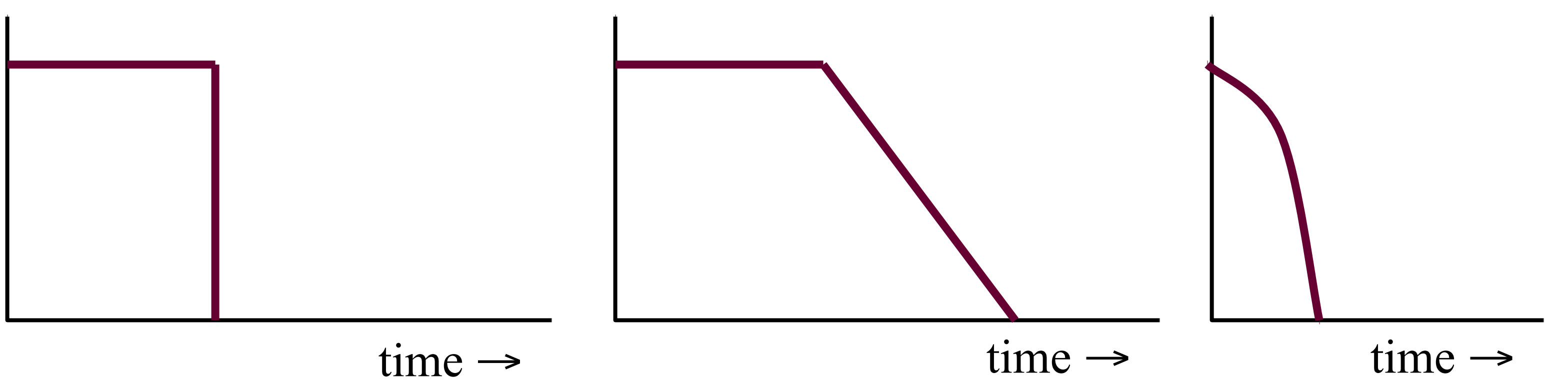
Real-Time Scheduling

What's a computation worth?



"Real Time": No (extra) value if early

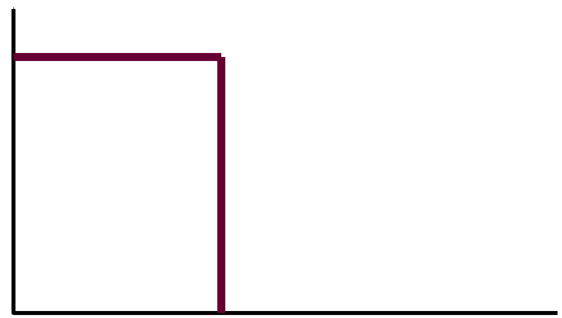
(or in some cases, curve just falls off fast)

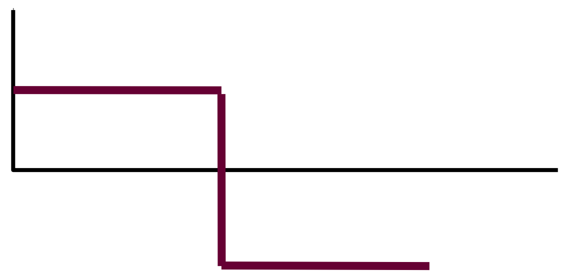


“Hard Real-Time” = ?

Multiple definitions are used

- “Very fast response time” – 10μs?
- “No value” if results are late
- “Very costly” if late
- “Never” late





Hard Real-Time Scheduling

Designers must describe task requirements

- Worst-case execution time of instruction sequences

"Prove" system response time

- Argument or automatic verifier

Cannot use indeterminate-time technologies

- Disks... Networks...

Solutions often involve

- Simplified designs
- Over-engineered systems
- Dedicated hardware
- Specialized OS

Soft Real-Time Scheduling

Computation still has value after deadline

- Think "User Interface"
- Many control systems
  - (if the fly-by-wire system doesn't move the elevator within 50ms, probably still good to to it within 100ms)

Performance is not critical (no one will die)

- YouTube video
- Skype
  - Note that late packets cause audio drop-out.
- CD-R writing software
  - Resulting CD can be corrupted

Soft Real-Time Scheduling

Now commonly supported in generic OS

- POSIX real-time extensions for Unix

Priority-based scheduler

Preemptible kernel implementation

Summary

Round-robin is ok for simple cases

- Certainly 80% of the conceptual weight
- *Certainly* good enough for P3
  - Speaking of P3...
    - Understand preemption, don't evade it

"Real" systems

- Some multi-level feedback
- Probably some soft real-time
- Multi-processor scheduling is a big deal

Real-Time Systems Concepts

- Terminology: soft, hard, deadline
- Key issue: "priority inversion" (see text)