The scheduling problem:
- Have \( k \) jobs ready to run
- Have \( n \geq 1 \) CPUs that can run them

Which jobs should we assign to which CPU(s)?
Outline

1. Textbook scheduling
2. Priority scheduling
3. Advanced scheduling topics
When do we schedule CPU?

- Scheduling decisions may take place when a process:
  1. Switches from running to waiting state
  2. Switches from running to ready state
  3. Switches from new/waiting to ready
  4. Exits

- Non-preemptive schedules use 1 & 4 only
- Preemptive schedulers run at all four points
• Why do we care?
  - What goals should we have for a scheduling algorithm?
Scheduling criteria

- **Why do we care?**
  - What goals should we have for a scheduling algorithm?

- **Throughput** – # of processes that complete per unit time
  - Higher is better

- **Turnaround time** – time for each process to complete
  - Lower is better

- **Response time** – time from request to first response
  - I.e., time between waiting $\rightarrow$ ready transition and ready $\rightarrow$ running (e.g., key press to echo, not launch to exit)
  - Lower is better

- **Above criteria are affected by secondary criteria**
  - *CPU utilization* – fraction of time CPU doing productive work
  - *Waiting time* – time each process waits in ready queue
Example: FCFS Scheduling

- Run jobs in order that they arrive
  - Called “First-come first-served” (FCFS)
  - E.g., Say $P_1$ needs 24 sec, while $P_2$ and $P_3$ need 3.
  - Say $P_2, P_3$ arrived immediately after $P_1$, get:

  ![Diagram showing job execution times]

  - Dirt simple to implement—how good is it?
  - Throughput: 3 jobs / 30 sec = 0.1 jobs/sec
  - Turnaround Time: $P_1 : 24, P_2 : 27, P_3 : 30$
    - Average TT: $(24 + 27 + 30)/3 = 27$
  - Can we do better?
FCFS continued

- Suppose we scheduled $P_2, P_3$, then $P_1$
  - Would get:

  ![Diagram](image)

  - Throughput: 3 jobs / 30 sec = 0.1 jobs/sec
  - Turnaround time: $P_1 : 30, P_2 : 3, P_3 : 6$
    - Average TT: $(30 + 3 + 6)/3 = 13 – much less than 27
  - Lesson: scheduling algorithm can reduce TT
    - Minimizing waiting time can improve RT and TT
  - Can a scheduling algorithm improve throughput?
FCFS continued

- Suppose we scheduled $P_2$, $P_3$, then $P_1$
  - Would get:

```
0  3  6  30
P_2  P_3  P_1
```

- Throughput: 3 jobs / 30 sec = 0.1 jobs/sec
- Turnaround time: $P_1$: 30, $P_2$: 3, $P_3$: 6
  - Average TT: $(30 + 3 + 6)/3 = 13$ – much less than 27

- Lesson: scheduling algorithm can reduce TT
  - Minimizing waiting time can improve RT and TT

- Can a scheduling algorithm improve throughput?
  - Yes, if jobs require both computation and I/O
View CPU and I/O devices the same

- CPU is one of several devices needed by users’ jobs
  - CPU runs compute jobs, Disk drive runs disk jobs, etc.
  - With network, part of job may run on remote CPU

- Scheduling 1-CPU system with $n$ I/O devices like scheduling asymmetric $(n + 1)$-CPU multiprocessor
  - Result: all I/O devices + CPU busy $\implies (n + 1)$-fold throughput gain!

- Example: disk-bound grep + CPU-bound matrix multiply
  - Overlap them just right? throughput will be almost doubled
Bursts of computation & I/O

- Jobs contain I/O and computation
  - Bursts of computation
  - Then must wait for I/O

- To maximize throughput, maximize both CPU and I/O device utilization

- How to do?
  - Overlap computation from one job with I/O from other jobs
  - Means *response time* very important for I/O-intensive jobs: I/O device will be idle until job gets small amount of CPU to issue next I/O request
• What does this mean for FCFS?
FCFS Convoy effect

- CPU-bound jobs will hold CPU until exit or I/O (but I/O rare for CPU-bound thread)
  - Long periods where no I/O requests issued, and CPU held
  - Result: poor I/O device utilization

- Example: one CPU-bound job, many I/O bound
  - CPU-bound job runs (I/O devices idle)
  - Eventually, CPU-bound job blocks
  - I/O-bound jobs run, but each quickly blocks on I/O
  - CPU-bound job unblocks, runs again
  - All I/O requests complete, but CPU-bound job still hogs CPU
  - I/O devices sit idle since I/O-bound jobs can’t issue next requests

- Simple hack: run process whose I/O completed
  - What is a potential problem?
FCFS Convoy effect

- CPU-bound jobs will hold CPU until exit or I/O (but I/O rare for CPU-bound thread)
  - Long periods where no I/O requests issued, and CPU held
  - Result: poor I/O device utilization

- Example: one CPU-bound job, many I/O bound
  - CPU-bound job runs (I/O devices idle)
  - Eventually, CPU-bound job blocks
  - I/O-bound jobs run, but each quickly blocks on I/O
  - CPU-bound job unblocks, runs again
  - All I/O requests complete, but CPU-bound job still hogs CPU
  - I/O devices sit idle since I/O-bound jobs can’t issue next requests

- Simple hack: run process whose I/O completed
  - What is a potential problem? I/O-bound jobs can starve CPU-bound one
• **Shortest-job first (SJF) attempts to minimize TT**
  - Schedule the job whose next CPU burst is the shortest
  - Misnomer unless “job” = one CPU burst with no I/O

• **Two schemes:**
  - *Non-preemptive* – once CPU given to the process it cannot be preempted until completes its CPU burst
  - *Preemptive* – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt (Known as the Shortest-Remaining-Time-First or SRTF)

• **What does SJF optimize?**
• **Shortest-job first (SJF)** attempts to minimize TT
  - Schedule the job whose next CPU burst is the shortest
  - Misnomer unless "job" = one CPU burst with no I/O

• Two schemes:
  - *Non-preemptive* – once CPU given to the process it cannot be preempted until completes its CPU burst
  - *Preemptive* – if a new process arrives with CPU burst length less than remaining time of current executing process, preempt (Known as the *Shortest-Remaining-Time-First* or SRTF)

• What does SJF optimize?
  - Gives minimum average *waiting time* for a given set of processes
Examples

<table>
<thead>
<tr>
<th>Process</th>
<th>Arrival Time</th>
<th>Burst Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>$P_2$</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$P_3$</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$P_4$</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

- Non-preemptive

- Preemptive

- Drawbacks?
SJF limitations

- Doesn’t always minimize average TT
  - Only minimizes waiting time
  - Example where turnaround time might be suboptimal?

- Can lead to unfairness or starvation

- In practice, can’t actually predict the future

- But can estimate CPU burst length based on past
  - Exponentially weighted average a good idea
  - $t_n$ actual length of process’s $n^{th}$ CPU burst
  - $\tau_{n+1}$ estimated length of proc’s $(n+1)^{st}$
  - Choose parameter $\alpha$ where $0 < \alpha \leq 1$
  - Let $\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$
SJF limitations

- Doesn’t always minimize average TT
  - Only minimizes waiting time
  - Example where turnaround time might be suboptimal?
  - Overall longer job has shorter bursts

- Can lead to unfairness or starvation

- In practice, can’t actually predict the future

- But can estimate CPU burst length based on past
  - Exponentially weighted average a good idea
  - $t_n$ actual length of process’s $n^{th}$ CPU burst
  - $\tau_{n+1}$ estimated length of proc’s $(n + 1)^{st}$
  - Choose parameter $\alpha$ where $0 < \alpha \leq 1$
  - Let $\tau_{n+1} = \alpha t_n + (1 - \alpha) \tau_n$
Exp. weighted average example

CPU burst ($t_i$)  6  4  6  4  13  13  13  
"guess" ($\tau_i$)  10  8  6  6  5  9  11  12  

...
Round robin (RR) scheduling

\[ P_1 \quad P_2 \quad P_3 \quad P_1 \quad P_2 \quad P_1 \]

- **Solution to fairness and starvation**
  - Preempt job after some time slice or *quantum*
  - When preempted, move to back of FIFO queue
  - (Most systems do some flavor of this)

- **Advantages:**
  - Fair allocation of CPU across jobs
  - Low average waiting time when job lengths vary
  - Good for responsiveness if small number of jobs

- **Disadvantages?**
• Varying sized jobs are good … what about same-sized jobs?

• Assume 2 jobs of time=100 each:

```
P_1  P_2  P_1  P_2  P_1  P_2  ...  P_1  P_2
0    1    2    3    4    5    6    198  199  200
```

• Even if context switches were free…
  - What would average turnaround time be with RR?
  - How does that compare to FCFS?
• Varying sized jobs are good …what about same-sized jobs?

• Assume 2 jobs of time=100 each:

- What would average turnaround time be with RR? 199.5
- How does that compare to FCFS? 150
What is the cost of a context switch?

- Brute CPU time cost in kernel:
  - Save and restore registers, etc.
  - Switch address spaces (expensive instructions)

- Indirect costs: cache, buffer cache, & TLB misses

CPU cache

/one.pnum
/two.pnum

/one.pnum/seven.pnum
/four.pnum/four.pnum
• What is the cost of a context switch?
• Brute CPU time cost in kernel
  - Save and restore registers, etc.
  - Switch address spaces (expensive instructions)
• Indirect costs: cache, buffer cache, & TLB misses

\[ P_1 \quad P_2 \]

CPU cache CPU cache
What is the cost of a context switch?

Brute CPU time cost in kernel
- Save and restore registers, etc.
- Switch address spaces (expensive instructions)

Indirect costs: cache, buffer cache, & TLB misses
How to pick quantum?
- Want much larger than context switch cost
- Majority of bursts should be less than quantum
- But not so large system reverts to FCFS

Typical values: 1–100 msec
Turnaround time vs. quantum

<table>
<thead>
<tr>
<th>process</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>6</td>
</tr>
<tr>
<td>$P_2$</td>
<td>3</td>
</tr>
<tr>
<td>$P_3$</td>
<td>1</td>
</tr>
<tr>
<td>$P_4$</td>
<td>7</td>
</tr>
</tbody>
</table>
Two-level scheduling

- Under memory constraints, may need to *swap* process to disk

- **Switching to swapped out process** very expensive
  - Swapped out process has most memory pages on disk
  - Will have to fault them all in while running
  - One disk access costs ~10ms. On 1GHz machine, 10ms = 10 million cycles!

- **Solution: Context-switch-cost aware scheduling**
  - Run in-core subset for “a while”
  - Then swap some between disk and memory

- **How to pick subset? How to define “a while”?**
  - View as scheduling *memory* before scheduling CPU
  - Swapping in process is cost of memory “context switch”
  - So want “memory quantum” much larger than swapping cost
1. Textbook scheduling
2. Priority scheduling
3. Advanced scheduling topics
Priority scheduling

- Associate a numeric priority with each process
  - E.g., smaller number means higher priority (Unix/BSD)
  - Or smaller number means lower priority (Pintos)
- Give CPU to the process with highest priority
  - Can be done preemptively or non-preemptively
- Note SJF is priority scheduling where priority is the predicted next CPU burst time
- Starvation – low priority processes may never execute
- Solution?
Priority scheduling

- Associate a numeric priority with each process
  - E.g., smaller number means higher priority (Unix/BSD)
  - Or smaller number means lower priority (Pintos)
- Give CPU to the process with highest priority
  - Can be done preemptively or non-preemptively
- Note SJF is priority scheduling where priority is the predicted next CPU burst time
- Starvation – low priority processes may never execute
- Solution?
  - Aging: increase a process’s priority as it waits
Multilevel feedback queues (BSD)

- Every runnable process on one of 32 run queues
  - Kernel runs process on highest-priority non-empty queue
    - Round-robin among processes on same queue
- Process priorities dynamically computed
  - Processes moved between queues to reflect priority changes
  - If a process gets higher priority than running process, run it
- Idea: Favor interactive jobs that use less CPU
Process priority

- **p_nice** – user-settable weighting factor
- **p_estcpu** – per-process estimated CPU usage
  - Incremented whenever timer interrupt found process running
  - Decayed every second while process runnable
  
  \[ p_{\text{estcpu}} \leftarrow \left( \frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1} \right) p_{\text{estcpu}} + p_{\text{nice}} \]
  
  - Load is sampled average of length of run queue plus short-term sleep queue over last minute
- **Run queue determined by** \( p_{\text{usrpri}}/4 \)
  
  \[ p_{\text{usrpri}} \leftarrow 50 + \left( \frac{p_{\text{estcpu}}}{4} \right) + 2 \cdot p_{\text{nice}} \]
  
  (value clipped if over 127)
Sleeping process increases priority

- \( p_{\text{estcpu}} \) not updated while asleep
  - Instead \( p_{\text{slptime}} \) keeps count of sleep time

- When process becomes runnable

\[
p_{\text{estcpu}} \leftarrow \left( \frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1} \right)^{p_{\text{slptime}}} \times p_{\text{estcpu}}
\]

  - Approximates decay ignoring nice and past loads

- Previous description based on [McKusick] (The Design and Implementation of the 4.4BSD Operating System)

---

\(^1\)See library.stanford.edu for off-campus access
Pintos notes

- Same basic idea for second half of project 1
  - But 64 priorities, not 128
  - Higher numbers mean higher priority
  - Okay to have only one run queue if you prefer
    (less efficient, but we won’t deduct points for it)

- Have to negate priority equation:

\[
\text{priority} = 63 - \left( \frac{\text{recent\_cpu}}{4} \right) - 2 \cdot \text{nice}
\]
Thread scheduling

• With thread library, have two scheduling decisions:
  - *Local Scheduling* – Thread library decides which user thread to put onto an available kernel thread
  - *Global Scheduling* – Kernel decides which kernel thread to run next

• Can expose to the user
  - E.g., `pthread_attr_setscope` allows two choices
    - `PTHREAD_SCOPE_SYSTEM` – thread scheduled like a process (effectively one kernel thread bound to user thread – Will return ENOTSUP in user-level pthreads implementation)
    - `PTHREAD_SCOPE_PROCESS` – thread scheduled within the current process (may have multiple user threads multiplexed onto kernel threads)
- **Say** $H$ at high priority, $L$ at low priority
  - $L$ acquires lock $l$.
  - Scenario 1: $H$ tries to acquire $l$, fails, spins. $L$ never gets to run.
  - Scenario 2: $H$ tries to acquire $l$, fails, blocks. $M$ enters system at medium priority. $L$ never gets to run.
  - Both scenes are examples of *priority inversion*

- **Scheduling** = deciding who should make progress
  - A thread’s importance should increase with the importance of those that depend on it
  - Naïve priority schemes violate this
Priority donation

- Say higher number = higher priority (like Pintos)
- Example 1: $L$ (prio 2), $M$ (prio 4), $H$ (prio 8)
  - $L$ holds lock $l$
  - $M$ waits on $l$, $L$’s priority raised to $L_1 = \max(M, L) = 4$
  - Then $H$ waits on $l$, $L$’s priority raised to $\max(H, L_1) = 8$
- Example 2: Same $L$, $M$, $H$ as above
  - $L$ holds lock $l$, $M$ holds lock $l_2$
  - $M$ waits on $l$, $L$’s priority now $L_1 = 4$ (as before)
  - Then $H$ waits on $l_2$. $M$’s priority goes to $M_1 = \max(H, M) = 8$, and $L$’s priority raised to $\max(M_1, L_1) = 8$
- Example 3: $L$ (prio 2), $M_1, \ldots M_{1000}$ (all prio 4)
  - $L$ has $l$, and $M_1, \ldots, M_{1000}$ all block on $l$. $L$’s priority is $\max(L, M_1, \ldots, M_{1000}) = 4$. 
1. Textbook scheduling

2. Priority scheduling

3. Advanced scheduling topics
**Multiprocessor scheduling issues**

- **Must decide on more than which processes to run**
  - Must decide on which CPU to run which process
- **Moving between CPUs has costs**
  - More cache misses, depending on arch. more TLB misses too
- **Affinity scheduling**—try to keep process/thread on same CPU

- But also prevent load imbalances
- Do *cost-benefit* analysis when deciding to migrate...
  affinity can also be harmful, particularly when tail latency is critical
• **Want related processes/threads scheduled together**
  - Good if threads access same resources (e.g., cached files)
  - Even more important if threads communicate often, otherwise must context switch to communicate

• **Gang scheduling**—schedule all CPUs synchronously
  - With synchronized quanta, easier to schedule related processes/threads together

![Diagram of CPU allocations]
Real-time scheduling

- **Two categories:**
  - *Soft real time*—miss deadline and CD will sound funny
  - *Hard real time*—miss deadline and plane will crash

- **System must handle periodic and aperiodic events**
  - E.g., processes A, B, C must be scheduled every 100, 200, 500 msec, require 50, 30, 100 msec respectively
  - *Schedulable* if \( \sum \frac{CPU}{period} \leq 1 \) (not counting switch time)

- **Variety of scheduling strategies**
  - E.g., first deadline first
    (works if schedulable, otherwise fails spectacularly)
Many modern schedulers employ notion of virtual time
- Idea: Equalize virtual CPU time consumed by different processes
- Higher-priority processes consume virtual time more slowly

Forms the basis of the current Linux scheduler, CFS

Case study: Borrowed Virtual Time (BVT) [Duda]

BVT runs process with lowest effective virtual time
- $A_i$ – actual virtual time consumed by process $i$
- effective virtual time $E_i = A_i - (\text{warp}_i \? W_i : 0)$
- Special warp factor allows borrowing against future CPU time
  …hence name of algorithm
Process weights

• Each process $i$’s faction of CPU determined by weight $w_i$
  - $i$ should get $w_i / \sum_j w_j$ faction of CPU
  - So $w_i$ is real seconds per virtual second that process $i$ has CPU
• When $i$ consumes $t$ CPU time, track it: $A_i += t / w_i$
• Example: gcc (weight 2), bigsim (weight 1)
  - Assuming no IO, runs: gcc, gcc, bigsim, gcc, gcc, bigsim, ...
  - Lots of context switches, not so good for performance
• Add in context switch allowance, $C$
  - Only switch from $i$ to $j$ if $E_j \leq E_i - C / w_i$
  - $C$ is wall-clock time ($\gg$ context switch cost), so must divide by $w_i$
  - Ignore $C$ if $j$ just became runnable...why?
Process weights

- Each process $i$’s faction of CPU determined by weight $w_i$
  - $i$ should get $w_i / \sum_j w_j$ faction of CPU
  - So $w_i$ is real seconds per virtual second that process $i$ has CPU

- When $i$ consumes $t$ CPU time, track it: $A_i += t/w_i$

- Example: gcc (weight 2), bigsim (weight 1)
  - Assuming no IO, runs: gcc, gcc, bigsim, gcc, gcc, bigsim, …
  - Lots of context switches, not so good for performance

- Add in context switch allowance, $C$
  - Only switch from $i$ to $j$ if $E_j \leq E_i - C/w_i$
  - $C$ is wall-clock time ($\gg$ context switch cost), so must divide by $w_i$
  - Ignore $C$ if $j$ just became runnable to avoid affecting response time
• gcc has weight 2, bigsim weight 1, $C = 2$, no I/O
  - bigsim consumes virtual time at twice the rate of gcc
  - Processes run for $C$ time after lines cross before context switch
Sleep/wakeup

- Must lower priority (increase $A_i$) after wakeup
  - Otherwise process with very low $A_i$ would starve everyone

- Bound lag with Scheduler Virtual Time (SVT)
  - SVT is minimum $A_j$ for all runnable threads $j$
  - When waking $i$ from voluntary sleep, set $A_i \leftarrow \max(A_i, SVT)$

- Note voluntary/involuntary sleep distinction
  - E.g., Don’t reset $A_j$ to SVT after page fault
  - Faulting thread needs a chance to catch up
  - But do set $A_i \leftarrow \max(A_i, SVT)$ after socket read

- Note: Even with SVT $A_i$ can never decrease
  - After short sleep, might have $A_i > SVT$, so $\max(A_i, SVT) = A_i$
  - $i$ never gets more than its fair share of CPU in long run
- gcc’s $A_i$ gets reset to SVT on wakeup
  - Otherwise, would be at lower (blue) line and starve bigsim
Real-time threads

- Also want to support time-critical tasks
  - E.g., mpeg player must run every 10 clock ticks

- Recall $E_i = A_i - (\text{warp}_i \ ? W_i : 0)$
  - $W_i$ is warp factor – gives thread precedence
  - Just give mpeg player $i$ large $W_i$ factor
  - Will get CPU whenever it is runnable
  - But long term CPU share won’t exceed $w_i / \sum_j w_j$

- Note $W_i$ only matters when warp$_i$ is true
  - Can set warp$_i$ with a syscall, or have it set in signal handler
  - Also gets cleared if $i$ keeps using CPU for $L_i$ time
  - $L_i$ limit gets reset every $U_i$ time
  - $L_i = 0$ means no limit – okay for small $W_i$ value
• mpeg player runs with $-50$ warp value
  - Always gets CPU when needed, never misses a frame
- mpeg goes into tight loop at time 5
- Exceeds $L_i$ at time 10, so $\text{warp}_i \leftarrow \text{false}$
BVT example: Search engine

- **Common queries 150 times faster than uncommon**
  - Have 10-thread pool of threads to handle requests
  - Assign $W_i$ value sufficient to process fast query (say 50)

- **Say 1 slow query, small trickle of fast queries**
  - Fast queries come in, warped by 50, execute immediately
  - Slow query runs in background
  - Good for turnaround time

- **Say 1 slow query, but many fast queries**
  - At first, only fast queries run
  - But SVT is bounded by $A_i$ of slow query thread $i$
  - Recall fast query thread $j$ gets $A_j = \max(A_j, SVT) = A_j$; eventually $SVT < A_j$ and a bit later $A_j - \text{warp}_j > A_i$.
  - At that point thread $i$ will run again, so no starvation
Case study: SMART

• Key idea: Separate importance from urgency
  - Figure out which processes are important enough to run
  - Run whichever of these is most urgent

• Importance = \( \langle priority, BVFT \rangle \) value tuple
  - priority – parameter set by user or administrator (higher is better)
    ▶ Takes absolute priority over BVFT
  - BVFT – Biased Virtual Finishing Time (lower is better)
    ▶ virtual time consumed + virtual length of next CPU burst
    ▶ I.e., virtual time at which quantum would end if process scheduled now
    ▶ Bias is like negative warp, see paper for details

• Urgency = next deadline (sooner is more urgent)
SMART algorithm

- If most important ready task (ready task with best value tuple) is conventional (not real-time), run it
- Consider all real-time tasks with better value tuples than the best ready conventional task
- For each such real-time task, starting from the best value-tuple
  - Can you run it without missing deadlines of more important tasks?
  - If so, add to schedulable set
- Run task with earliest deadline in schedulable set
- Send signal to tasks that won’t meet their deadlines