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 issues
4. Virtual time case studies
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?

- 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 → ready transition and ready → 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
Scheduling criteria

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  - What goals should we have for a scheduling algorithm?

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- 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 run times of $P_1, P_2, P_3$]

  $P_1$  $P_2$  $P_3$

  0  24  27  30

- 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?
Suppose we scheduled $P_2, P_3$, then $P_1$

- Would get:

![Sequence Diagram]

- 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?
Suppose we scheduled $P_2$, $P_3$, then $P_1$

- Would get:

```
0 3 6 9 15 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
Histogram of CPU-burst times

- 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?
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- 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?**
**SJF Scheduling**

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- **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
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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

- 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?
RR 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?
RR disadvantages

- Varying sized jobs are good ... what about same-sized jobs?
- Assume 2 jobs of time=100 each:

```
  P1  P2  P1  P2  P1  P2  ...  P1  P2
0 1  2  3  4  5  6  ...  198 199 200
```

- Even if context switches were free...
  - 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?
• 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
**Context switch costs**

- 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
Time quantum

- **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**

The graph shows the relationship between the time quantum and the average turnaround time for different processes. The table to the right lists the times for each process:

<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 $\sim$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 issues
4. Virtual time case studies
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

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• 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-robbins 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

\[
p_{estcpu} \leftarrow \left( \frac{2 \cdot \text{load}}{2 \cdot \text{load} + 1} \right) p_{estcpu} + p_{nice}
\]
- Load is sampled average of length of run queue plus short-term sleep queue over last minute

- **Run queue determined by** \( p_{usrpri}/4 \)

\[
p_{usrpri} \leftarrow 50 + \left( \frac{p_{estcpu}}{4} \right) + 2 \cdot p_{nice}
\]

(value clipped if over 127)
Sleeping process increases priority

• $p_{estcpu}$ not updated while asleep
  - Instead $p_{slptime}$ keeps count of sleep time

• When process becomes runnable

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

  - Approximates decay ignoring nice and past loads

• Previous description based on [McKusick]\(^1\) (The Design and Implementation of the 4.4BSD Operating System)

\(^1\)See library.stanford.edu for off-campus access
• 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:

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

- **With thread library, have two scheduling decisions:**
  - *Local Scheduling* – User-level thread library decides which user (green) thread to put onto an available native (i.e., kernel) thread
  - *Global Scheduling* – Kernel decides which native 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 native 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)
Thread dependencies

• Say $H$ at high priority, $L$ at low priority
  - $L$ acquires lock $\ell$.
  - Scenario 1 ($\ell$ a spinlock): $H$ tries to acquire $\ell$, fails, spins. $L$ never
    gets to run.
  - Scenario 2 ($\ell$ a mutex): $H$ tries to acquire $\ell$, fails, blocks. $M$ enters
    system at medium priority. $L$ never gets to run.
  - Both scenarios 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 $\ell$
  - $M$ waits on $\ell$, $L$’s priority raised to $L_1 = \max(M, L) = 4$
  - Then $H$ waits on $\ell$, $L$’s priority raised to $\max(H, L_1) = 8$

- **Example 2: Same $L$, $M$, $H$ as above**
  - $L$ holds lock $\ell_1$, $M$ holds lock $\ell_2$
  - $M$ waits on $\ell_1$, $L$’s priority now $L_1 = 4$ (as before)
  - Then $H$ waits on $\ell_2$. $M$’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 $\ell$, and $M_1, \ldots, M_{1000}$ all block on $\ell$. $L$’s priority is $\max(L, M_1, \ldots, M_{1000}) = 4$. 
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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, when tail latency is critical
Multiprocessor scheduling (cont)

- 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

```
CPU_1
  P_{1,1}  P_{1,2}  P_{1,3}  P_{1,4}

CPU_2
  P_{2,1}  P_{2,2}  P_{2,3}  P_{2,4}

CPU_3
  P_{3,1}  P_{3,2}  P_{3,3}  P_{3,4}

CPU_4
  P_{4,1}  P_{4,2}  P_{4,3}  P_{4,4}
```

Real-time scheduling

• Two categories:
  - *Soft real time*—miss deadline and audio playback 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)
1. Textbook scheduling
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4. Virtual time case studies
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

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  - $C$ 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 wakes up after I/O

- 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 \textit{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 \( \text{warp}_i \) is true
  - Can set \( \text{warp}_i \) 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 $\text{warp}_i \leftarrow \text{false}$
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 $A_j - W_j > A_i$.
- 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** = $\langle \text{priority}, \text{BVFT} \rangle$ *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.