Scheduling
Learning Outcomes

• Understand the role of the scheduler, and how its behaviour influences the performance of the system.

• Know the difference between I/O-bound and CPU-bound tasks, and how they relate to scheduling.
What is Scheduling?

– On a multi-programmed system
  • We may have more than one *Ready* process
– On a batch system
  • We may have many jobs waiting to be run
– On a multi-user system
  • We may have many users concurrently using the system
  • The *scheduler* decides who to run next.
    – The process of choosing is called *scheduling*. 
Is scheduling important?

• It is not in certain scenarios
  – If you have no choice
    • Early systems
      – Usually batching
      – Scheduling algorithm simple
        » Run next on tape or next on punch tape
  – Only one thing to run
    • Simple PCs
      – Only ran a word processor, etc….
    • Simple Embedded Systems
      – TV remote control, washing machine, etc….
Is scheduling important?

- It is in most realistic scenarios
  - Multitasking/Multi-user System
    - Example
      - Email daemon takes 2 seconds to process an email
      - User clicks button on application.
    - Scenario 1
      - Run daemon, then application
        » System appears really sluggish to the user
    - Scenario 2
      - Run application, then daemon
        » Application appears really responsive, small email delay is unnoticed
- Scheduling decisions can have a dramatic effect on the perceived performance of the system
  - Can also affect correctness of a system with deadlines
Application Behaviour

- Bursts of CPU usage alternate with periods of I/O wait

(a) Long CPU burst

(b) Short CPU burst

Waiting for I/O

Time
**Application Behaviour**

(a) CPU-Bound process
- Spends most of its computing
- Time to completion largely determined by received CPU time

(b) Diagram showing
- Long CPU burst
- Short CPU burst
- Waiting for I/O
b) I/O-Bound process
   - Spend most of its time waiting for I/O to complete
     - Small bursts of CPU to process I/O and request next I/O
   - Time to completion largely determined by I/O request time
Observation

- We need a mix of CPU-bound and I/O-bound processes to keep both CPU and I/O systems busy.
- Process can go from CPU- to I/O-bound (or vice versa) in different phases of execution.
Key Insight

- Choosing to run an I/O-bound process delays a CPU-bound process by very little
- Choosing to run a CPU-bound process prior to an I/O-bound process delays the next I/O request significantly
  - No overlap of I/O waiting with computation
  - Results in device (disk) not as busy as possible

⇒ Generally, favour I/O-bound processes over CPU-bound processes
When is scheduling performed?

- A new process
  - Run the parent or the child?
- A process exits
  - Who runs next?
- A process waits for I/O
  - Who runs next?
- A process blocks on a lock
  - Who runs next? The lock holder?
- An I/O interrupt occurs
  - Who do we resume, the interrupted process or the process that was waiting?
- On a timer interrupt? (See next slide)
- Generally, a scheduling decision is required when a process (or thread) can no longer continue, or when an activity results in more than one ready process.
Preemptive versus Non-preemptive Scheduling

- **Non-preemptive**
  - Once a thread is in the *running* state, it continues until it completes, blocks on I/O, or voluntarily yields the CPU
  - A single process can monopolise the entire system

- **Preemptive Scheduling**
  - Current thread can be interrupted by OS and moved to *ready* state.
  - Usually after a timer interrupt and process has exceeded its maximum run time
    - Can also be as a result of higher priority process that has become *ready* (after I/O interrupt).
  - Ensures fairer service as single thread can’t monopolise the system
    - Requires a timer interrupt
Categories of Scheduling Algorithms

• The choice of scheduling algorithm depends on the goals of the application (or the operating system)
  – No one algorithm suits all environments

• We can roughly categorise scheduling algorithms as follows
  – Batch Systems
    • No users directly waiting, can optimise for overall machine performance
  – Interactive Systems
    • Users directly waiting for their results, can optimise for users perceived performance
  – Realtime Systems
    • Jobs have deadlines, must schedule such that all jobs (predictably) meet their deadlines.
Goals of Scheduling Algorithms

• All Algorithms
  – Fairness
    • Give each process a *fair* share of the CPU
  – Policy Enforcement
    • What ever policy chosen, the scheduler should ensure it is carried out
  – Balance/Efficiency
    • Try to keep all parts of the system busy
Goals of Scheduling Algorithms

• Interactive Algorithms
  – Minimise *response time*
    • Response time is the time difference between issuing a command and getting the result
      – E.g selecting a menu, and getting the result of that selection
    • Response time is important to the user’s perception of the performance of the system.
  – Provide *Proportionality*
    • Proportionality is the user expectation that short jobs will have a short response time, and long jobs can have a long response time.
    • Generally, favour short jobs
Goals of Scheduling Algorithms

• Real-time Algorithms
  – Must meet deadlines
    • Each job/task has a deadline.
    • A missed deadline can result in data loss or catastrophic failure
      – Aircraft control system missed deadline to apply brakes
  – Provide Predictability
    • For some apps, an occasional missed deadline is okay
      – E.g. DVD decoder
    • Predictable behaviour allows smooth DVD decoding with only rare skips
Interactive Scheduling
Round Robin Scheduling

- Each process is given a timeslice to run in
- When the timeslice expires, the next process preempts the current process, and runs for its timeslice, and so on
  - The preempted process is placed at the end of the queue
- Implemented with
  - A ready queue
  - A regular timer interrupt
Example

• 5 Process
  – Process 1 arrives slightly before process 2, etc…
  – All are immediately runnable
  – Execution times indicated by scale on x-axis
Round Robin Schedule

Timeslice = 1 unit
Round Robin Schedule

Timeslice = 3 units
Round Robin

• **Pros**
  – Fair, easy to implement

• **Con**
  – Assumes everybody is equal

• **Issue: What should the timeslice be?**
  – Too short
    • Waste a lot of time switching between processes
    • Example: timeslice of 4ms with 1 ms context switch = 20% round robin overhead
  – Too long
    • System is not responsive
    • Example: timeslice of 100ms
      – If 10 people hit “enter” key simultaneously, the last guy to run will only see progress after 1 second.
    • Degenerates into FCFS if timeslice longer than burst length
Priorities

• Each Process (or thread) is associated with a priority
• Provides basic mechanism to influence a scheduler decision:
  – Scheduler will always chooses a thread of higher priority over lower priority
• Priorities can be defined internally or externally
  – Internal: e.g. I/O bound or CPU bound
  – External: e.g. based on importance to the user
Example

- 5 Jobs
  - Job number equals priority
  - Priority 1 > priority 5
  - Release and execution times as shown

- Priority-driven preemptively scheduled
Example
Example

J1

J2

J3

J4

J5
Example
Example
Example
Example

Graph showing the timeline and tasks for J1, J2, J3, J4, and J5.
Example

J1
J2
J3
J4
J5

0  2  4  6  8  10  12  14  16  18  20
Example

J1
J2
J3
J4
J5
Example

J1
J2
J3
J4
J5
Example

J1

J2

J3

J4

J5
Example

J1
J2
J3
J4
J5

0 2 4 6 8 10 12 14 16 18 20
Example
Example

J1
J2
J3
J4
J5

0 2 4 6 8 10 12 14 16 18 20
Example
Example

0  2  4  10
6  8  12  14  20

J1
J2
J3
J4
J5
Example

J1
J2
J3
J4
J5
Example

J1

J2

J3

J4

J5
Example

```
J1
J2
J3
J4
J5
```

```
0  2  4  6  8  10 12 14 16 18 20
```
Example
Priorities

- Usually implemented by multiple priority queues, with round robin on each queue
- Con
  - Low priorities can starve
    - Need to adapt priorities periodically
      - Based on ageing or execution history
Traditional UNIX Scheduler

- Two-level scheduler
  - High-level scheduler schedules processes between memory and disk
  - Low-level scheduler is CPU scheduler
- Based on a multi-level queue structure with round robin at each level

```
Highest priority
  ...  
-4   Waiting for disk I/O
-3   Waiting for disk buffer
-2   Waiting for terminal input
-1   Waiting for terminal output
  0   Waiting for child to exist
  0   User priority 0
  1   User priority 1
  2   User priority 2
  3   User priority 3
    ...  
Lowest priority
```

- Process waiting in kernel mode
- Process waiting in user mode
- Process queued on priority level 3
Traditional UNIX Scheduler

• The highest priority (lower number) is scheduled
• Priorities are re-calculated once per second, and re-inserted in appropriate queue
  – Avoid starvation of low priority threads
  – Penalise CPU-bound threads
Traditional UNIX Scheduler

- **Priority = CPU\_usage +nice +base**
  - **CPU\_usage** = number of clock ticks
    - Decays over time to avoid permanently penalising the process
  - **Nice** is a value given to the process by a user to permanently boost or reduce its priority
    - Reduce priority of background jobs
  - **Base** is a set of hardwired, negative values used to boost priority of I/O bound system activities
    - Swapper, disk I/O, Character I/O
Multiprocessor Scheduling

• Given $X$ processes (or threads) and $Y$ CPUs,
  – how do we allocate them to the CPUs
A Single Shared Ready Queue

- When a CPU goes idle, it takes the highest priority process from the shared ready queue.

![Diagram](image)
Single Shared Ready Queue

• **Pros**
  – Simple
  – Automatic load balancing

• **Cons**
  – Lock contention on the ready queue can be a major bottleneck
    • Due to frequent scheduling or many CPUs or both
  – Not all CPUs are equal
    • The last CPU a process ran on is likely to have more related entries in the cache.
Affinity Scheduling

• Basic Idea
  – Try hard to run a process on the CPU it ran on last time

• One approach: *Multiple Queue Multiprocessor Scheduling*
Multiple Queue SMP Scheduling

- Each CPU has its own ready queue
- Coarse-grained algorithm assigns processes to CPUs
  - Defines their affinity, and roughly balances the load
- The bottom-level fine-grained scheduler:
  - Is the frequently invoked scheduler (e.g. on blocking on I/O, a lock, or exhausting a timeslice)
  - Runs on each CPU and selects from its own ready queue
    - Ensures affinity
  - If nothing is available from the local ready queue, it runs a process from another CPUs ready queue rather than go idle
    - Termed “Work stealing”
Multiple Queue SMP Scheduling

• Pros
  – No lock contention on per-CPU ready queues in the (hopefully) common case
  – Load balancing to avoid idle queues
  – Automatic affinity to a single CPU for more cache friendly behaviour