Operating Systems

Steven Hand

12 lectures for CST Ia

Easter Term 2000

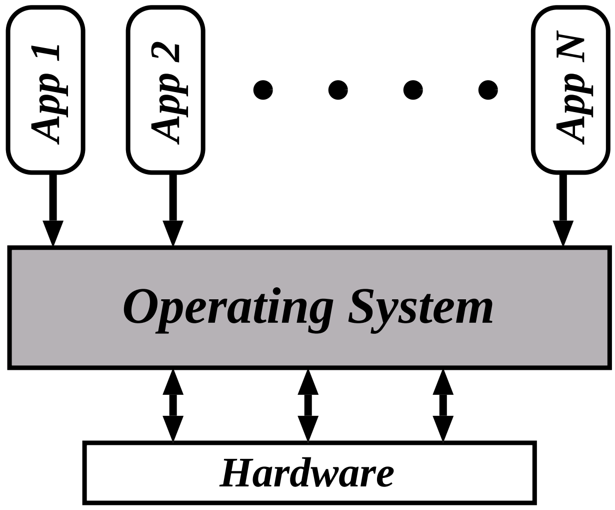
Part II: Operating System Functions

(Handout 1 of 2)

What is an Operating System?

- A program which controls the execution of all other programs (applications).
- Acts as an intermediary between the user(s) and the computer.
- Objectives:
  - convenience,
  - efficiency,
  - extensibility.
- Similar to a government ...

An Abstract View



- The Operating System (OS):
  - controls all execution.
  - multiplexes resources between applications.
  - abstracts away from complexity.
- Typically also have some *libraries* and some *tools* provided with OS.
- Are these part of the OS? Is IE4 a tool?
  - no-one can agree ...
- For us, the OS $\approx$ the *kernel*.

In The Beginning ...

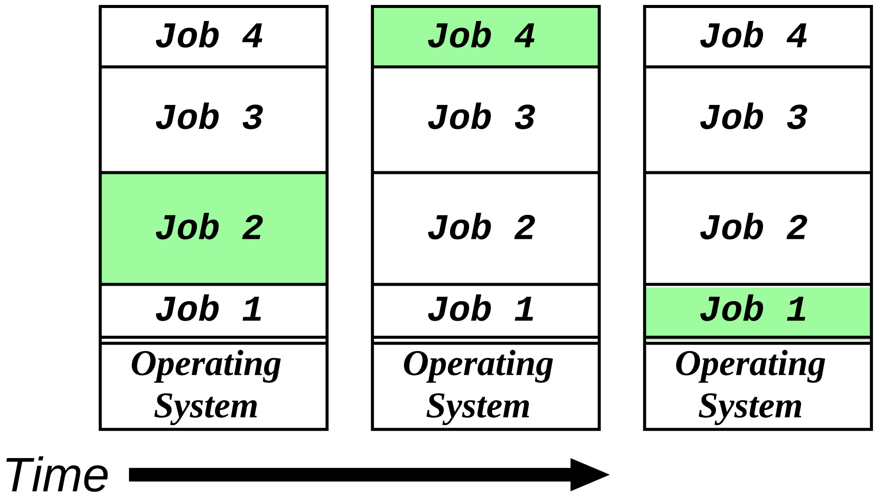
- 1949: First stored-program machine (EDSAC)
- to ~ 1955: "Open Shop".
  - large machines with vacuum tubes.
  - I/O by paper tape / punch cards.
  - user = programmer = operator.
- To reduce cost, hire an *operator*:
  - programmers write programs and submit tape/cards to operator.
  - operator feeds cards, collects output from printer.
- Management like it.
- Programmers hate it.
- Operators hate it.

⇒ need something better.

Batch Systems

- Introduction of tape drives allow *batching* of jobs:
  - programmers put jobs on cards as before.
  - all cards read onto a tape.
  - operator carries input tape to computer.
  - results written to output tape.
  - output tape taken to printer.
- Computer now has a *resident monitor*:
  - Initially control is in monitor.
  - Monitor reads job and transfer control.
  - At end of job, control transfers back to monitor.
- Even better: *spooling systems*.
  - use interrupt driven I/O.
  - use magnetic disk to cache input tape.
  - fire operator.
- Monitor now *schedules* jobs ...

Multi-Programming

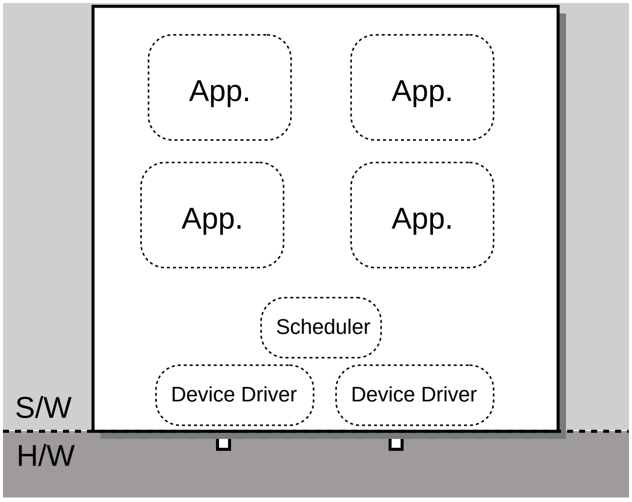


- Use memory to cache jobs from disk ⇒ more than one job active simultaneously.
- Two stage scheduling:
  1. select jobs to load: *job scheduling*.
  2. select resident job to run: *CPU scheduling*.
- Users want more interaction ⇒ *time-sharing*:
- e.g. CTSS, TSO, Unix, VMS, Windows NT ...

Today and Tomorrow

- Single user systems: cheap and cheerful.
  - personal computers.
  - no other users $\Rightarrow$ ignore protection.
  - e.g. DOS, Windows, Win 95/98, ...
- RT Systems: power is nothing without control.
  - hard-real time: nuclear reactor safety monitor.
  - soft-real time: mp3 player.
- Parallel Processing: the need for speed.
  - SMP: 2–8 processors in a box.
  - MIMD: super-computing.
- Distributed computing: global processing?
  - Java: the network is the computer.
  - CORBA: the computer is the network.

Monolithic Operating Systems



- Oldest kind of OS structure ("modern" examples are DOS, original MacOS)
- Problem: applications can e.g.
  - trash OS software.
  - trash another application.
  - hoard CPU time.
  - abuse I/O devices.
  - etc ...
- No good for fault containment (or multi-user).
- Need a better solution ...

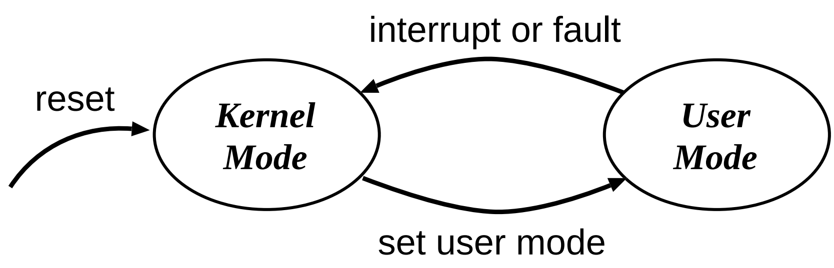
Dual-Mode Operation

- Want to stop buggy (or malicious) program from doing bad things.

⇒ provide *hardware* support to differentiate between (at least) two modes of operation.

1. *User Mode* : when executing on behalf of a user (i.e. application programs).
2. *Kernel Mode* : when executing on behalf of the operating system.

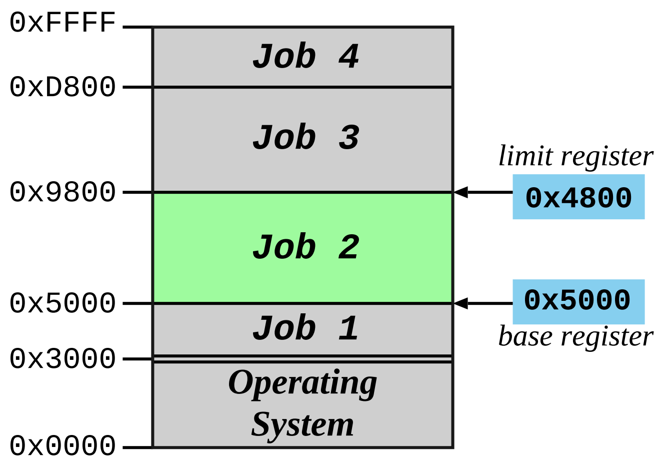
- Hardware contains a mode-bit, e.g. 0 means kernel, 1 means user.



- Certain machine instructions only possible in kernel mode . . .

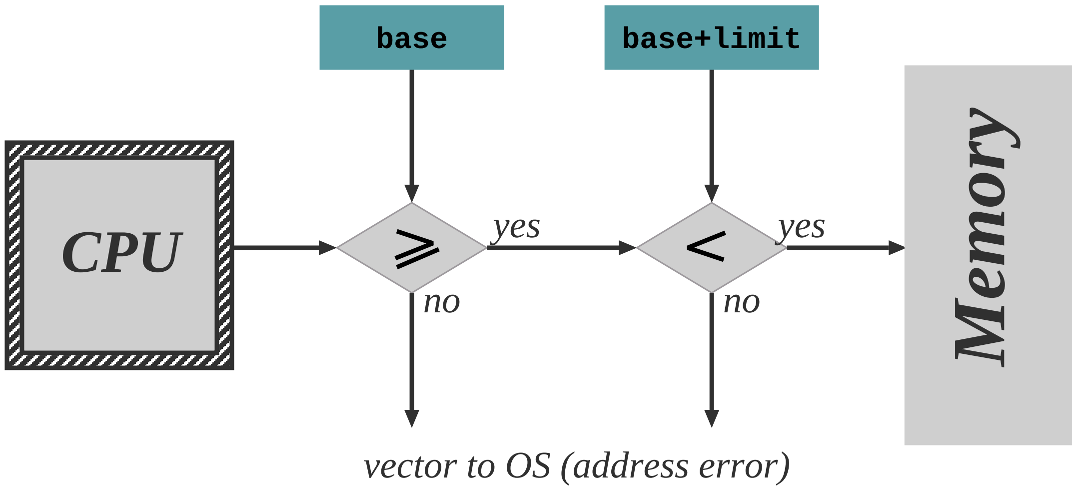
Protecting I/O & Memory

- First try: make I/O instructions privileged.
  - applications can't mask interrupts.
  - applications can't control I/O devices.
- But:
  1. Application can rewrite interrupt vectors.
  2. Some devices accessed via *memory*
- Hence need to protect memory also ...
- e.g. define a *base* and a *limit* for each program.



- Accesses outside allowed range are protected.

Protection Hardware



- Hardware checks every memory reference.
- Access out of range ⇒ vector into operating system (just as for an interrupt).
- Only allow *update* of base and limit registers in kernel mode.
- Typically disable memory protection in kernel mode (although a bad idea).
- Other hardware protection schemes possible ...

Protecting the CPU

- Need to ensure that the OS stays in control.

  $\Rightarrow$ use a *timer*.

- Usually use a *countdown* timer, e.g.
  1. Set timer to initial value (e.g. `0xFFFF`).
  2. Every *tick* (e.g. $1 \mu s$), timer decrements value.
  3. When value hits zero, interrupt.

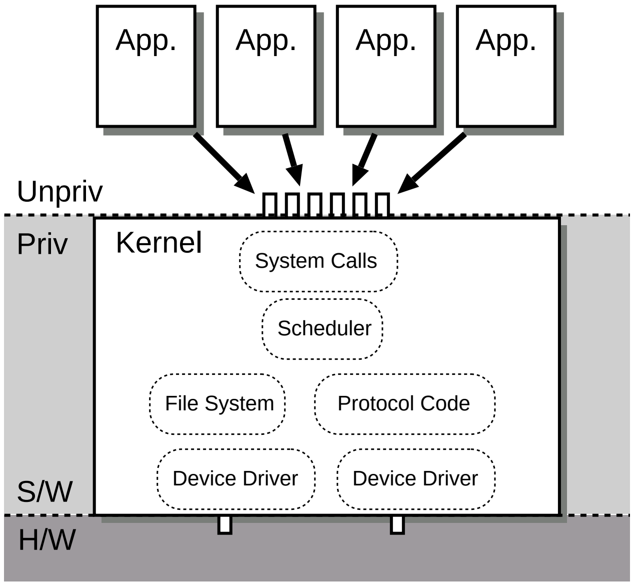
- (Modern timers have programmable tick rate.)

- Hence OS gets to run periodically and do its stuff.

- Need to ensure only OS can load timer, and that interrupt cannot be masked.
  – use same scheme as for other devices.

- Same scheme can be used to implement time-sharing.

Kernel-Based Operating Systems



- Applications can't do I/O due to protection

  ⇒ operating system does it on their behalf.

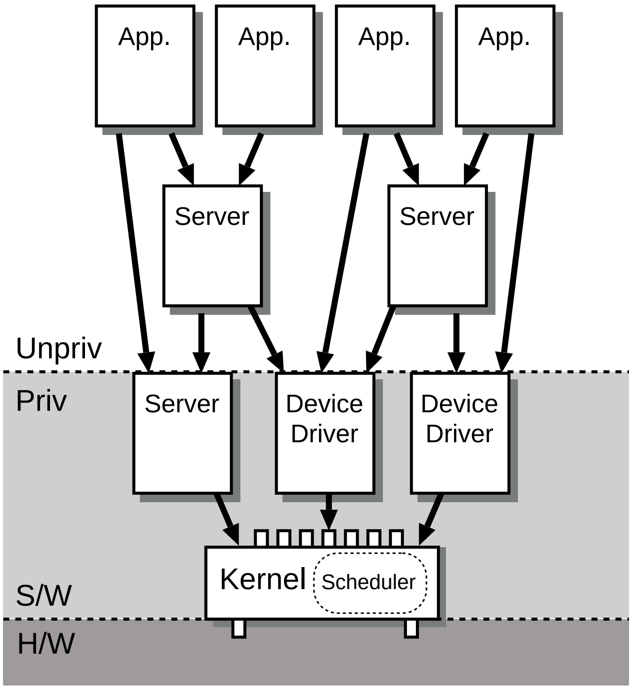
- Need secure way for application to invoke operating system:

  ⇒ require a special (unprivileged) instruction to allow transition from user to kernel mode.

- Generally called a *software interrupt* since operates similarly to (hardware) interrupt . . .

- Set of OS services accessible via software interrupt mechanism called *system calls*.

Microkernel Operating Systems



- Alternative structure:
  - Push some OS services into *servers*.
  - Servers may be privileged (i.e. operate in kernel mode).
- Increases both *modularity* and *extensibility*.
- Still access kernel via system calls, but need new way to access servers:

  ⇒ interprocess communication (IPC) schemes.

Kernels versus Microkernels

- Lots of IPC adds overhead

  $\Rightarrow$ microkernels usually perform less well.

- Microkernel implementation sometimes tricky: need to worry about synchronisation.

- Microkernels often end up with redundant copies of OS data structures.

$\Rightarrow$ today most common operating systems blur the distinction between kernel and microkernel.

- e.g. linux is “kernel”, but has kernel modules and certain servers.

- e.g. Windows NT was originally microkernel (3.5), but now (4.0) pushed lots back into kernel for performance.

- Still not clear what the best OS structure is, or how much it really matters ...

Operating System Functions

- Regardless of structure, OS needs to *securely multiplex resources*, i.e.

  1. protect applications from each other, yet
  2. share physical resources between them.

- Also usually want to *abstract* away from grungy harware, i.e. OS provides a *virtual machine*:

  – share CPU (in time) and provide a virtual processor,

  – allocate and protect memory and provide a virtual address space,

  – present (relatively) hardware independent virtual devices.

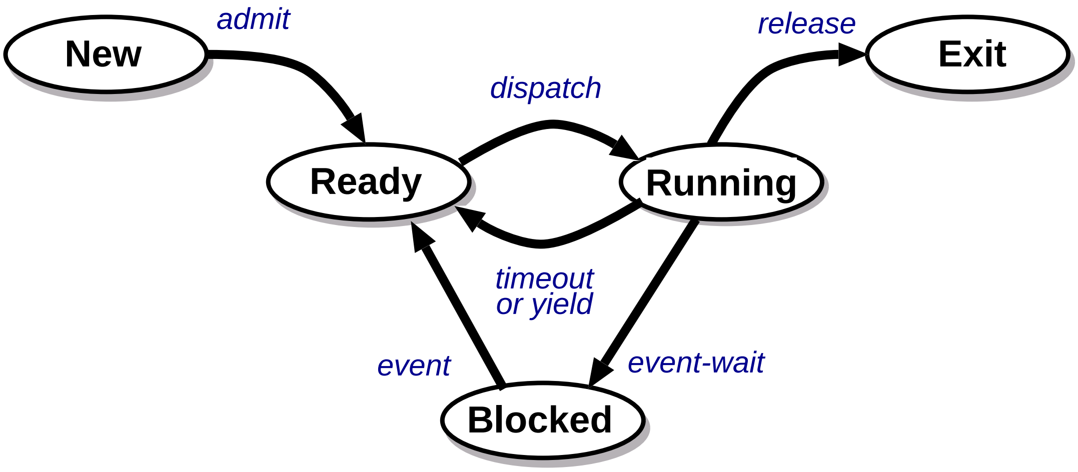
  – divide up storage space by using filing systems.

- Remainder of this part of the course will look at each of the above areas in turn ...

Process Concept

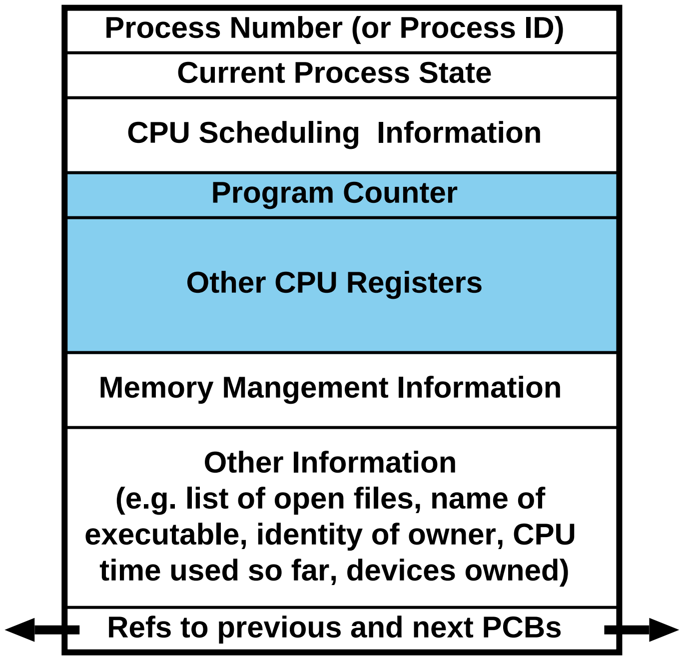
- From user's point of view, the operating system is there to execute programs:
  - on batch system, refer to *jobs*
  - on interactive system, refer to *processes*
  - (we'll use both terms fairly interchangeably)
- Process $\neq$ Program:
  - A program is *static*, while a process is *dynamic*
  - In fact, a process $\triangleq$ "a program in execution"
- (Note: "program" here is pretty low level, i.e. native machine code or *executable*)
- Process includes:
  1. program counter
  2. stack
  3. data section
- Processes execute on *virtual processors*

Process States



- As a process executes, it changes *state*:
  - *New*: the process is being created
  - *Running*: instructions are being executed
  - *Ready*: the process is waiting for the CPU (and is prepared to run at any time)
  - *Blocked*: the process is waiting for some event to occur (and cannot run until it does)
  - *Exit*: the process has finished execution.
- The operating system is responsible for maintaining the state of each process.

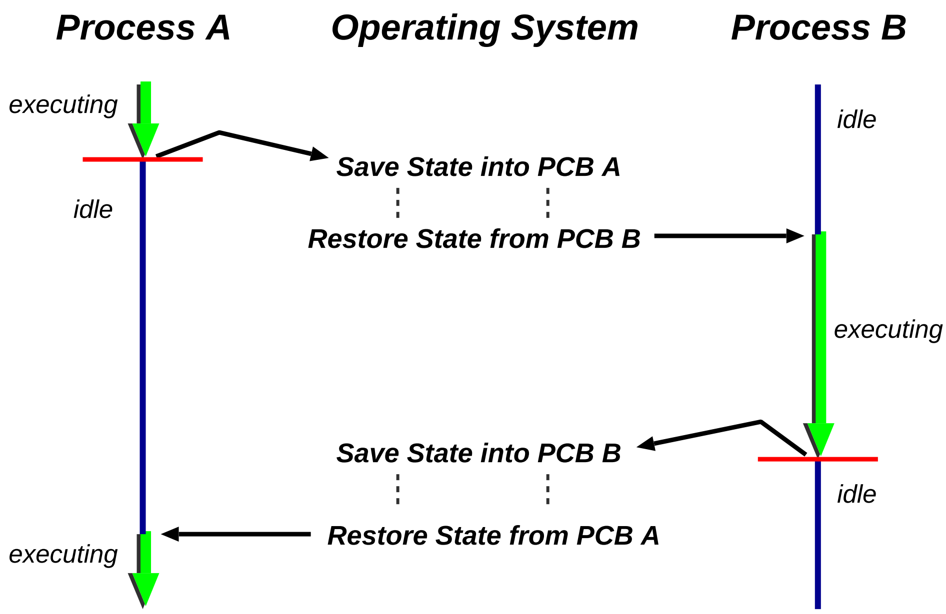
Process Control Block



OS maintains information about every process in a data structure called a *process control block* (PCB):

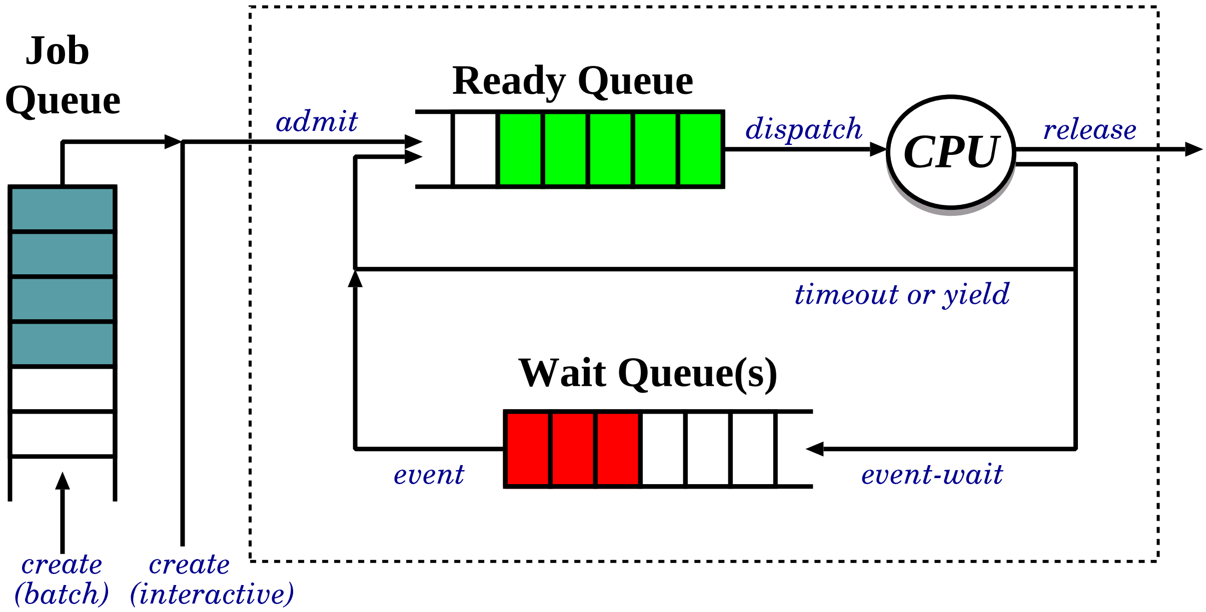
- Unique process identifier
- Process state (*Running*, *Ready*, etc.)
- CPU scheduling & accounting information
- Program counter & CPU Registers
- Memory management information
- ...

Context Switching



- *process context* = machine environment during the time the process is actively using the CPU.
- i.e. context includes program counter, general purpose registers, processor status register, . . .
- To switch between processes, the OS must:
  a) save the context of the currently executing process (if any), and
  b) restore the context of that being resumed.
- Time taken depends on h/w support.

Scheduling Queues



- Job Queue: batch processes awaiting admission.
- Ready Queue: set of all processes residing in main memory, ready and waiting to execute.
- Wait Queue(s): set of processes waiting for an I/O device (or for other processes)
- Long-term & short-term schedulers:
  - *Job scheduler* selects which processes should be brought into the ready queue.
  - *CPU scheduler* selects which process should be executed next and allocates CPU.

Process Creation

- Nearly all systems are *hierarchical*: parent processes create children processes.
- Resource sharing:
  - Parent and children share all resources.
  - Children share subset of parent's resources.
  - Parent and child share no resources.
- Execution:
  - Parent and children execute concurrently.
  - Parent waits until children terminate.
- Address space:
  - Child duplicate of parent.
  - Child has a program loaded into it.
- E.g. Unix:
  - `fork()` system call creates a new process
  - all resources shared (child is a clone).
  - `execve()` system call used to replace the process' memory space with a new program.
- NT/2000: `CreateProcess()` system call includes name of program to be executed.

Process Termination

- Process executes last statement and asks the operating system to delete it (**exit**):
  - Output data from child to parent (**wait**)
  - Process' resources are deallocated by the OS.
- Process performs an illegal operation, e.g.
  - makes an attempt to access memory to which it is not authorised,
  - attempts to execute a privileged instruction
- Parent may terminate execution of child processes (**abort**, **kill**), e.g. because
  - Child has exceeded allocated resources
  - Task assigned to child is no longer required
  - Parent is exiting ("cascading termination")
  - (many operating systems do not allow a child to continue if its parent terminates)
- E.g. Unix has `wait()`, `exit()` and `kill()`
- E.g. NT/2000 has `ExitProcess()` for self and `TerminateProcess()` for others.

Process Blocking

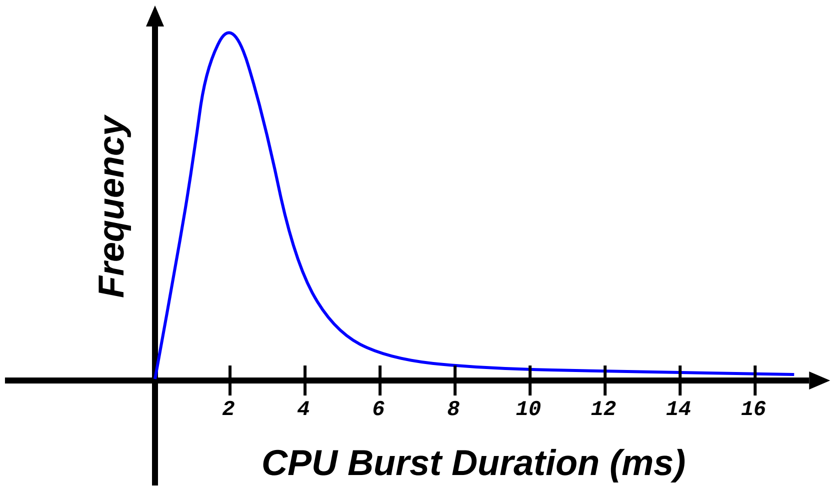
- In general a process blocks on an *event*, e.g.
  - an I/O device completes an operation,
  - another process sends a message
- Assume OS provides some kind of general-purpose blocking primitive, e.g. `await()`.
- Need care handling concurrency issues, e.g.

```
if(no key being pressed) {
   await(keypress);
   print("Key has been pressed!\n");
}
// handle keyboard input
```

  What happens if a key is pressed at the first '{' ?

- (This is a *big* area: lots more detail next year.)
- In this course we'll assume problems of this sort do not arise.

CPU-I/O Burst Cycle



- CPU-I/O Burst Cycle: process execution consists of a *cycle* of CPU execution and I/O wait.
- Processes can be described as either:
  1. I/O-bound: a process which spends more time doing I/O that than computation; has many short CPU bursts.
  2. CPU-bound: a process which spends more time doing computations; has few very long CPU bursts.
- Observe most processes execute for at most a few milliseconds before blocking

$\Rightarrow$ need multiprogramming to obtain decent overall CPU utilization.

CPU Scheduler

Recall: CPU scheduler selects one of the ready processes and allocates the CPU to it.

- Can choose a new process to run when:
  1. a running process blocks (`running` → `blocked`)
  2. a timer expires (`running` → `ready`)
  3. a waiting process unblocks (`blocked` → `ready`)
  4. a process terminates (`running` → `exit`)
- If only make scheduling decision under 1, 4 ⇒ have a *non-preemptive* scheduler:
  - ✔ simple to implement
  - ✘ open to denial of service
    - e.g. Windows 3.11.
- Otherwise the scheduler is *preemptive*.
  - ✔ solves DoS problem
  - ✘ introduces concurrency problems . . .

Idle system

What do we do if there is no ready process?

- halt processor (until interrupt arrives)
  - ✔ saves power (and heat!)
  - ✘ might take too long.
- busy wait in scheduler
  - ✔ quick response time
  - ✘ ugly, useless
- invent idle process, always available to run
  - ✔ gives uniform structure
  - ✔ could use it to run checks
  - ✘ uses some memory
  - ✘ can slow interrupt response

Scheduling Criteria

A variety of metrics may be used:

1. CPU utilization: the fraction of the time the CPU is being used (and not for idle process!)

2. Throughput: # of processes that complete their execution per time unit.

3. Turnaround time: amount of time to execute a particular process.

4. Waiting time: amount of time a process has been waiting in the ready queue.

5. Response time: amount of time it takes from when a request was submitted until the first response is produced (in time-sharing systems)

Sensible scheduling strategies might be:

- Maximize throughput or CPU utilization

- Minimize average turnaround time, waiting time or response time.

Also need to worry about *fairness* and *liveness*.

First-Come, First-Served (FCFS) Scheduling

- Depends on order processes arrive, e.g.

Process	Burst Time
P_1	25
P_2	4
P_3	9

- If processes arrive in the order P_1, P_2, P_3:

  - Waiting time for P_1=0; P_2=25; P_3=29;
  - Average waiting time: $(0 + 25 + 29)/3 = 18$.

- If processes arrive in the order P_3, P_2, P_1:

  - Waiting time for P_1=13; P_2=8; P_3=0;
  - Average waiting time: $(13 + 8 + 0)/3 = 7$.
  - i.e. over twice as good!

- First case poor due to *convoy effect*.

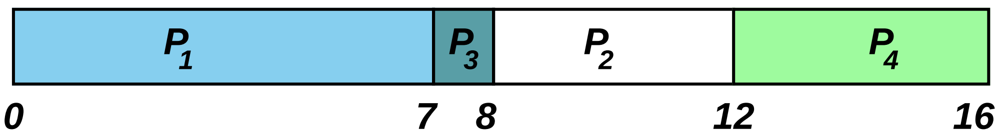
SJF Scheduling

Intuition from FCFS leads us to *shortest job first* (SJF) scheduling.

- Associate with each process the length of its next CPU burst.
- Use these lengths to schedule the process with the shortest time.
- (FCFS can be used to break ties.)

For example:

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4



- Waiting time for P_1=0; P_2=6; P_3=3; P_4=7;
- Average waiting time: $(0 + 6 + 2 + 7)/4 = 3.75$.

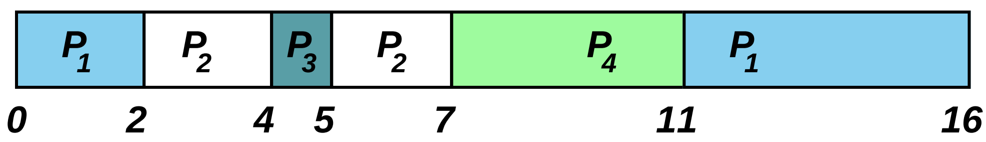
SJF is optimal in that it gives the minimum average waiting time for a given set of processes.

SRTF Scheduling

- SRTF = Shortest Remaining-Time First.
- Just a preemptive version of SJF.
- i.e. if a new process arrives with a CPU burst length less than the *remaining time* of the current executing process, preempt.

For example:

Process	Arrival Time	Burst Time
P_1	0	7
P_2	2	4
P_3	4	1
P_4	5	4



- Waiting time for P_1=9; P_2=1; P_3=0; P_4=2;
- Average waiting time: $(9 + 1 + 0 + 2)/4 = 3$.

What are the problems here?

Predicting Burst Lengths

- For both SJF and SRTF require the next "burst length" for each process $\Rightarrow$ need to estimate it.

- Can be done by using the length of previous CPU bursts, using exponential averaging:

  1. $t_n =$ actual length of n^{th} CPU burst.
  2. $\tau_{n+1} =$ predicted value for next CPU burst.
  3. For $\alpha, 0 \leq \alpha \leq 1$ define:

  $$\tau_{n+1} = \alpha t_n + (1 - \alpha)\tau_n$$

- If we expand the formula we get:

  $$\tau_{n+1} = \alpha t_n + \ldots + (1 - \alpha)^j \alpha t_{n-j} + \ldots + (1 - \alpha)^{n+1}\tau_0$$

- Choose value of α according to our belief about the system, e.g. if we believe history irrelevant, choose $\alpha \approx 1$ and then get $\tau_{n+1} \approx t_n$.

- In general an exponential averaging scheme is a good predictor if the variance is small.

Round Robin Scheduling

Define a small fixed unit of time called a *quantum* (or *time-slice*), typically 10-100 milliseconds. Then:

- Process at the front of the ready queue is allocated the CPU for (up to) one quantum.
- When the time has elapsed, the process is preempted and appended to the ready queue.

Round robin has some nice properties:

- Fair: if there are n processes in the ready queue and the time quantum is q, then each process gets $1/n^{\text{th}}$ of the CPU.
- Live: no process waits more than $(n-1)q$ time units before receiving a CPU allocation.
- Typically get higher average turnaround time than SRTF, but better average *response time*.

But tricky choosing correct size quantum:

- q too large $\Rightarrow$ FCFS/FIFO
- q too small $\Rightarrow$ context switch overhead too high.

Static Priority Scheduling

- A priority value (an integer) is associated with each process.

- The CPU is allocated to the process with the highest priority (smallest integer $\equiv$ highest priority)
  - preemptive
  - non-preemptive

- e.g. SJF is a priority scheduling algorithm where priority is the predicted next CPU burst time.

- Problem: how to resolve ties?
  - round robin with time-slicing
  - allocate quantum to each process in turn.
  - Problem: biased towards CPU intensive jobs.
    - ∗ per-process quantum based on usage?
    - ∗ ignore?

- Problem: starvation ...

Dynamic Priority Scheduling

- Use same scheduling algorithm, but allow priorities to change over time.
- e.g. simple aging:
  - processes have a (static) *base priority* and a dynamic *effective priority*.
  - if process starved for k seconds, increment effective priority.
  - once process runs, reset effective priority.
- e.g. computed priority:
  - First used in Dijkstra's THE
  - time slots: ... , t, $t+1$, ...
  - in each time slot t, measure the CPU usage of process j: u^j
  - priority for process j in slot $t+1$: $p^j_{t+1} = f(u^j_t, p^j_t, u^j_{t-1}, p^j_{t-1}, \ldots)$
  - e.g. $p^j_{t+1} = p^j_t/2 + ku^j_t$
  - penalises CPU bound → supports I/O bound.
- today such computation considered acceptable ...

Multilevel Queue

- Ready queue partitioned into separate queues, e.g.
  - foreground (interactive),
  - background (batch)
- Each queue has its own scheduling algorithm, e.g.
  - foreground: RR,
  - background: FCFS
- Scheduling must also be done between the queues:
  - Fixed priority scheduling; i.e., serve all from foreground and then from background.
  - Time slice: each queue gets a certain amount of CPU time which it can divide between its processes, e.g. 80% to foreground via RR, 20% to background in FCFS.
- Also get *multilevel feedback queue*:
  - as above, but processes can move between the various queues.
  - can be used to implement dynamic priority schemes, among others.