Advanced Operating Systems: Three Easy Pieces

1. Virtualization:
1.1 The CPU

Outline

- **Process** and **thread:**
  - Abstraction
  - Interlude (intervening)
- **Ensuring Processes cannot harm each other** – System Calls
- **Scheduling**: separation of policy and mechanism
- **Multiprocessor** scheduling
- **Multi-level Feedback Queue**: MLFQ

- The abstraction
- Interlude

Process and Threads

The Abstraction: The Process

How to provide the illusion of many CPUs?

- **CPU virtualizing**
  - **The OS can promote** the illusion that many virtual CPUs exist.
  - **Time sharing**: Running one process, then stopping it and running another
    - The potential cost (context switch) is a performance issue.

A Process

A process is a running program / program in execution.

- **A process Comprises of:**
  - **Memory (address space)**
    - Instructions
    - Data section
  - **Registers**
    - Program Counter (PC)
    - Stack Pointer (SP)
  - **Data structures** to help the OS manage the process

Process API

- **These APIs are available on any modern OS:**
  - **Create**
    - Create a new process to run a program
  - **Destroy**
    - Halt a runaway process
  - **Wait**
    - Wait for a process to stop running
  - **Miscellaneous Control (Suspend/Resume)**
    - Some kind of method to suspend a process and then resume it
  - **Status**
    - Get some status info about a process

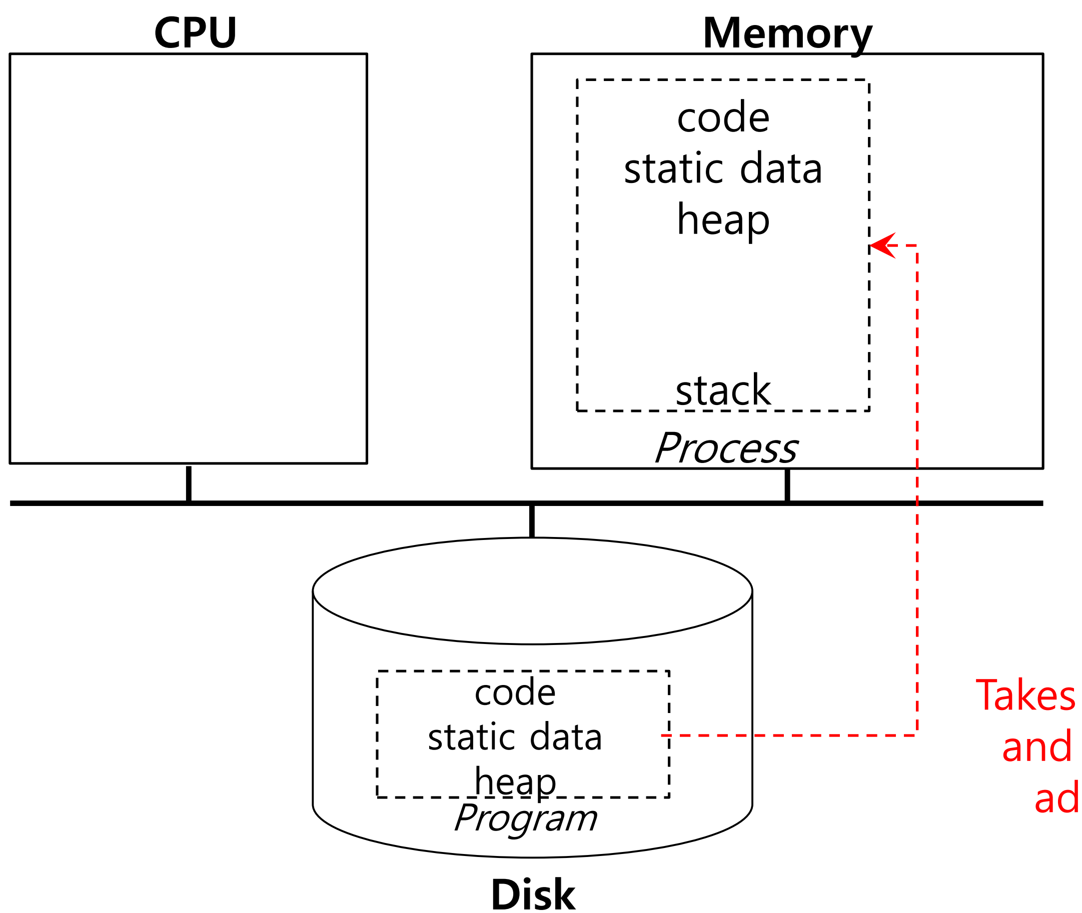
Process Creation

1. **Load** a program code into memory, into the address space of the process:
   - Programs initially reside on disk in *executable format*.
   - OS performs the loading process lazily (i.e., partial load):
     - Loading pieces of code or data (dynamic loader) only as they are needed during program execution.
2. **The program's** run-time **stack** is allocated.
   - **Use the stack for** *local variables*, *function parameters*, and *return address*.
   - **Initialize the stack with arguments** → as an example, argc and the argv array of main() function

Process Creation (Cont.)

3. **The program's heap** is created.
   - Used for explicitly requested dynamically allocated memory.
   - Program request such space by calling malloc() and free it by calling free().
4. **The OS** do some other initialization tasks:
   - **input/output (I/O) setup**
     - Each process by default has three open file descriptors, i.e., Standard input, output and error
5. **Start the program** running at the entry point, namely main().
   - **The OS *transfers control*** of the CPU to the newly-created process.

Loading: From Program To Process

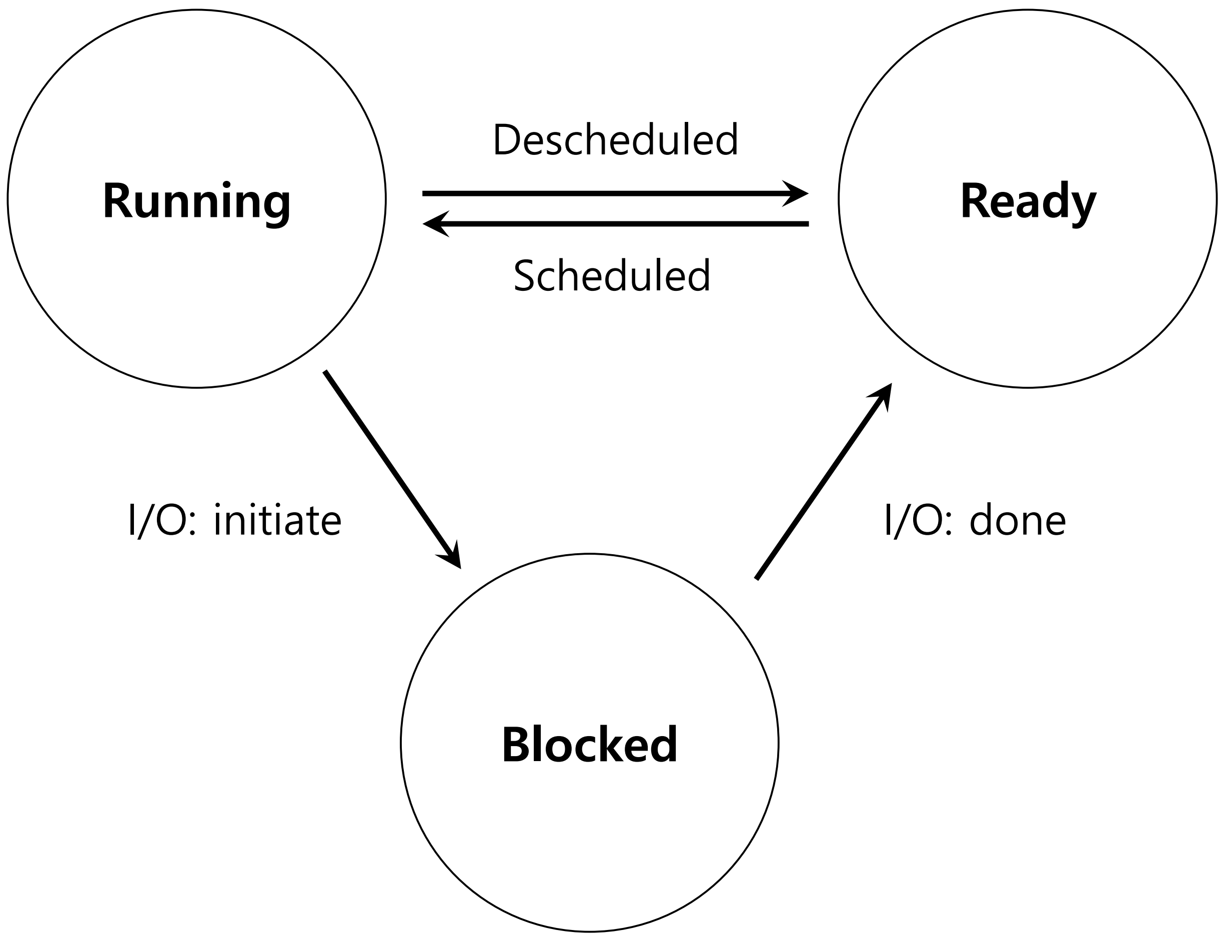


Loading:
Takes on-disk program and write it into the address space of process

Process States

- **A process can be one of three states**:
  - **Running**
    - A process is running on a processor.
  - **Ready**
    - A process is ready to run but for some reason the OS has chosen not to run it at this given moment.
  - **Blocked**
    - A process has performed some kind of I/O operation.
    - When a process initiates an I/O request to a disk, it becomes blocked and thus some other process can use the processor.

Process State Transition



Data structures

- **The OS** has some key data structures that track various relevant pieces of information.
  - **Process list/queue**
    - Ready processes queue
    - Blocked processes queue
    - Current running process
  - **Register context**
- **PCB(Process Control Block)**
  - A C-structure that contains information about each process such as pid, ppid, p_signal, address of u_area, etc.

Example) The xv6 kernel Proc Structure

```
// the registers xv6 will save and restore
// to stop and subsequently restart a process
struct context {
    int eip;   // Index pointer register
    int esp;   // Stack pointer register
    int ebx;   // Called the base register
    int ecx;   // Called the counter register
    int edx;   // Called the data register
    int esi;   // Source index register
    int edi;   // Destination index register
    int ebp;   // Stack base pointer register
};

// the different states a process can be in
enum proc_state { UNUSED, EMBRYO, SLEEPING,
                  RUNNABLE, RUNNING, ZOMBIE };
```

Example) The xv6 kernel Proc Structure (Cont.)

```
// the information xv6 tracks about each process
// including its register context and state
struct proc {
    char    *mem;                // Start of process memory
    uint    sz;                        // Size of process memory
    char    *kstack;             // Bottom of kernel stack
                                 // for this process
    enum    proc_state state;    // Process state
    int     pid;                 // Process ID
    struct proc *parent;         // Parent process
    void    *chan;               // If non-zero, sleeping on chan
    int     killed;              // If non-zero, have been killed
    struct file *ofile[NOFILE]; // Open files
    struct inode *cwd;           // Current directory
    struct context context;      // Switch here to run process
    struct trapframe *tf;        // Trap frame for the
    ….                           // current interrupt
};
```

Interlude: Process API

The fork() System Call

- **Create a new process**
  - The newly-created process has its own copy of the **address space**, **registers**, and **PC**.

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

int main(int argc, char *argv[]){
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {          // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
    } else {              // parent goes down this path (main)
        printf("hello, I am parent of %d (pid:%d)\n",
                                        rc, (int) getpid());
    }
    return 0;
}
```

Calling fork() example (Cont.)

Result (Not deterministic)

No guarantee if it is the parent or the child will resume execution first?

```
prompt> ./p1
hello world (pid:29146)
hello, I am parent of 29147 (pid:29146)
hello, I am child (pid:29147)
prompt>
```

or

```
prompt> ./p1
hello world (pid:29146)
hello, I am child (pid:29147)
hello, I am parent of 29147 (pid:29146)
prompt>
```

The wait() System Call

- This system call won’t return until the child has run and exited.

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/wait.h>

int main(int argc, char *argv[]){
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {  // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
    } else {                   // parent goes down this path (main)
        int wc = wait(NULL);    // wc = child pid that terminated
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
                                   rc, wc, (int) getpid());
    }
    return 0;
}
```

My child pid   Pid of the terminated child   My (parent) pid

The wait() System Call (Cont.)

Result (Deterministic)

Parent will wait for the child to exit before it resumes execution…

```
prompt> ./p2
hello world (pid:29266)
hello, I am child (pid:29267)
hello, I am parent of 29267 (wc:29267) (pid:29266)
prompt>
```

The exec() System Call

- Run a program that is different from the calling program:

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <sys/wait.h>

int main(int argc, char *argv[]){
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {                    // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) {            // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
        char *myargs[3];
        myargs[0] = strdup("wc");          // program: "wc" (word count)
        myargs[1] = strdup("p3.c"); // argument: file to count content
        myargs[2] = NULL;                  // marks end of array
        …
```

The exec() System Call (Cont.)

(Cont.)

```
…
        execvp(myargs[0], myargs); // runs word count ≡ wc filename
        printf("this shouldn't print out");
    } else {                        // parent goes down this path (main)
        int wc = wait(NULL);        // wc = child pid that exited
                                    // rc = pid of the child
                                    // In this csenario: wc == rc
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
                                   rc, wc, (int) getpid());
    }
    return 0;
}
```

Result

```
prompt> ./p3
hello world (pid:29383)
hello, I am child (pid:29384)
29 107 1030 p3.c
<#lines   #words   #characters  file name>
hello, I am parent of 29384 (wc:29384) (pid:29383)
prompt>
```

All of the above with redirection

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <fcntl.h>
#include <sys/wait.h>

int
main(int argc, char *argv[]){
    int rc = fork();
    if (rc < 0) {          // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child: redirect standard output to a file
        close(STDOUT_FILENO);
        open("./p4.output", O_CREAT|O_WRONLY|O_TRUNC, S_IRWXU);
        …
```

All of the above with redirection (Cont.)

(Cont.)

```
        …
        // now exec "wc"...
        char *myargs[3];
        myargs[0] = strdup("wc");           // program: "wc" (word count)
        myargs[1] = strdup("p4.c");         // argument: file to count
        myargs[2] = NULL;                   // marks end of array
        execvp(myargs[0], myargs);          // runs word count
    } else {                            // parent goes down this path (main)
        int wc = wait(NULL);
    }
    return 0;
}
```

Result

```
prompt> ./p4
prompt> cat p4.output
32 109 846 p4.c
<#lines  #words  #characters  file name>
prompt>
```

Operating System Roles?

- **What is a resource and its abstraction?**
  1. **CPU:** process and/or thread
  2. **Memory:** address space
  3. **Device/Disk:** files

Physical Resource	Abstraction
CPU	Process / Thread
Memory	Address Space
Disk	Files

Ensuring Processes cannot harm each other – System Calls

Mechanism: Limited Direct Execution

How to efficiently virtualize the CPU with control?

- The OS needs to share the physical CPU by time sharing.

- **Issues:**
  - **Performance**: How can we implement virtualization without adding excessive overhead to the system?
  - **Control**: How can we run processes efficiently while retaining control over the CPU?

Direct Execution

- Just run the program directly on the CPU:

OS	Program
1. Create entry for process list 2. Allocate memory for program 3. Load program into memory 4. Set up stack with `argc` / `argv` 5. Clear registers 6. Execute call `main()`	
	7. Run `main()` 8. Execute `return` from `main()`
9. Free memory of process 10. Remove from process list	

Without *limits* on running programs,
the OS wouldn't be in control of anything and
thus would be "just a library"

Problem 1: Restricted Operation

- **What if a process** wishes to perform some kind of restricted operation such as …
  - Issuing an I/O request to a disk
  - Gaining access to more system resources such as CPU or memory

- **Solution**: Using protected control transfer:
  - **User mode:** Applications do not have full access to hardware resources.
  - **Kernel mode:** The OS has access to the full resources of the machine

System Call

- **Allow the kernel** to carefully expose certain key pieces of functionality (i.e., provide concrete system-level services through set of system calls) to user program, such as:
  - Accessing the file system
  - Creating and destroying processes
  - Communicating with other processes
  - Allocating more memory
  - Performing any I/O

System Call (Cont.)

- **Trap** instruction
  - **Set up kernel stack** (create stack frame in kernel stack)
  - **Jump into the kernel**
  - **Raise the privilege level** to kernel mode

- **Return-from-trap** instruction
  - **Return into the calling user program** (extract stack frame from the kernel stack)
  - **Reduce the privilege level** back to user mode

Limited Direction Execution Protocol: Execute User program

OS @ boot (kernel mode)	Hardware
initialize trap table	
	remember address of … syscall handler

OS @ run (kernel mode)	Hardware	Program (user mode)
Create new entry for process[ ] Allocate memory for program. Load program into memory Setup user stack with argv Fill kernel stack with reg/PC **return-from -trap**		
	restore regs from kernel stack move to user mode jump to main	
		Run main() … Call system (system Call) **trap** into OS

time

Limited Direction Execution Protocol: Execute System Call

OS @ run (kernel mode)	Hardware	Program (user mode)
	(Cont.)	
	save regs to kernel stack move to kernel mode jump to trap handler	
Handle trap Do work of syscall **return-from-trap**		
	restore regs from kernel stack move to user mode jump to PC after trap	
		… return from main trap (via `exit()`)
Free memory of process Remove from process list		

time

Problem 2:
Switching Between Processes

- How can the OS **regain control** of the CPU so that it can switch between *processes*?
  - **A cooperative Approach**: **Wait for system calls to be issued by the user**
  - **A Non-Cooperative Approach**: **The OS takes control unilaterally**

A cooperative Approach:
Wait for system calls

- **Processes periodically give up the CPU** by making **system calls** such as yield:
  - **The OS decides** to run some other task.
  - **Application also transfer control to the OS** when they do something illegal.
    - Divide by zero (exception)
    - Try to access memory that it shouldn't be able to access (exception)
  - **Ex for Wait for system calls:** Early versions of the Macintosh OS, The old Xerox Alto system

A process gets stuck in an infinite loop – not giving up the CPU
→ Reboot the machine!

A Non-Cooperative Approach: OS Takes Control

- **A timer interrupt**
  - **During the boot sequence**, the OS starts the timer.
  - **The timer** raise an interrupt every so many milliseconds
  - **When the interrupt is raised:**
    - The currently running process is halted.
    - Save enough of the state of the program
    - A pre-configured interrupt handler in the OS runs.

A timer interrupt gives OS the ability to run and schedule the CPU.

Saving and Restoring Context

- **Scheduler makes a decision (on return from the clock interrupt):**
  - **Whether to continue/resume** running the **current process**, or switch to a **different one** (how)?
  - **If the decision is made to switch**, the OS executes <u>context switch</u>.

Context Switch

- **A low-level piece of assembly code:**
  - **Save few register values** for the current process onto its kernel stack
    - General purpose registers
    - PC
    - kernel stack pointer
  - **Restore few register values** for the soon-to-be-executing process from its kernel stack
  - **Switch to the kernel stack** for the soon-to-be-executing process

Limited Direction Execution Protocol (Timer interrupt)

OS @ boot (kernel mode)	Hardware
initialize trap table	
	remember address of … syscall handler timer handler
start interrupt timer	
	start timer interrupt CPU in X ms

OS @ run (kernel mode)	Hardware	Program (user mode)
		Process A is running Clock interrupt happens …
	timer interrupt save regs(A) to k-stack(A) move to kernel mode jump to trap handler	

Limited Direction Execution Protocol (Timer interrupt)

OS @ run (kernel mode)	Hardware	Program (user mode)
	jump to trap handler *(Cont.)*	
Handle the trap Call switch() routine save regs(A) to proc-struct(A) restore regs(B) from proc-struct(B) switch to k-stack(B) **return-from-trap (into B)**		
	restore regs(B) from k-stack(B) move to user mode jump to B's PC	
		Process B is now running …

The xv6 Context Switch Code

```
# void swtch(struct context **old, struct context *new);
#
# Save current register context in old
# and then load register context from new.
.globl swtch
swtch:
        # Save old registers (Save)
        movl 4(%esp), %eax          # put old ptr into eax
        popl 0(%eax)                # save the old IP
        movl %esp, 4(%eax)          # and stack
        movl %ebx, 8(%eax)          # and other registers
        movl %ecx, 12(%eax)
        movl %edx, 16(%eax)
        movl %esi, 20(%eax)
        movl %edi, 24(%eax)
        movl %ebp, 28(%eax)

        # Load new registers (restore)
        movl 4(%esp), %eax          # put new ptr into eax
        movl 28(%eax), %ebp         # restore other registers
        movl 24(%eax), %edi
        movl 20(%eax), %esi
        movl 16(%eax), %edx
        movl 12(%eax), %ecx
        movl 8(%eax), %ebx
        movl 4(%eax), %esp          # stack is switched here
        pushl 0(%eax)               # return addr put in place
        ret                         # finally return into new ctxt
```

Worried About Concurrency?

- **What happens if**, during interrupt or trap handling, another interrupt occurs?
- **OS handles these situations:**
  - **Disable interrupts** during interrupt processing
  - Use a number of sophisticated **locking** schemes to protect concurrent access to internal data structures.

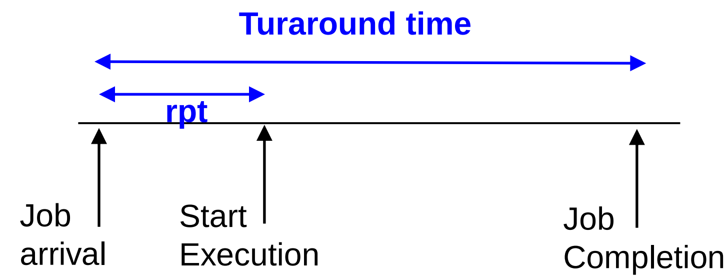
Scheduling: separation of Policy and Mechanism

Scheduling: Introduction

Scheduling: Introduction

- **Workload assumptions (for simplicity):**
  1. **Each job runs** for the **same amount of time** **(time slice).**
  2. **All jobs arrive at** the same time.
  3. **All jobs only use** the **CPU** (i.e., they perform no I/O).
  4. **The run-time** of each job is known.

Scheduling Metrics



- **Performance metric: Response time**
  - The time at which **the job start execution** minus the time at which **the job arrived** in the system.

$$T_{\text{response time}} = T_{\text{first run time}} - T_{\text{arrival time}}$$

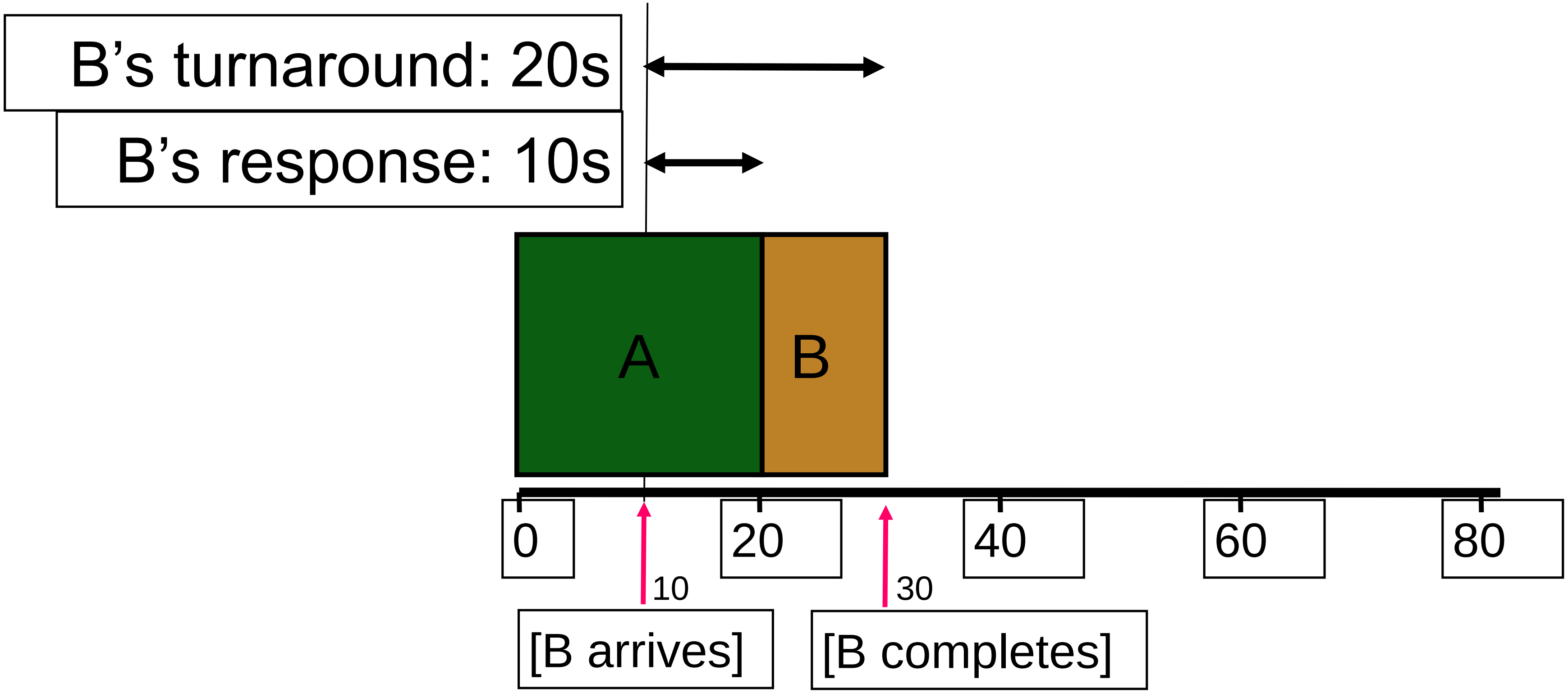
- **Performance metric: Turnaround time**
  - The time at which **the job completes** minus the time at which **the job arrived** in the system.

$$T_{turnaround} = T_{completion} - T_{arrival}$$

- **Waiting time metric: Waiting time**

$$T_{\text{waiting}} = T_{\text{turnaround}} - T_{\text{service-time}}$$

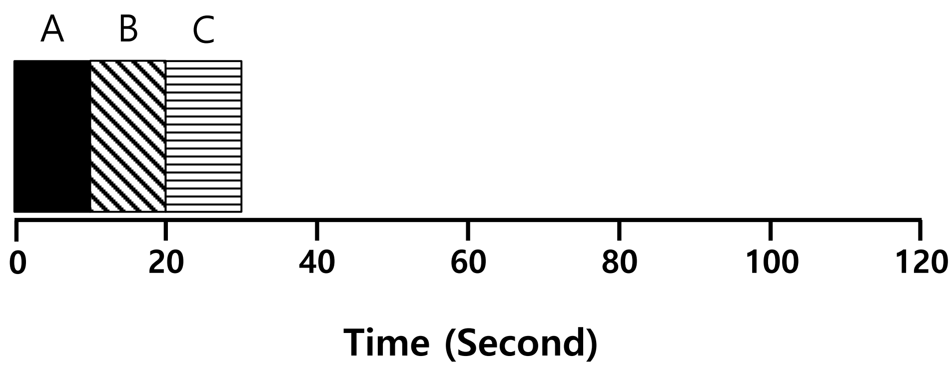
Scheduling Metrics



- **Another metric is fairness:**
  - **Performance** and **fairness** are often at odds in scheduling.

First In, First Out (FIFO)

- **First Come, First Served (FCFS)**
  - **Very simple** and easy to implement
- **Example:**
  1. **Each job** runs for 10 seconds.
  2. **A arrived** just before B which arrived just before C.

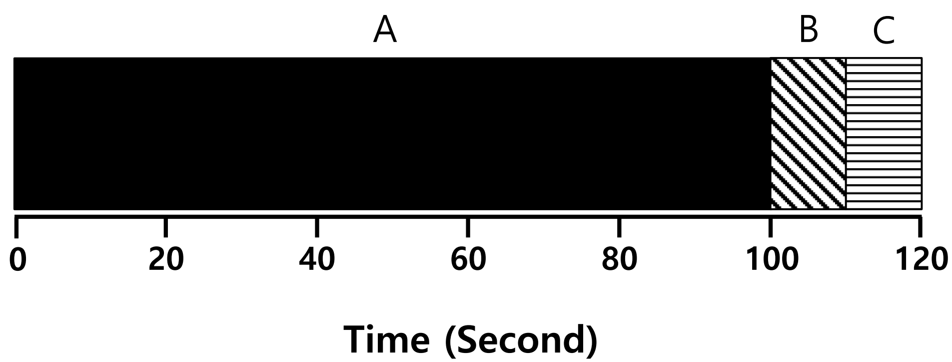


Avg TAT = 20 sec , while service time is 10 sec for A, B and C

$$Average\ turnaround\ time = \frac{10+20+30}{3} = 20\ sec$$

Why FIFO is not that great? – Convoy effect

- **Let's relax assumption-1 (pg 46):** Each job **no longer** runs for the same amount of time.
- **Example:**
  - **A runs** for 100 seconds, B and C run for 10 each.
  - **A arrived** just before B which arrived just before C.

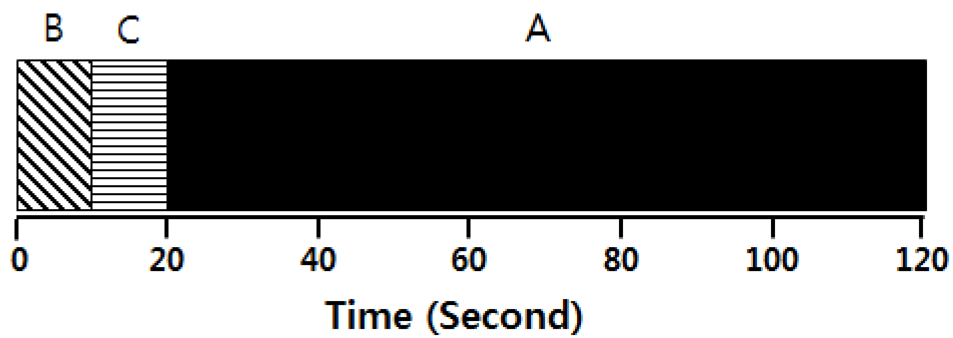


Avg TAT = 110 sec , while service time is 10 sec for B and C

$$\textit{Average turnaround time} = \frac{100 + 110 + 120}{3} = 110\ sec$$

Shortest Job First (SJF)

- **Run the shortest job first**, then the next shortest, and so on:
  - **Non-preemptive scheduler**
- **Example:**
  - A runs for 100 seconds, B and C run for 10 each.
  - A arrived just before B which arrived just before C.

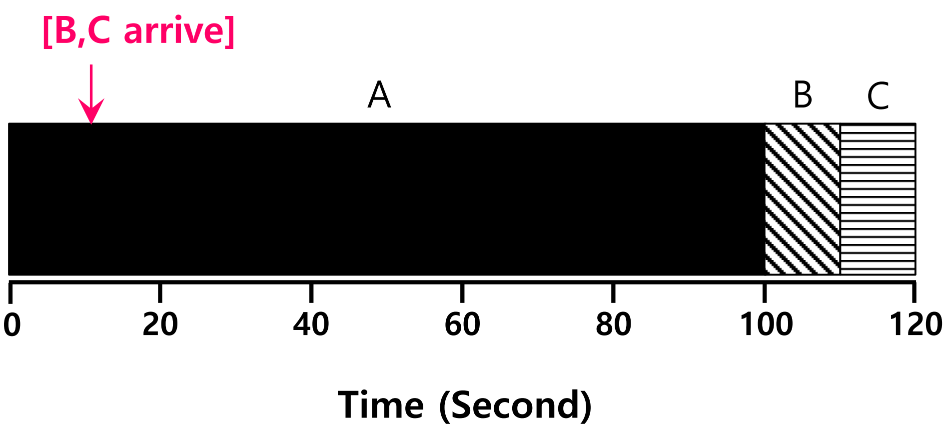


Avg TAT = 50 sec, while service time is 10 sec for B and C and 100 sec for A

$$\textit{Average turnaround time} = \frac{10 + 20 + 120}{3} = 50\ sec$$

SJF with Late Arrivals from B and C

- **Let's relax assumption 2 (pg 46):** Jobs can arrive at any time.
- **Example:**
  - A arrives at t=0 and needs to run for 100 seconds.
  - B and C arrive at t=10 and each need to run for 10 seconds.



Avg TAT = 103 sec, while service time is 10 sec for B and C

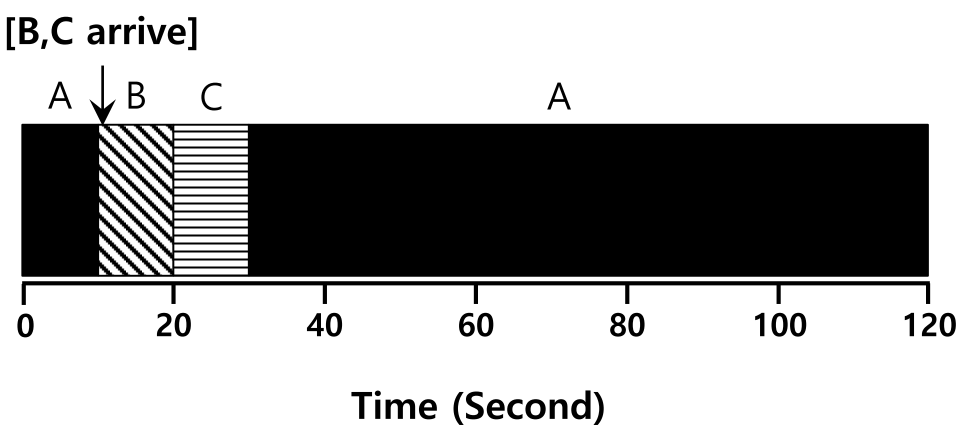
$$Average\ turnaround\ time = \frac{100 + (110 - 10) + (120 - 10)}{3} = 103.33\ sec$$

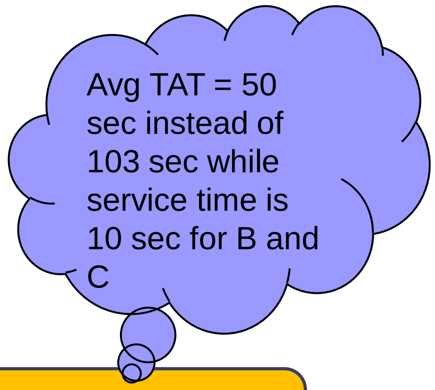
Shortest Time-to-Completion First (STCF)

- **Add preemption to SJF:**
  - Also knows as **Preemptive Shortest Job First** (PSJF)
- **A new job enters the system:**
  - Determine between the remaining time of current jobs and the new job
  - Schedule the job which has the least time left

Shortest Time-to-Completion First (STCF)

- **Example:**
  - A arrives at t=0 and needs to run for 100 seconds.
  - B and C arrive at t=10 and each need to run for 10 seconds





$$\text{Average turnaround time} = \frac{(120-0)+(20-10)+(30-10)}{3} = 50\ sec$$

New scheduling metric: Response time

- **The time from when the job arrives** to the **first time it is scheduled to run**.

$$T_{response} = T_{firstrun} - T_{arrival}$$

  - **STCF** (Shortest To Complete First) and related disciplines are not particularly good for response time.

How can we build a scheduler that is sensitive to response time?

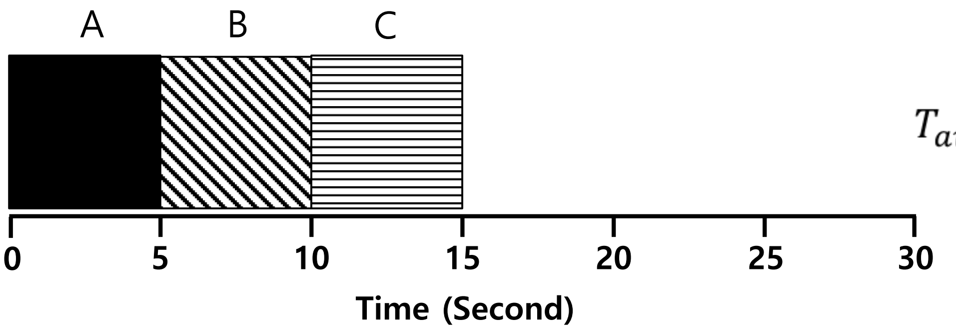
Round Robin (RR) Scheduling

- **Time slicing Scheduling**
  - **Run a job** for a time slice (say 1 sec) and then switch to the next job in the **run queue** until the jobs are finished.
    - Time slice is sometimes called a scheduling quantum.
  - **It repeatedly** does so until all jobs are finished.
  - **The length of a time slice** must be *a multiple of* the timer-interrupt period (say 20 msec).

RR is fair, but performs poorly on metrics such as turnaround time

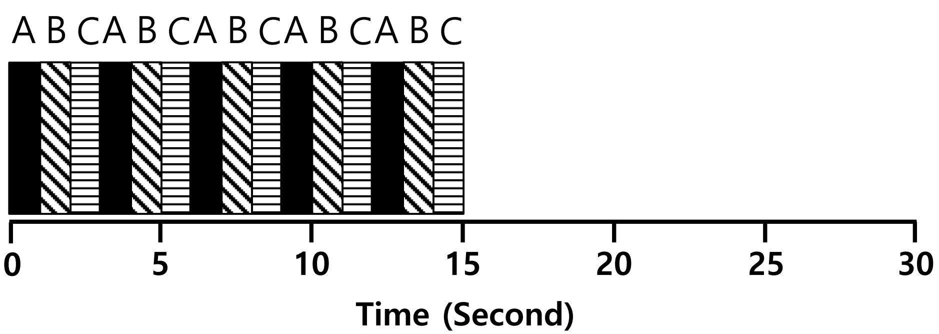
RR Scheduling Example

- A, B and C arrive at the same time.
- They each wish to run for 5 seconds.



$$T_{average\ response} = \frac{0+5+10}{3} = 5sec$$

SJF (Bad for Response Time)



$$T_{average\ response} = \frac{0+1+2}{3} = 1sec$$

RR with a time-slice of 1sec (Good for Response Time and Not for Turn-Around Time)

The length of the time slice is critical

- **The shorter time slice (RR)**
  - **Better** response time
  - **The cost of context switching** will dominate overall performance ☻.

- **The longer time slice (RR)**
  - **Amortize** the cost of switching
  - **Worse** response time

Deciding on the length of the time slice presents a trade-off to a system designer

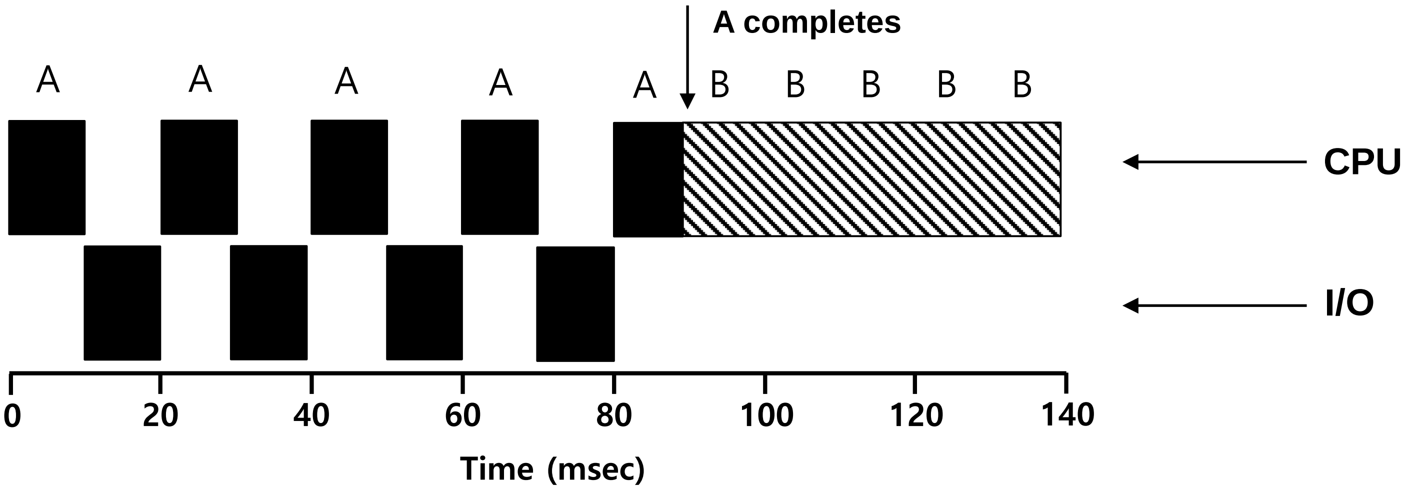
Incorporating I/O with RR

- **Let's relax assumption 3 (pg. 46)**: All programs perform I/O

- **Example:**
  - A and B need 50ms of CPU time each.
  - A runs CPU for 10ms periodically and performs an I/O between every two CPU runs, i.e., A runs 5 CPU periods and 4 I/O
    - I/Os each take 10ms
  - B simply uses the CPU for 50ms and performs no I/O
  - The scheduler runs A first, then B after

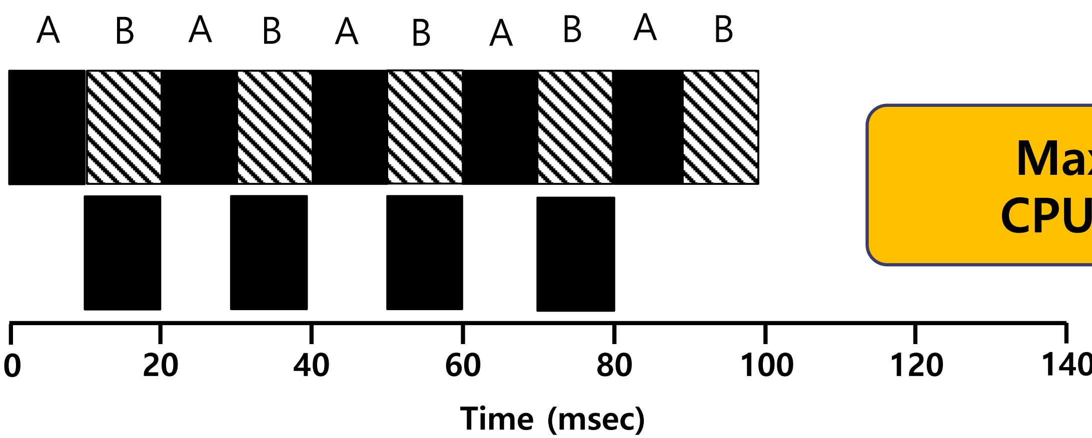
Incorporating I/O with RR (Cont.)

RPT = (0 + 90)/2
= 45
TAT = (90 + 140)/2
= 115
CPU Util = 100/140
= 71.5%



Poor Use of Resources

RPT = (0 + 10)/2
= 5
TAT = (90 + 100)/2
= 95
CPU Util = 100/100
= 100%



Overlap Allows Better Use of Resources

Maximize the CPU utilization

Incorporating I/O with RR (Cont.)

- **When a job initiates an I/O request:**
  - The job is blocked waiting for I/O completion.
  - The OS scheduler should schedule another job on the CPU.
- **When the I/O completes:**
  - An interrupt is raised.
  - The OS moves the process from blocked back to the end of the ready state.

Scheduling: Proportional Share

Proportional Share Scheduler

- **Fair-share scheduler**
  - Guarantee that each job obtain *a certain percentage* of CPU time.
  - Not optimized for turnaround time or response time

Basic Concept

- **Tickets:**
  - Represent the share of a resource that a process should receive
  - The percent of tickets represents its share of the system resource in question.

- **Example:**
  - **There are two processes, A and B and 100 total tickets:**
    - Process A has 75 tickets → receive 75% of the CPU
    - Process B has 25 tickets → receive 25% of the CPU

Lottery scheduling

- **The scheduler picks <u>a winning ticket</u>:**
  - Load the state of that *winning process* and run it.
- **Example:**
  - There are 100 tickets
    - Process A has 75 tickets: 0 ~ 74 (out of 100)
    - Process B has 25 tickets: 75 ~ 99 (out of 100)

  Generate random number between 0 - 99

Scheduler's winning tickets:	63	85	70	39	76	17	29	41	36	39	10	99	68	83	63
Resulting scheduler:	A	B	A	A	B	A	A	A	A	A	A	B	A	B	A

The longer these two jobs compete,
The more likely they are to achieve the desired percentages.

Ticket Mechanisms

- **Ticket currency:**
  - A user allocates tickets among their own jobs in whatever currency they would like.
  - The system converts the currency into the correct global value.
  - **Example:**
    - There are 200 tickets (Global currency)
    - User (Process type A) has 100 tickets & 2 processes (A1, A2)
    - User (Process type B) has 100 tickets & 1 process (B1)

User A → *500* (A's currency) to A1 → *50* (global currency)
→ *500* (A's currency) to A2 → *50* (global currency)

User B → *100* (B's currency) to B1 → *100* (global currency)

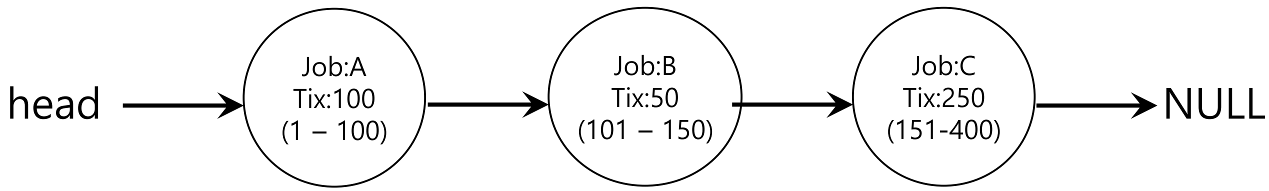
Ticket Mechanisms (Cont.)

- **Ticket transfer:**
  - A process can temporarily <u>hand off</u> *its tickets* to another process.

- **Ticket inflation:**
  - A process can <u>temporarily raise or lower</u> the number of tickets it owns.
  - If any one process needs *more CPU time*, it can boost its tickets.

Implementation

- **Example:** There are three processes, A, B, and C.
  - **Keep the processes in a list:**




```
// counter: used to track if we've found the winner yet
int counter = 0;

// winner: use some call to a random number generator to
// get a value, between 0 and the total # of tickets (400)
int winner = getrandom(0, totaltickets);

// current: use this to walk through the list of jobs
node_t *current = head;

// loop until the sum of ticket values is > the winner
while (current) {
        counter = counter + current→tickets;
        if (counter > winner)
                break; // found the winner (i.e., current)
        current = current->next;
}
// 'current' is the winner: schedule it...
```

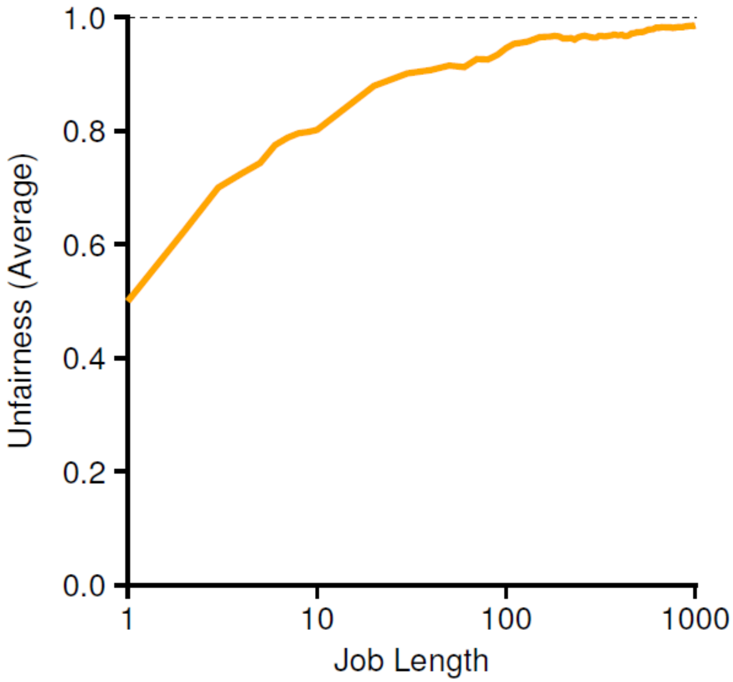
Implementation (Cont.)

- **U: unfairness metric**
  - The time the first job completes divided by the time that the second job completes. ← For equal service time $TAT_1/TAT_2 = 1$
- **Example:** Assume two jobs arrive at the same time:
  - **There are two jobs, each jobs has runtime 10:**
    - First job finishes at time 10
    - Second job finishes at time 20
  - $U = \frac{10}{20} = 0.5$
  - U will be close to 1 when both jobs finish at nearly the same time.

\# Unfairness metric is between 0.5 – 1.0
\# TAT is "Turn Around Time"

Lottery Fairness Study

- There are two jobs:
  - Each jobs has the same number of tickets (100).



When the job length (service time) is not very long,
average unfairness can be quite severe (number/small number).

Stride Scheduling

- **Stride** of each process (opposite of # of tickets)
  - Stride = (A large number) / (the number of tickets of the process)
  - **Example**: Assume a large number = 10,000
    - Process A has 100 tickets → stride of A is (10,000/100) = 100
    - Process B has 50 tickets → stride of B is (10,000/50) = 200
- Select process with lowest "Pass" value (measure for how long you ran = sum of strides process ran so far) to run (take it out of the queue); "Pass" is a measure that enables processes with high tickets (i.e., low stride) to run more frequently
- Run the selected process
- When done with the quantum, increment process "Pass" value by its "stride" value and put it back in the queue

```
current = remove_min(queue);          // pick client with minimum pass
schedule(current);                    // use resource for quantum
current->pass += current->stride;     // compute next pass using stride
insert(queue, current);               // put back into the queue
```

A pseudo code implementation

Stride Scheduling Example

Stride = 10,000 / tickets

Pass(A) tickets = 100 (stride=100)	Pass(B) Tickets = 50 (stride=200)	Pass(C) Tickets = 250 (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	…

Pass

If new job enters with pass value 0,
It will monopolize the CPU!

Multiprocessor Scheduling

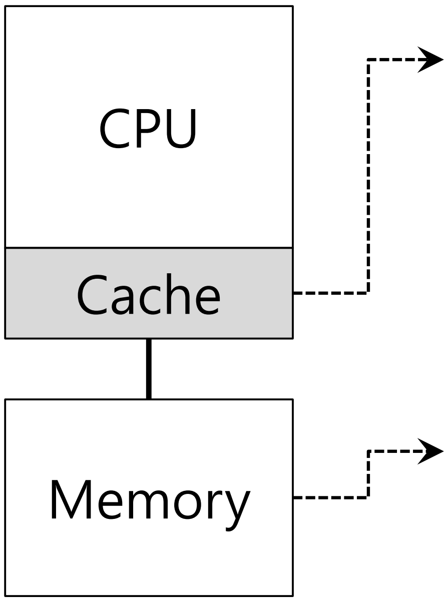
Multiprocessor Scheduling

- The rise of the **multicore processor** is the source of multiprocessor-scheduling proliferation.
  - **Multicore**: Multiple CPU cores are packed onto a single chip and sharing memory.

- Adding more CPUs <u>does not</u> make that single application run faster → You'll have to rewrite application to run in parallel, using **threads**.

How to schedule jobs on Multiple CPUs?

Single CPU with cache



Cache

- Small, fast memories
- Hold copies of popular data that is found in the main memory.
- Utilize *temporal* and *spatial* locality

Main Memory

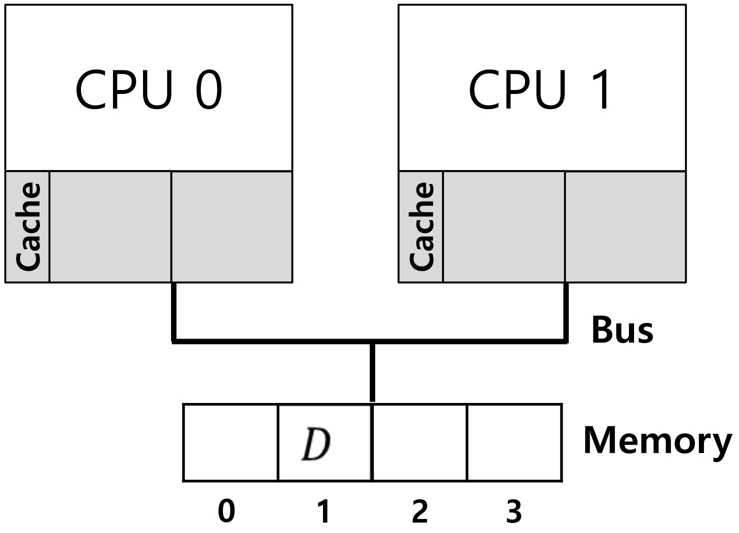
- Holds all of the data
- Access to main memory is slower than cache.

By keeping data in cache, the system can make slow memory appear to be a fast one

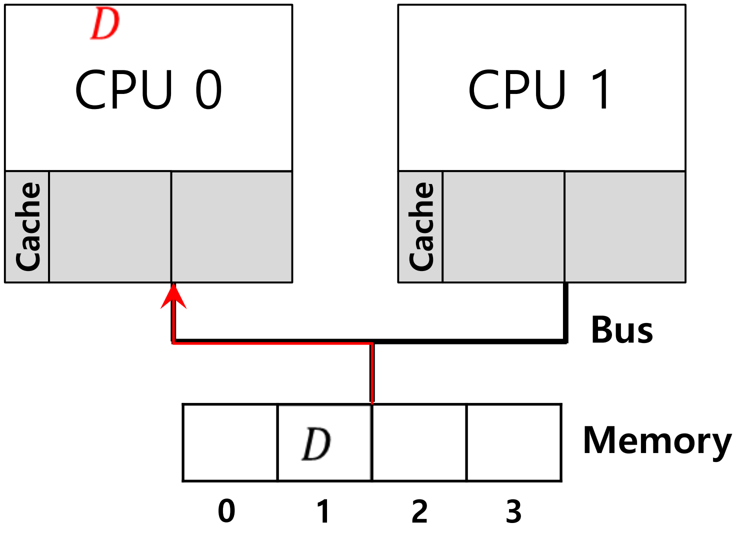
Cache coherence

- Consistency of shared resource data stored in multiple caches.

0. Two CPUs with caches sharing memory

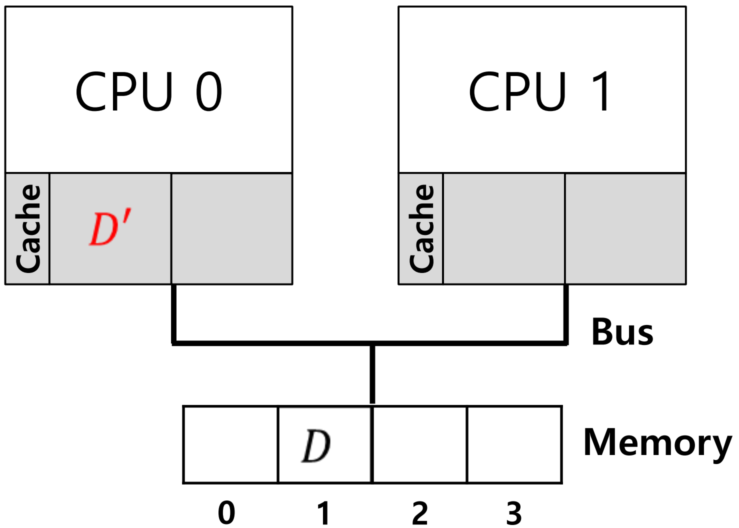


1. CPU0 reads a data at address 1.

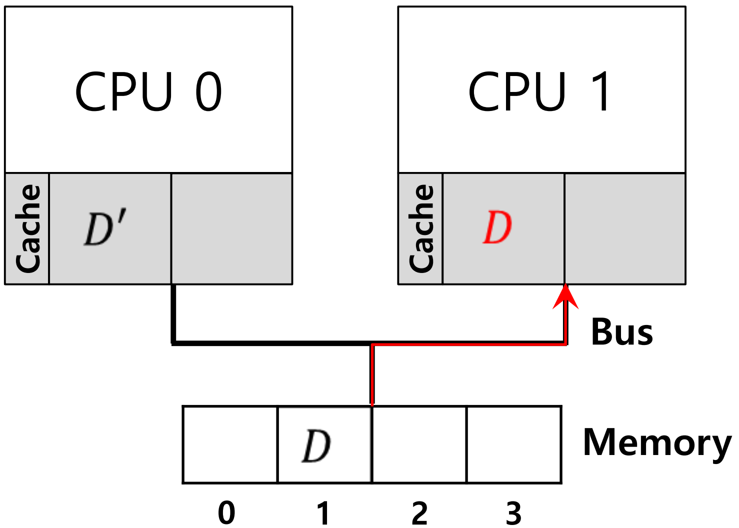


Cache coherence (Cont.)

2. D is updated and CPU1 is scheduled.



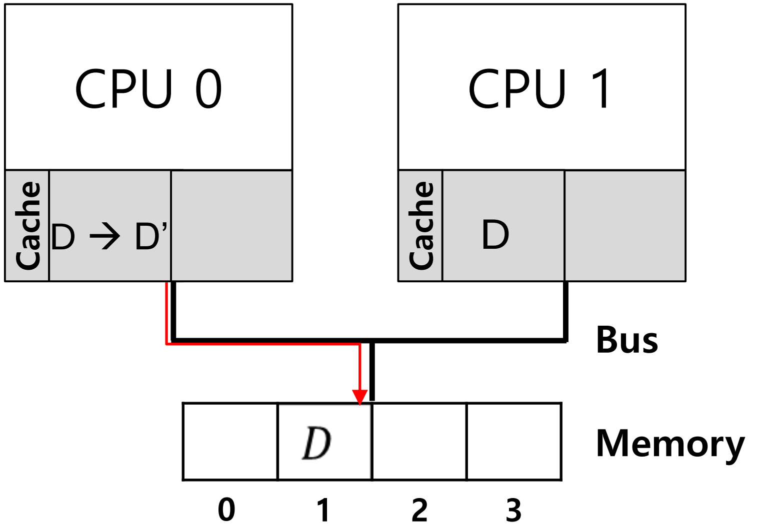
3. CPU1 re-reads the value at address A



CPU1 gets the old value D instead of the correct value D'.

Cache coherence solution

- **Bus snooping:**
  - **Each cache** pays attention to memory updates by **observing the bus**.



  - **When a CPU** sees an update for a data item it holds in its cache, it will notice the change and either invalidate its copy or update it.

Don't forget synchronization

- When accessing shared data across CPUs, **mutual exclusion** primitives should be used to guarantee correctness.

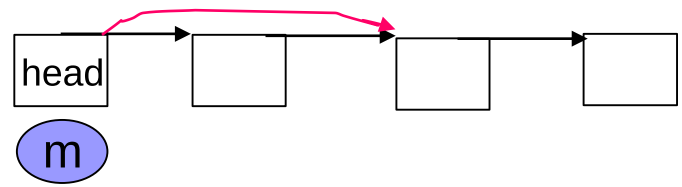
```
typedef struct __Node_t {
        int value;
        struct __Node_t *next;
} Node_t;

int List_Pop() {
        Node_t *tmp = head;          // remember old head ...
        int value = head->value;     // ... and its value
        head = head->next;           // advance head to next pointer
        free(tmp);                   // free old head
        return value;                // return value at head
}
```

Simple List Delete Code

Don’t forget synchronization (Cont.)

- Solution




```
pthread_mtuex_t  m;
typedef struct __Node_t {
        int value;
        struct __Node_t *next;
} Node_t;

int List_Pop() {
        lock(&m)
        Node_t *tmp = head;          // remember old head ...
        int value = head->value;     // ... and its value
        head = head->next;           // advance head to next pointer
        free(tmp);                   // free old head
        unlock(&m)
        return value;                // return value at head
}
```

Simple List Delete Code with lock

Cache Affinity

- **Keep a process** on **the same CPU** if at all possible:
  - **A process typically** builds up a fair bit of state in the cache of a CPU.
  - **The next time** the process run, it will run faster if some of its state is *already present* in the cache on that CPU.

A multiprocessor scheduler should consider cache affinity when making its scheduling decision.

Single queue Multiprocessor Scheduling (SQMS)

- Put all jobs that need to be scheduled into a single queue:
  - Each CPU simply picks the next job from the globally shared queue.
  - **Cons:**
    - Some form of **locking** have to be inserted → Lack of scalability
    - **Cache affinity, i.e., lack of**
    - **Example:**

      Queue → A → B → C → D → E → NULL

    - **Possible job scheduler across CPUs:**

P.S. Process A switches between different CPUs constantly after every quantum

CPU0	A	E	D	C	B	... (repeat) ...
CPU1	B	A	E	D	C	... (repeat) ...
CPU2	C	B	A	E	D	... (repeat) ...
CPU3	D	C	B	A	E	... (repeat) ...

Scheduling Example with Cache affinity

Queue → A → B → C → D → E → NULL

CPU0	A	E	A	A	A	... (repeat) ...
CPU1	B	B	E	B	B	... (repeat) ...
CPU2	C	C	C	E	C	... (repeat) ...
CPU3	D	D	D	D	E	... (repeat) ...

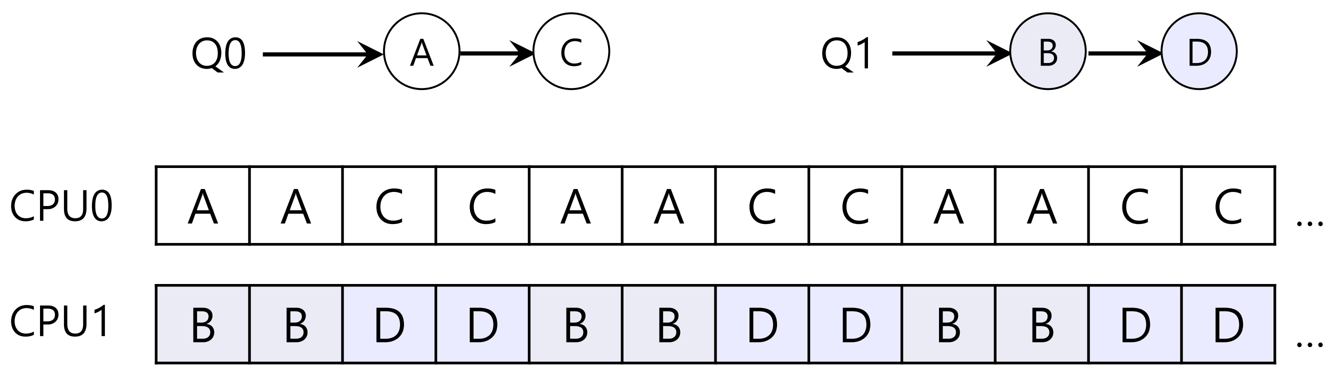
- **Preserving affinity for most**
  - Jobs A through D are not moved across processors.
  - Only job E Migrating from CPU to CPU.
- Implementing such a scheme can be **complex**.

Multi-queue Multiprocessor Scheduling (MQMS)

- **MQMS** consists of multiple scheduling queues:
  - Each queue per CPU will follow a particular scheduling discipline.
  - When a job enters the system, it is placed in **exactly one** scheduling queue.
  - Avoid/Minimize the problems of information sharing and synchronization.

MQMS Example

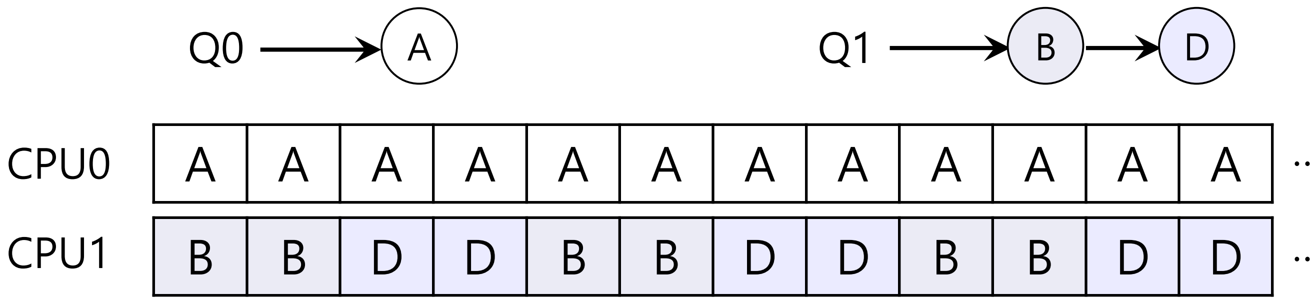
- **With designated processes** on every processor and use **round robin** between processes on each CPU, the system might produce a schedule that looks like this:



MQMS provides more scalability and cache affinity.

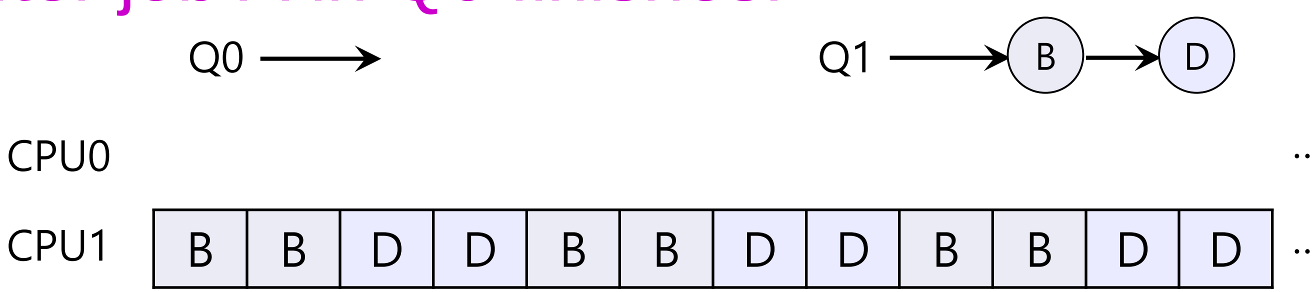
Load Imbalance issue of MQMS

- After job C in Q0 finishes:



A gets twice as much CPU as B and D.

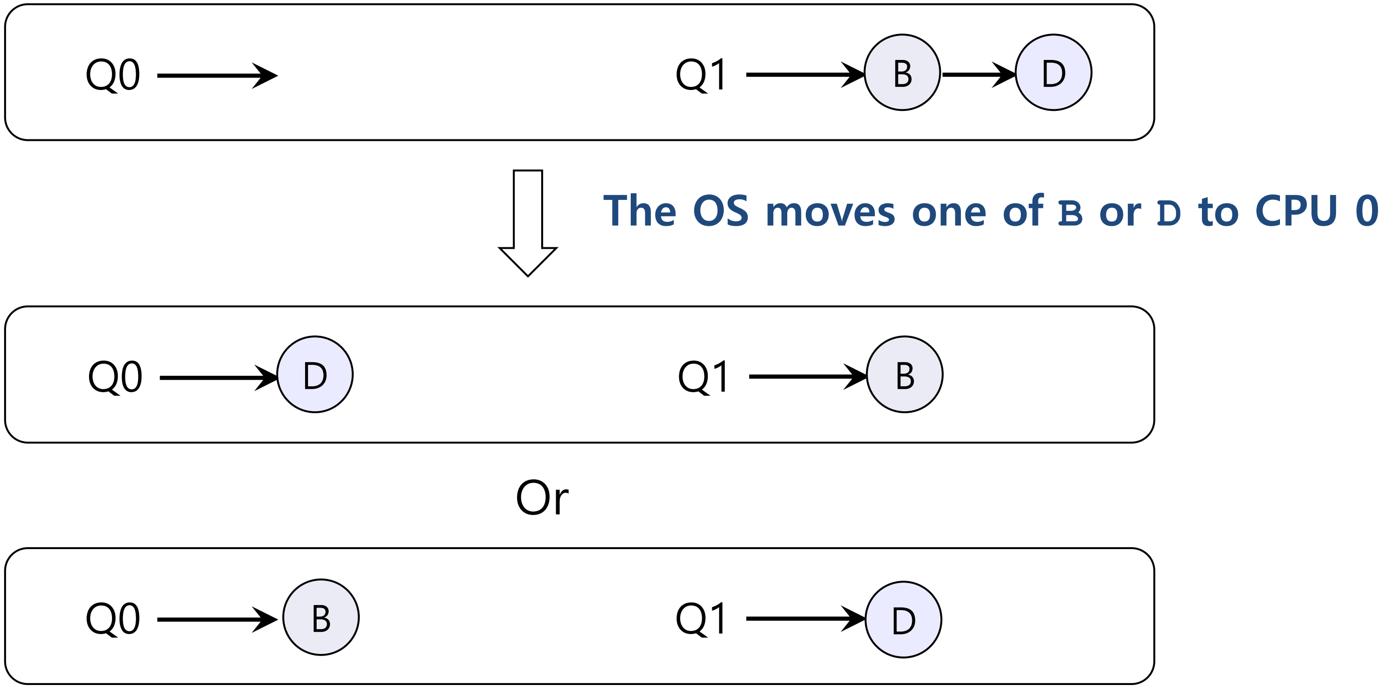
- After job A in Q0 finishes:



CPU0 will be left idle!

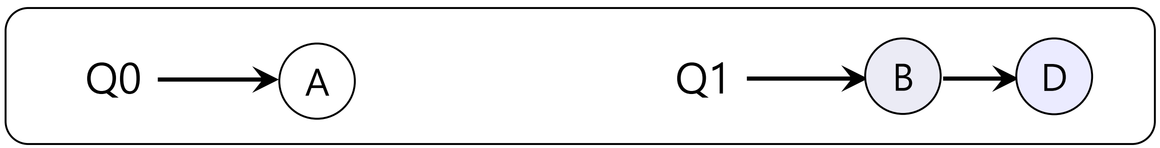
How to deal with load imbalance?

- **The answer** is to move jobs (**Migration**) – rebalance the workload:
  - **Example:**

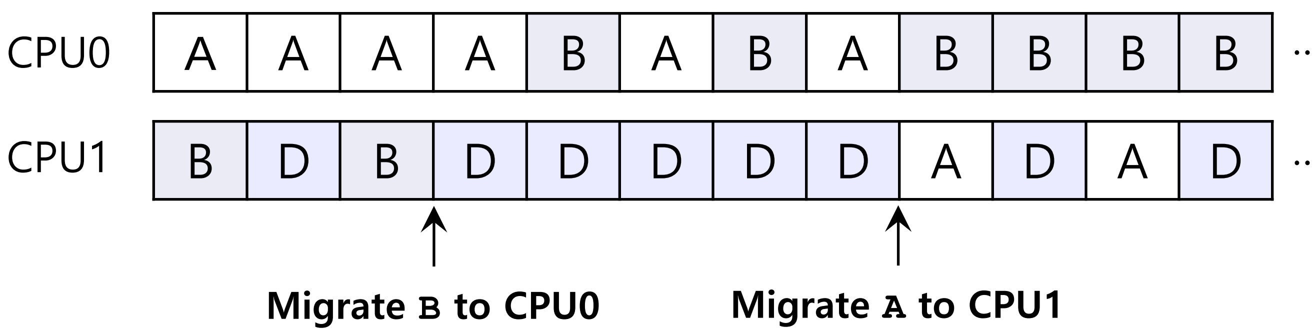


How to deal with load imbalance? (Cont.)

- A more tricky case:



- A possible migration pattern:
  - Keep switching jobs:



Work Stealing

- **Move jobs between queues:**
  - **Implementation:**
    - A source queue that is <u>low on jobs</u> is picked.
    - The source queue occasionally peeks at another target queue.
    - If the target queue is <u>more full than</u> the source queue, the source will "**steal**" one or more jobs from the target queue.
  - **Cons:**
    - *High overhead, no CPU affinity,* and trouble *scaling*

Linux Multiprocessor Schedulers

- **O(1):**
  - A Priority-based scheduler
  - Use Multiple queues
  - Change a process's priority over time
  - Schedule those with highest priority
  - Interactivity is a particular focus
- **Completely Fair Scheduler (CFS – Linux 2.6.23):**
  - Deterministic proportional-share approach
  - Multiple queues
  - Goal is to maximize CPU utilization in interactive environment; instead of queue use Red/Black tree to order jobs execution

Linux Multiprocessor Schedulers (Cont.)

- **BF (Brain F) Scheduler (BFS):**
  - **A single queue** approach
  - **Proportional-share**
  - **Based on** Earliest Eligible Virtual Deadline First (EEVDF)
  - **BFS** has been retired in favor of MuQSS (Multiple Queue Skiplist Scheduler - a re-written implementation of the same concept)

Multi-level Feedback Queue Scheduling – Advanced Scheduling

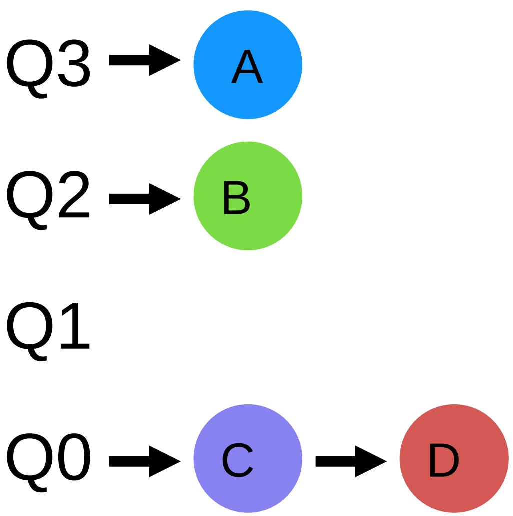
MLFQ

- **Goal:** general-purpose scheduling
- **Must support** two job types with distinct goals
  - "**interactive**" programs care about response time
  - "**batch**" programs care about turnaround time
- **Approach:** multiple levels of round-robin; each level has higher priority than lower levels and preempts them

MLFQ: Priorities

Rule 1: If priority(X) > Priority(Y), X runs

Rule 2: If priority(X) == Priority(Y), X & Y run in RR



“Multi-level”

How to know how to set priority?

Approach 1: nice

Approach 2: history “feedback”

MLFQ: Rules

Rule 1: If priority(X) > Priority(Y), X runs

Rule 2: If priority(X) == Priority(Y), X & Y run in RR

More rules:

Rule 3: Processes start at top priority

Rule 4: If job uses whole slice, demote process
(longer time slices result in lower priorities)

END