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)
    - …..
  - **Meta data - Data structures** to help the OS manage the process such as process table entry, user_area, etc.

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

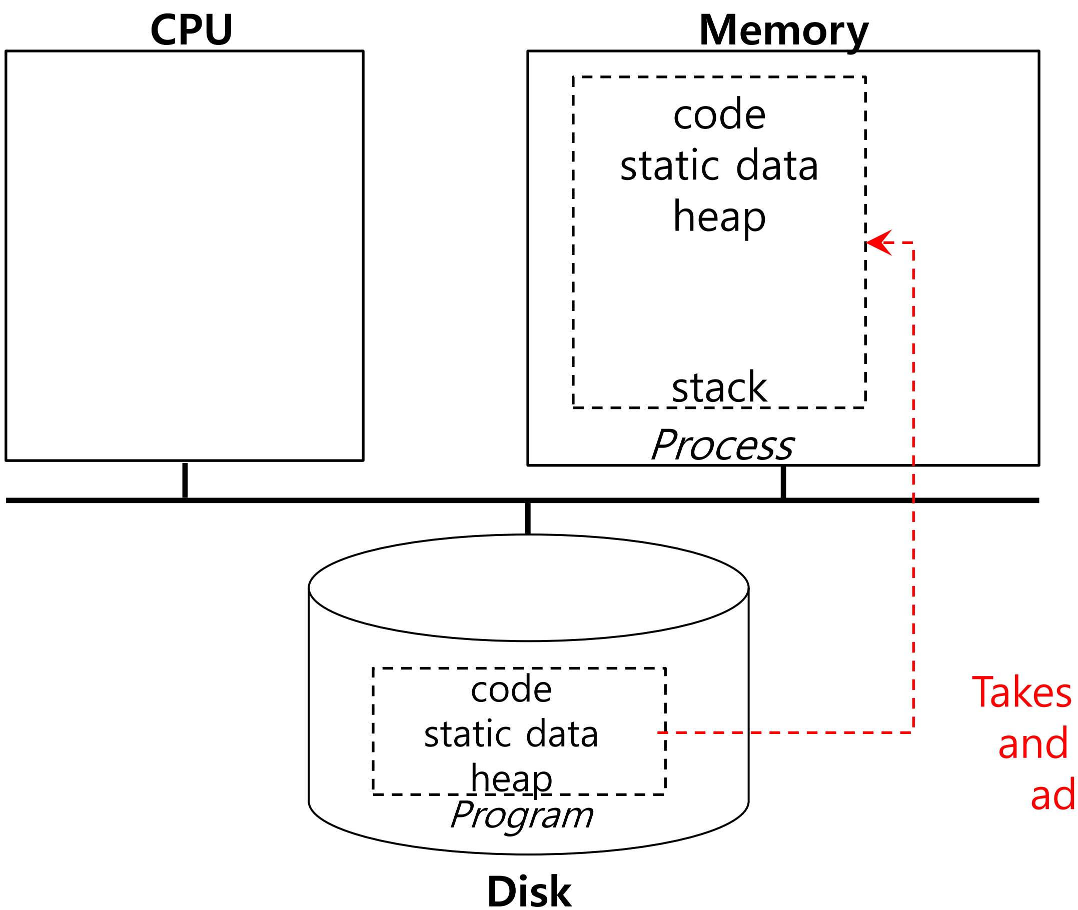
Process Creation

1. **Load** a program code into memory, into the address space of the process:
   - Programs initially reside on disk in *executable format (a.out)*.
   - 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 on Disk to Process in Memory

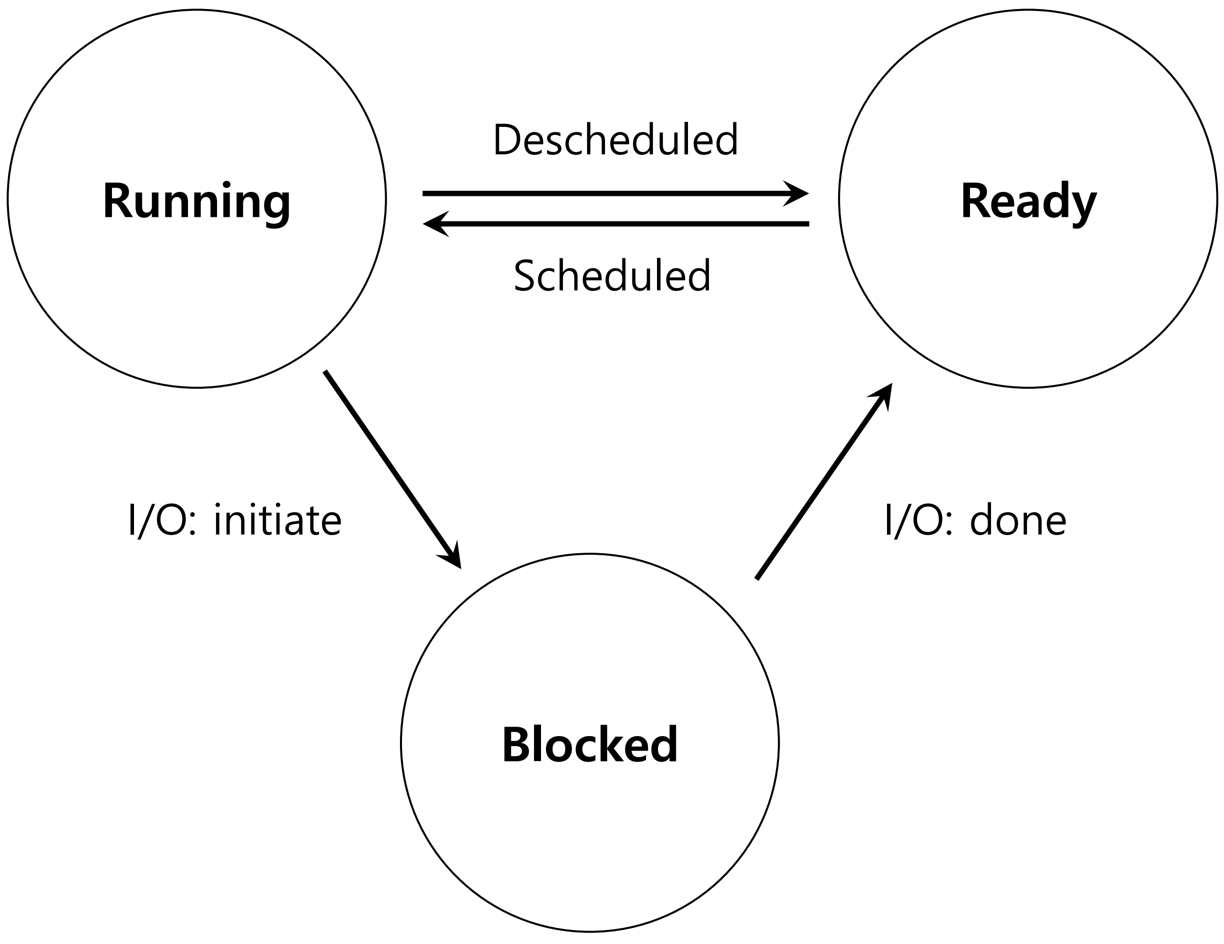


Loading:
Takes on-disk program and write it into the address space of process

Process States

- **A process can be in 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
    - **Running:** Current running process (comes only from the Ready queue)
  - **Register context**
- **PCB(Process Control Block): Unix Proc[ ] table**
  - 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 general-purpose 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 (being created), 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();       // rc is a pid
    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 parent 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);    // parent wait for child exit,
                                // 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)run different prog
        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
        …
```

```
% wc   p3.c
```

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>               # output of WC
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                                     # Output of WC
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 between processes 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 in the 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 the 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 direct access to hardware resources.
  - **Kernel mode:** The OS has access to the full resources of the machine

System Call

- **Allows the kernel** to carefully expose certain key pieces of system-level 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 including user-level return address)
  - **Jump into the kernel**
  - **Raise the privilege level** to kernel mode

<Execute the user service request in the kernel>

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

Limited Direction Execution Protocol: Execute (a.out) User program

OS @ boot (kernel mode)	**Hardware**	
OS Boot: **Initialize trap table**	remember address of … syscall handler	

Exec user program (trap)

OS @ run (kernel mode)	**Hardware**	**Program (user mode)**
Setup user stack with argv Fill kernel stack with reg/PC Create new entry for process[ ] Allocate memory for program. Load program into memory **return-from - trap**		
	restore regs/PC 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/PC to kernel stack move to kernel mode jump to trap handler	
Handle trap: Do work of syscall **return-from-trap**		
	restore regs/PC 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)
  - **Example 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 repeatedly
  - **When the interrupt is raised:**
    - The currently running process is halted.
    - Save enough of the state of the program to be able to resume in the future
    - 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 but before resuming the current user-level process), either to:**
  - **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 context switch.

Context Switch

- **A low-level piece of assembly code:**
  - **Save few register values** for the current process into its kernel stack and its PCB:
    - General purpose registers
    - PC
    - kernel stack pointer (SP)
  - **Restore few register values** for the soon-to-be-executing process from its kernel stack and its PCB
  - **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) & PCB(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 Assume time to switch: **Call switch() routine** save regs(A) to proc-struct(A) restore regs(B) from proc-struct(B) switch SP to k-stack(B) **return-from-trap (into B)**		
	restore regs/PC(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 ← single CPU
  - Use a number of sophisticated **locking** schemes to protect concurrent access to internal data structures ← SMP

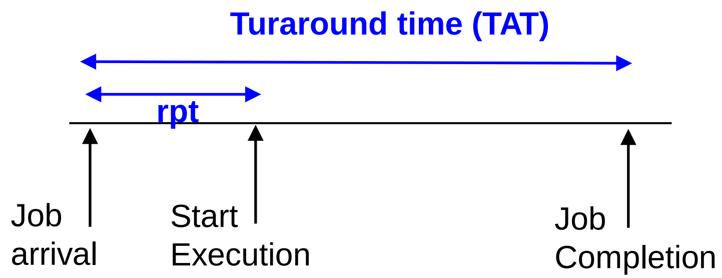
Scheduling: separation of Policy and Mechanism

Scheduling: Introduction

Scheduling: Introduction

- **Workload assumptions (for simplicity):**
  1. **Early UNIX** assigns **fixed time slice** to a process. **Linux** uses Fair Scheduler where each process is assigned a **proportion time** slice (time slice depends on the load and is not fixed value).
  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/tracked.

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.

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

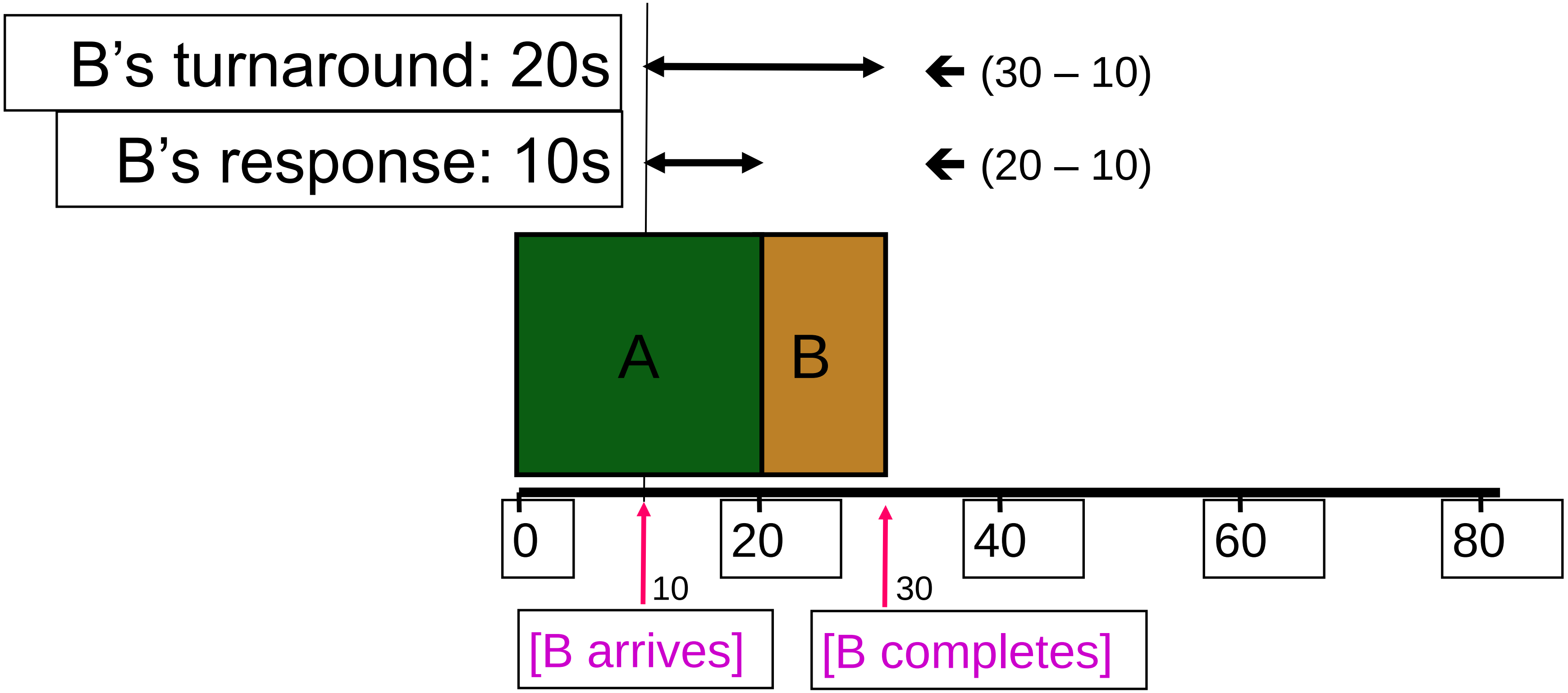
- **Performance metric: Turnaround time**
  - The time at which **the job completes** minus the time at which **the job arrived** in the system.

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

- **Waiting time metric: Waiting time**

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

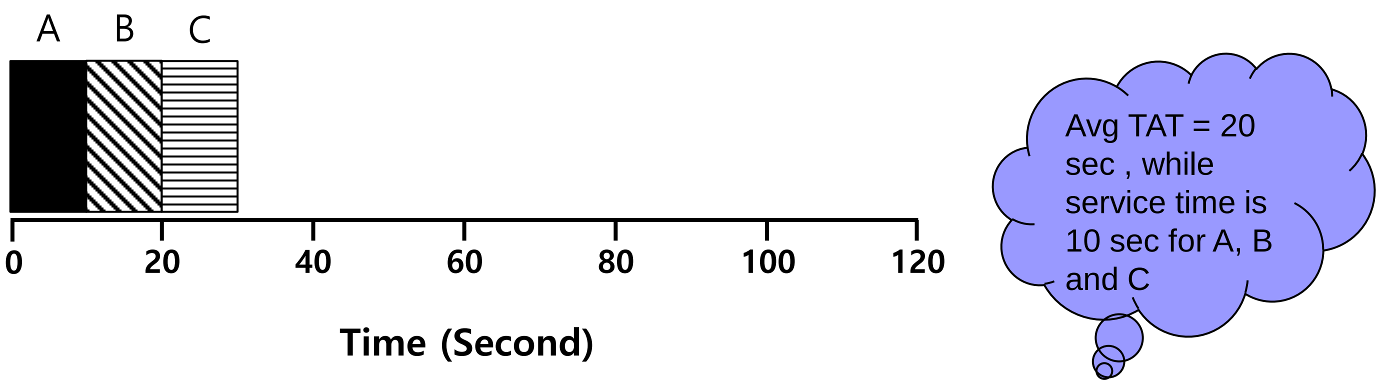
Scheduling Metrics



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

First In, First Out (FIFO)

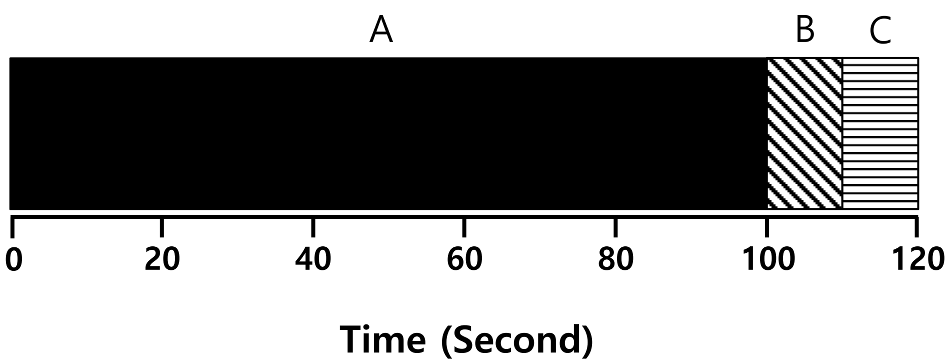
- First Come, First Served (FCFS)
  - **Very simple** and easy to implement
- Example:
  1. **Assume each job** runs for 10 seconds.
  2. **A arrived** just before B which arrived just before C.



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

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.

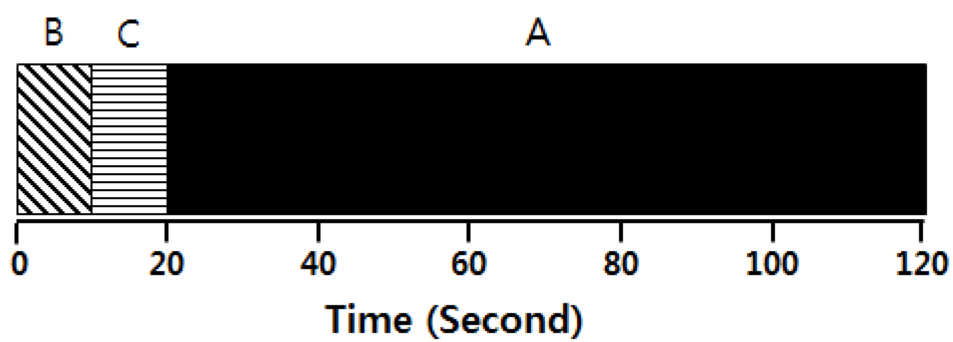


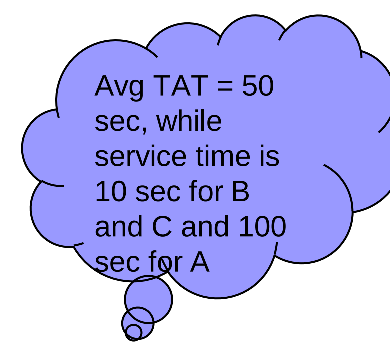
Avg TAT = 110 sec , while service time is 10 sec for B and C

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

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.

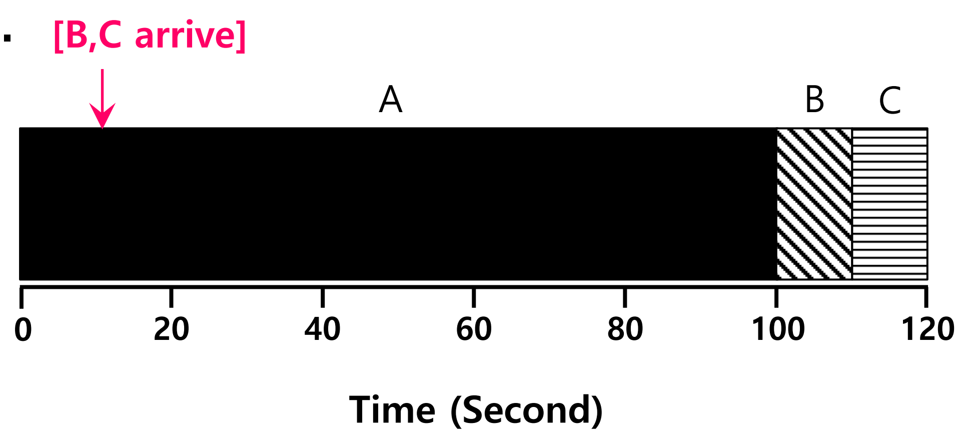




$$Average\ turnaround\ time = \frac{10 + 20 + 120}{3} = 50\ sec$$

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

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

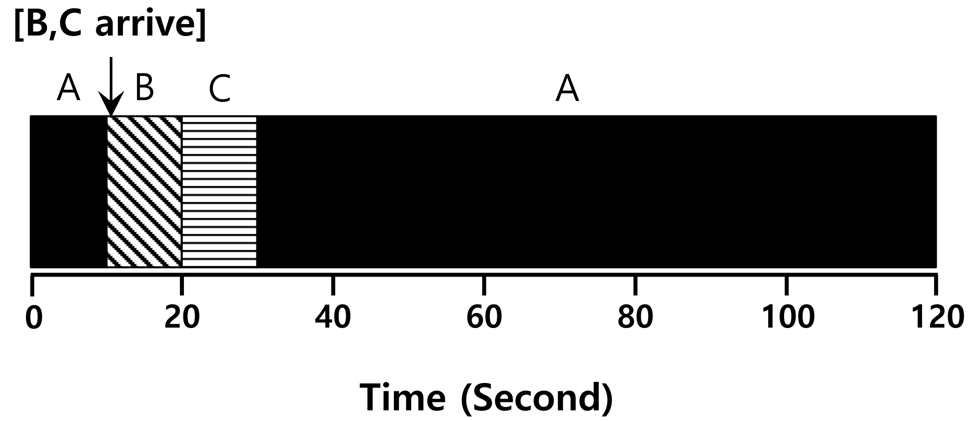
Shortest Time-to-Completion First (STCF)

- **Add preemption to SJF:**
  - Also known as **Preemptive Shortest Job First** (PSJF)

- **A new job enters the system:**
  - Determine between the remaining time of current jobs and the new arrived 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



Avg TAT = 50 sec instead of 103 sec while service time is 10 sec for B and C

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

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?

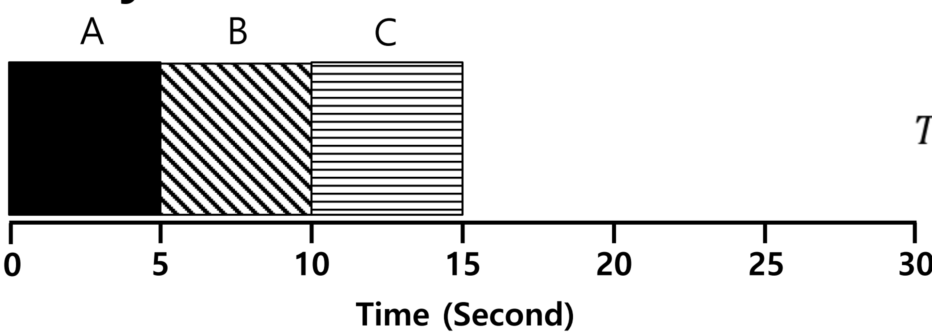
Round Robin (RR) Scheduling

- **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 time slice = 20 msec).

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

RR Scheduling Example

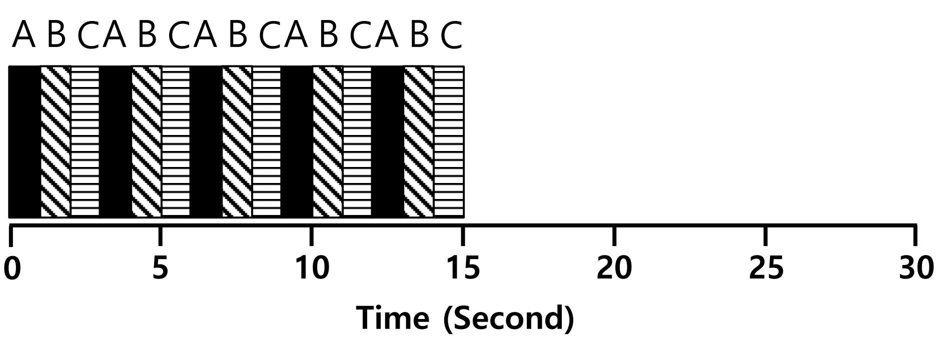
- A, B and C arrive at the same time.
- They each wish to run for 5 seconds.



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

T_{TAT} = (5+10+15)/3 = 5 sec

SJF (Bad for Response Time)



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

T_{TAT} = (13+14+15)/3 = 14 sec

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

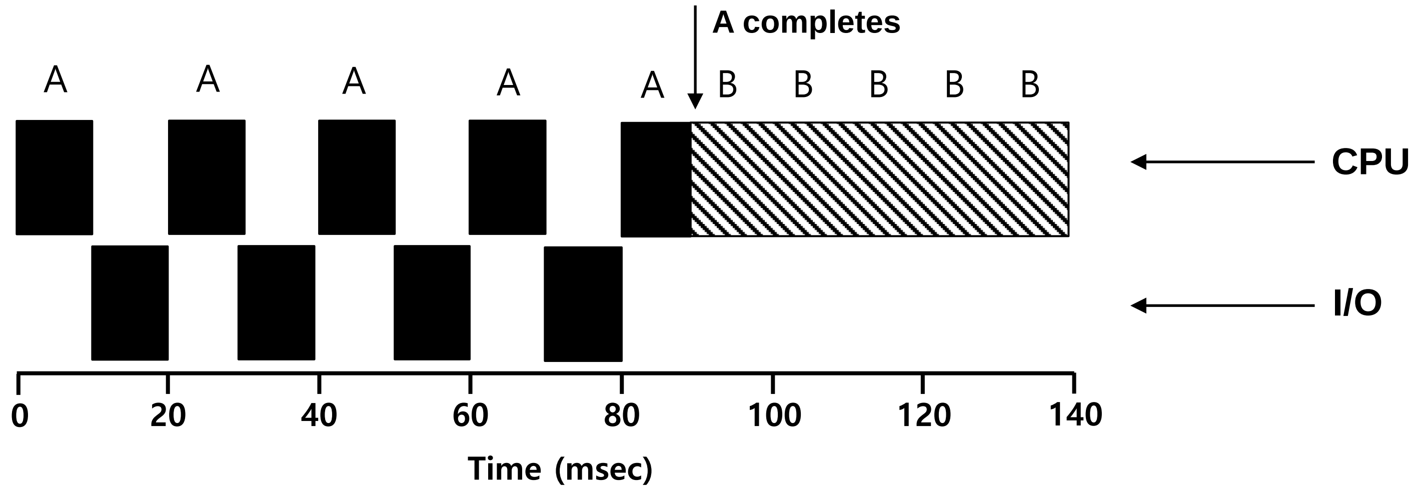
Incorporating I/O with RR

- **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

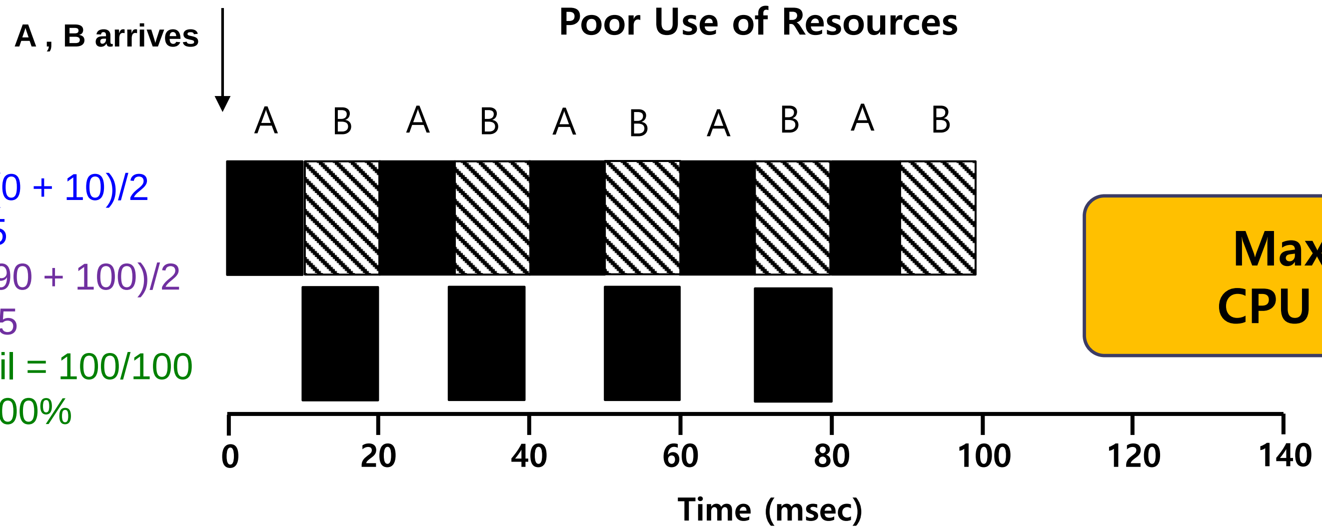
Incorporating I/O with RR (Cont.)

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 queue back to the end of the ready queue.

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 your tickets to total tickets represents your 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 a winning ticket:**
  - 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

A:B = 11:4

**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 → *50* (A's currency) to A1 → *50* (global currency) ➔ 25%
→ *50* (A's currency) to A2 → *50* (global currency) ➔ 25%

User B → *100* (B's currency) to B1 → *100* (global currency) ➔ 50%

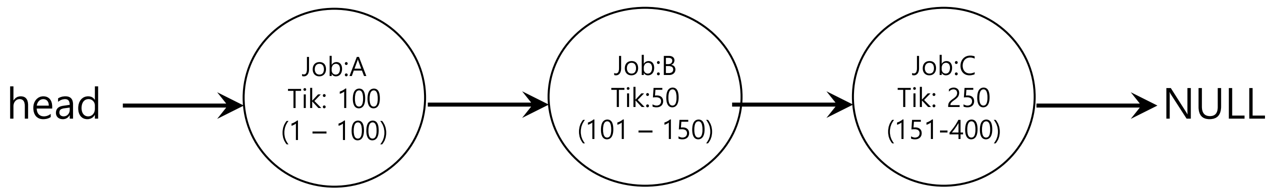
Ticket Mechanisms (Cont.)

- **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.)

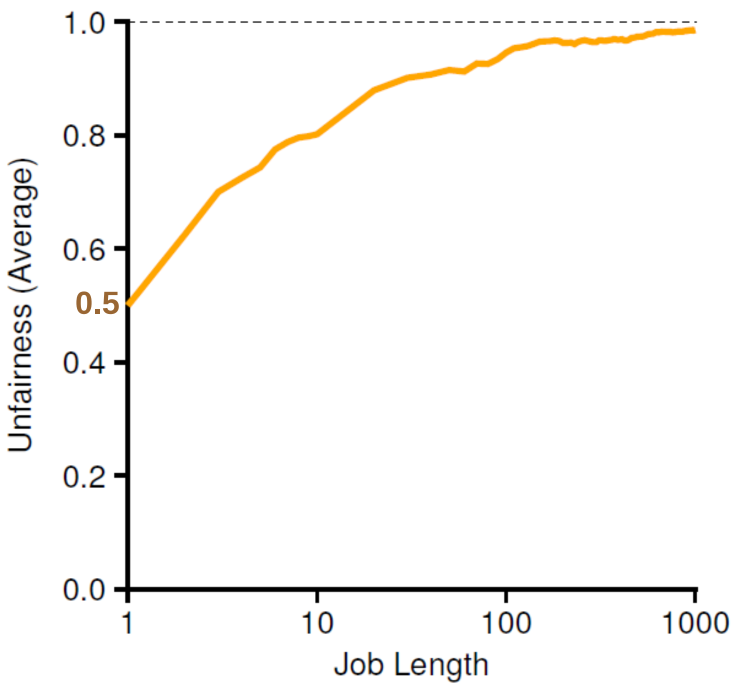
- **U: unfairness metric**
  - The time the first job completes divided by the time that the second job completes. ➔ For equal service time $TAT_1/TAT_2 = 1$
- **Example:** Assume two jobs arrive at the same time:
  - **There are two jobs, each jobs has runtime 10:**
    - First job finishes at time 10
    - Second job finishes at time 20 // it means strict sequential execution
  - 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

Ticket
Stride = 1/ticket
Pass = sum strides

Run process with smalless pass

- Stride of each process (opposite or inverse 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) a quantum time; "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 new pass for current proc 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

A:B:C = 2:1:5
Perfect !

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

Multiprocessor (SMP) Scheduling

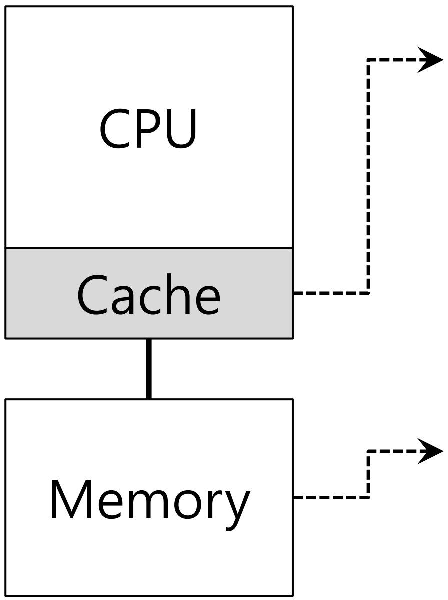
Multiprocessor Scheduling

- 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 <u>popular</u> data that was accessed from the main memory.
- Utilize *temporal* and *spatial* locality

Main Memory

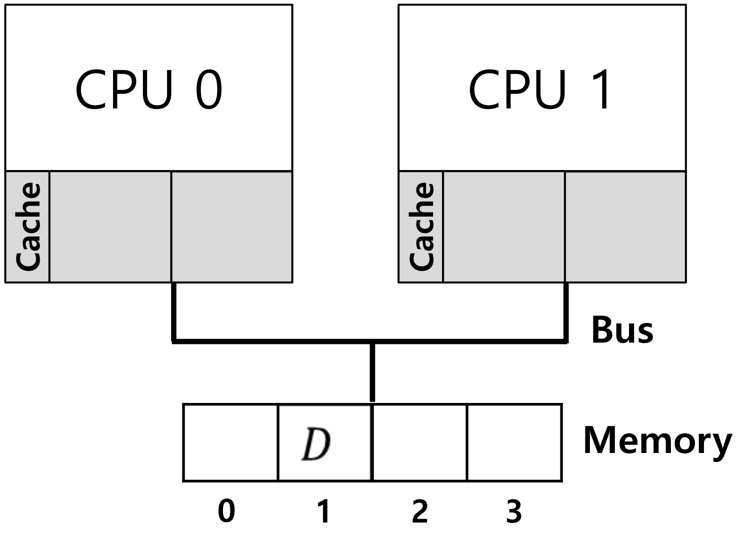
- Holds all relevant data
- Access to main memory is slower than cache.

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

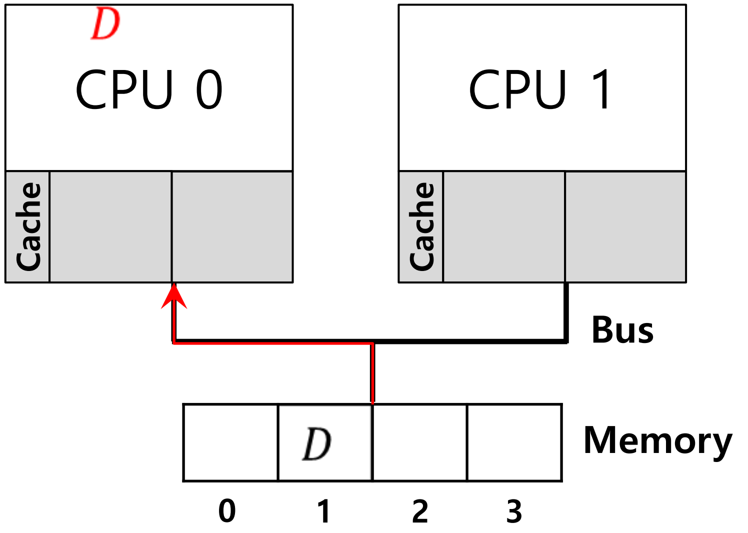
Cache coherence

- Consistency of shared resource data stored in multiple caches.

0. Two CPUs with caches sharing memory

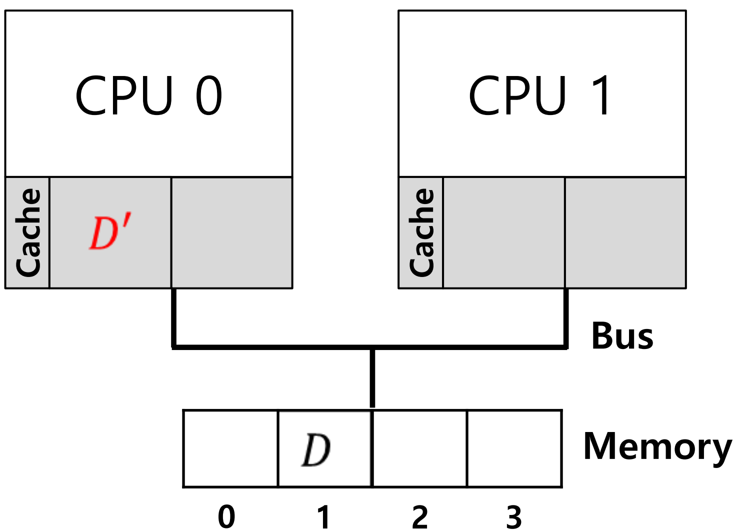


1. CPU0 reads a data at address 1.

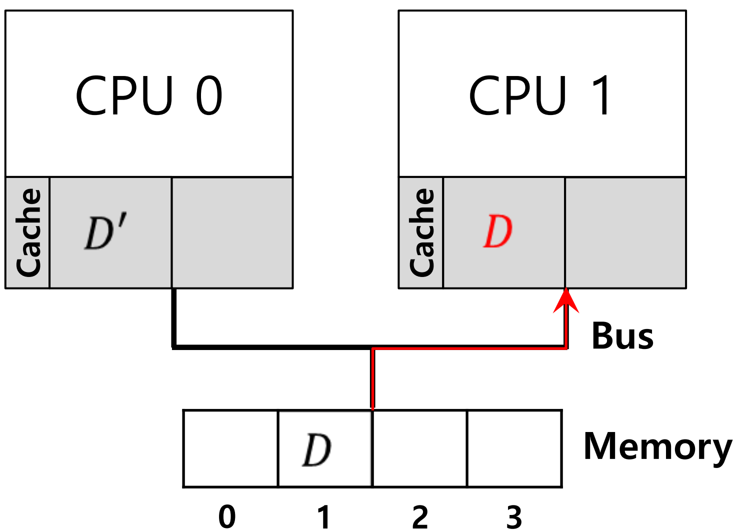


Cache coherence (Cont.)

2. D is updated and CPU1 is scheduled.



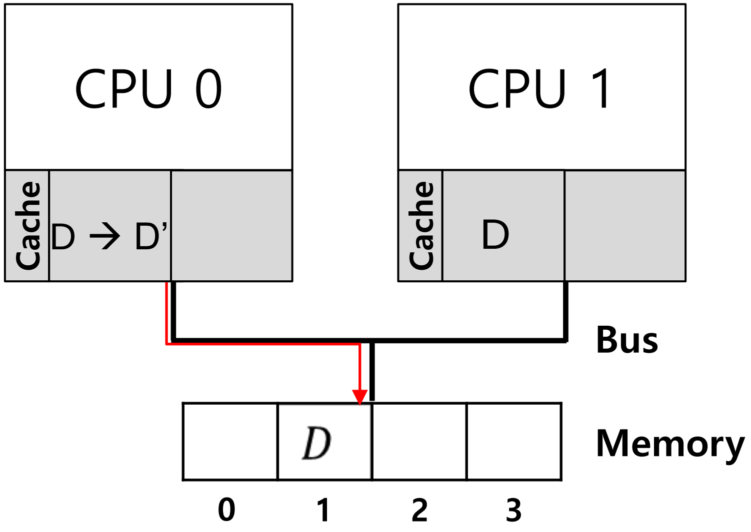
3. CPU1 re-reads the value at address 1



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

Cache coherence solution

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



  - **When a CPU (CPU1)** sees an update for a data item (CPU 0 updating RAM) that it (CPU 1) 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.

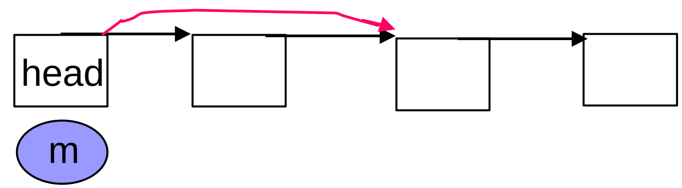
```c
typedef struct __Node_t {
        int value;
        struct __Node_t *next;
} Node_t;                                // linked list

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 Delete to 1st entry in a linked-list Code – Incorrect code (concurrency)

Don’t forget synchronization (Cont.)

- Solution




```
pthread_mtuex_t  m;                   // lock for the whole linked list

typedef struct __Node_t {
          int value;
          struct __Node_t *next;
} Node_t;                               // linked list

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 the process** on **the same CPU during execution** 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

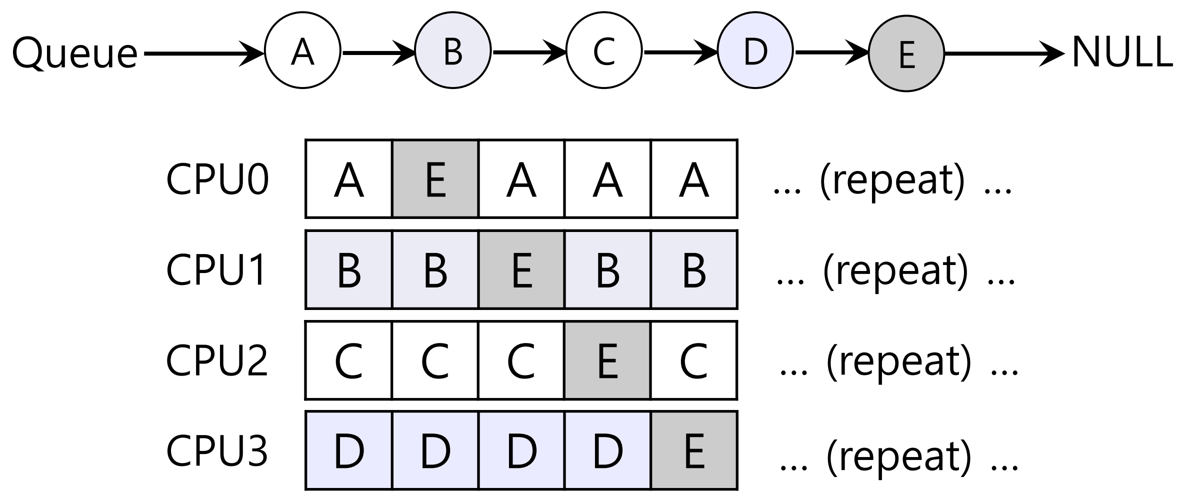
- **Possible job scheduler across CPUs:**

P.S. Each Process 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

- **<u>Preserving affinity</u> for most (i.e., except E)**



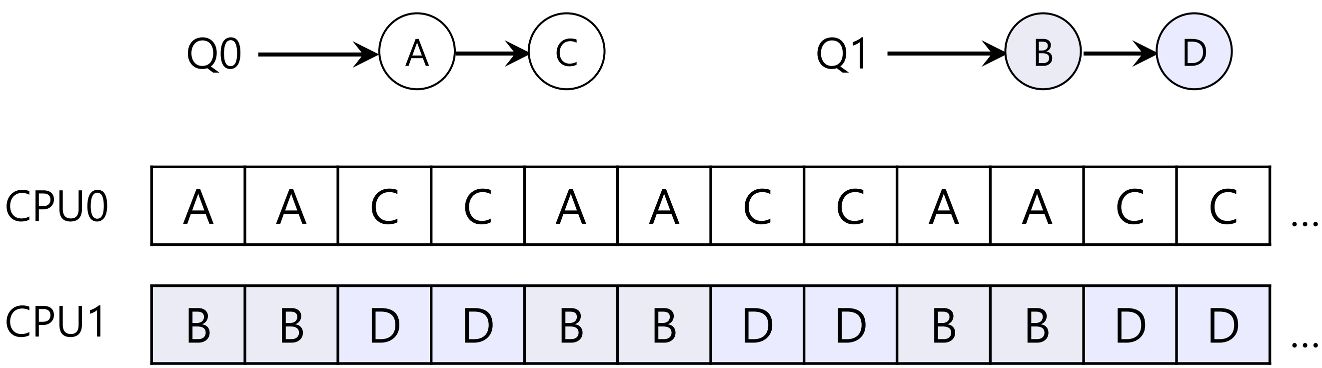
  - Jobs A through D are not moved across processors.
  - Only job E Migrating from CPU to CPU.
- Implementing such a scheme can be **complex**.

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:**

Q0 → A   Q1 → B → D

CPU0	A	A	A	A	A	A	A	A	A	A	A	A	…
CPU1	B	B	D	D	B	B	D	D	B	B	D	D	…

`A` gets twice as much CPU as `B` and `D`.

- **After job A in Q0 finishes:**

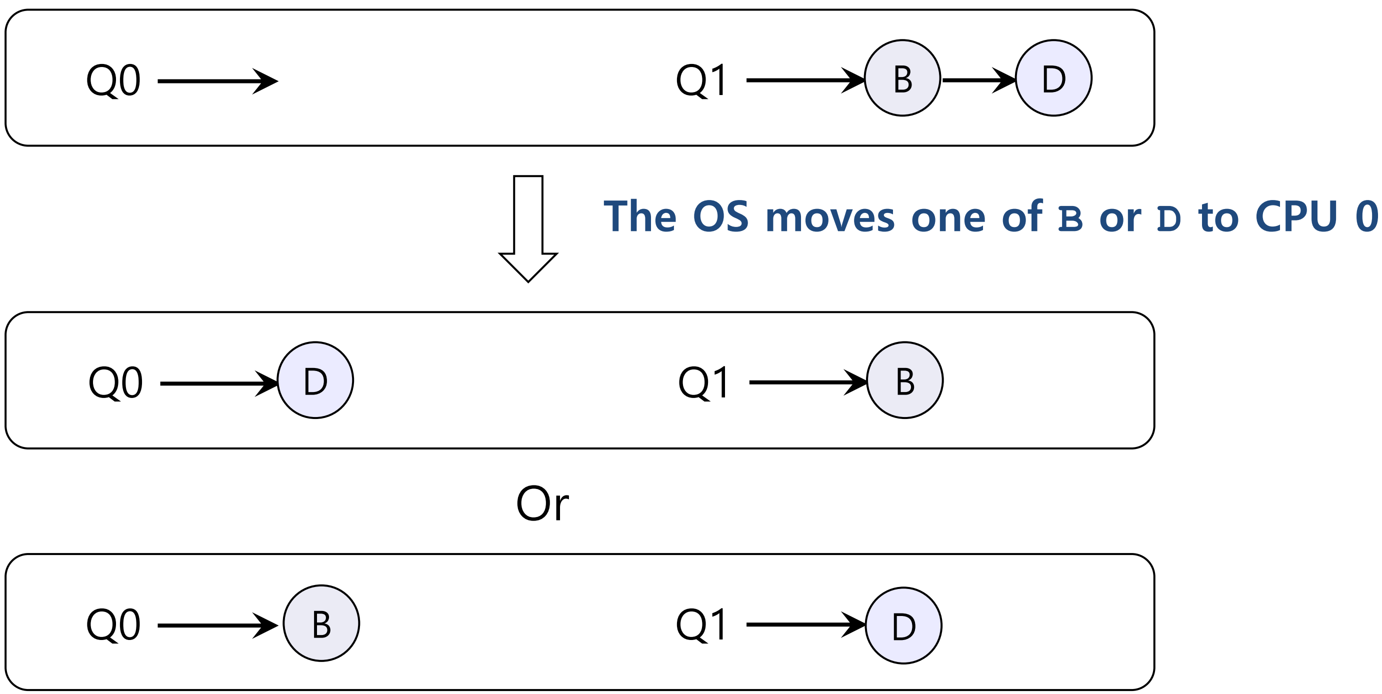
Q0 →   Q1 → B → D

CPU0													…
CPU1	B	B	D	D	B	B	D	D	B	B	D	D	…

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:

CPU0	A	A	A	A	B	A	B	A	B	B	B	B	…
CPU1	B	D	B	D	D	D	D	D	A	D	A	D	…

Migrate `B` to CPU0 **Migrate `A` to CPU1**

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 using a 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) – leverage “nice” support
  - **BFS** has been retired in favor of MuQSS (**Mu**ltiple **Q**ueue **S**kiplist **S**cheduler - a re-written implementation of the same concept)

Multi-level Feedback Queue Scheduling – Advanced Scheduling

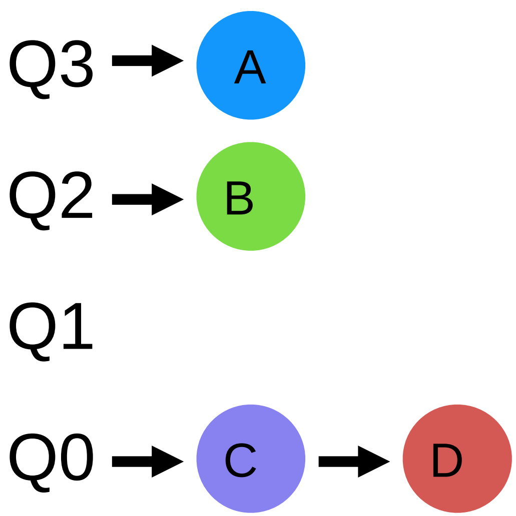
MLFQ: Multi-level Feedback Queue

- **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)

Rule 5: If job do not use the whole time slice (i.e., issuing system call or I/O), promote the process to the next higher queue

END