Review of Operating Systems

Operating System: Three Easy Pieces

What a happens when a program runs?

- A running program executes instructions.
  1. The processor **fetches** an instruction from memory.
  2. **Decode**: Figure out which instruction this is
  3. **Execute**: i.e., add two numbers, access memory, check a condition, jump to function, and so forth.
  4. The processor moves on to the **next instruction** and so on.

Operating System (OS)

- Responsible for
  - Making it easy to **run** programs
  - Allowing programs to **share** memory
  - Enabling programs to **interact** with devices

OS is in charge of making sure the system operates correctly and efficiently.

Virtualization

- The OS takes a physical resource and transforms it into a virtual form of itself.
  - **Physical resource**: Processor, Memory, Disk …
  - The virtual form is more general, powerful and easy-to-use.
  - Sometimes, we refer to the OS as a **virtual machine**.

System call

- System call allows user **to tell the OS what to do**.
  - The OS provides some interface (APIs, standard library).
  - A typical OS exports a few hundred system calls.
    - Run programs
    - Access memory
    - Access devices

The OS is a resource manager.

- The OS **manage resources** such as *CPU*, *memory* and *disk*.
- The OS allows
  - Many programs to run → Sharing the CPU
  - Many programs to *concurrently* access their own instructions and data → Sharing memory
  - Many programs to access devices → Sharing disks

Virtualizing the CPU

- The system has a very large number of virtual CPUs.
  - Turning a single CPU into a seemingly infinite number of CPUs.
  - Allowing many programs to seemingly run at once

    → **Virtualizing the CPU**

Virtualizing the CPU (Cont.)

```
1       #include <stdio.h>
2       #include <stdlib.h>
3       #include <sys/time.h>
4       #include <assert.h>
5       #include "common.h"
6
7       int
8       main(int argc, char *argv[])
9       {
10              if (argc != 2) {
11                      fprintf(stderr, "usage: cpu <string>\n");
12                      exit(1);
13              }
14              char *str = argv[1];
15              while (1) {
16                      Spin(1); // Repeatedly checks the time and
                                    returns once it has run for a second
17                      printf("%s\n", str);
18              }
19              return 0;
20      }
```

Simple Example(`cpu.c`): Code That Loops and Prints

All Code in--> https://github.com/remzi-arpacidusseau/ostep-code

Virtualizing the CPU (Cont.)

- Execution result 1.

```
prompt> gcc -o cpu cpu.c -Wall
prompt> ./cpu "A"
A
A
A
^C
prompt>
```

Run forever; Only by pressing “Control-c” can we halt the program

Virtualizing the CPU (Cont.)

- Execution result 2.

```
prompt> ./cpu A & ; ./cpu B & ; ./cpu C & ; ./cpu D &
[1] 7353
[2] 7354
[3] 7355
[4] 7356
A
B
D
C
A
B
D
C
A
C
B
D
...
```

Even though if we have only one processor, all four of programs seem to be running at the same time!

Virtualizing Memory

- The physical memory is *an array of bytes*.
- A program keeps all of its data structures in memory.
  - **Read memory** (load):
    - Specify an address to be able to access the data
  - **Write memory** (store):
    - Specify the data to be written to the given address

Virtualizing Memory (Cont.)

- A program that Accesses Memory (`mem.c`)

```
1       #include <unistd.h>
2       #include <stdio.h>
3       #include <stdlib.h>
4       #include "common.h"
5
6       int
7       main(int argc, char *argv[])
8       {
9               int *p = malloc(sizeof(int));  // a1: allocate some
                                                  memory
10              assert(p != NULL && "Error on malloc");
11              printf("(%d) address of p: %08x\n",
12                      getpid(), (unsigned) p);  // a2: print out the
                                                  address of the memory
13              *p = 0;  // a3: put zero into the first slot of the memory
14              while (1) {
15                      Spin(1);
16                      *p = *p + 1;
17                      printf("(%d) p: %d\n", getpid(), *p); // a4
18              }
19              return 0;
20      }
```

Virtualizing Memory (Cont.)

- The output of the program `mem.c`

```
prompt> ./mem
(2134) memory address of p: 00200000
(2134) p: 1
(2134) p: 2
(2134) p: 3
(2134) p: 4
(2134) p: 5
^C
```

  - The newly allocated memory is at address `00200000`.
  - It updates the value and prints out the result.

Virtualizing Memory (Cont.)

- Running `mem.c` multiple times

```
prompt> ./mem &; ./mem &
[1] 24113
[2] 24114
(24113) memory address of p: 00200000
(24114) memory address of p: 00200000
(24113) p: 1
(24114) p: 1
(24114) p: 2
(24113) p: 2
(24113) p: 3
(24114) p: 3
...
```

  - It is as if each running program has its **own private memory**.
    - Each running program has allocated memory at the same address.
    - Each seems to be updating the value at `00200000` independently.
  - CAVEAT: In current systems, ASLR (Address Space Layout Randomization) Makes this to change. To disable it:
    - Linux: `echo 0> /proc/sys/kernel/randomize_va_space`
    - OSX: gcc -o mem mem.c -Wall -Wl,-no_pie

Virtualizing Memory (Cont.)

- Each process accesses its own private **virtual address space**.
  - The OS maps address space onto the physical memory.
  - A memory reference within one running program does not affect the address space of other processes.
  - Physical memory is a shared resource, managed by the OS.

Persistence

- Devices such as DRAM store values in a volatile.
- *Hardware* and *software* are needed to store data persistently.
  - **Hardware**: I/O device such as a hard drive, solid-state drives(SSDs)
  - **Software**:
    - File system manages the disk.
    - File system is responsible for storing any files the user creates.

Persistence (Cont.)

- Create a file (`/tmp/file`) that contains the string "hello world"

```
1       #include <stdio.h>
2       #include <unistd.h>
3       #include <assert.h>
4       #include <fcntl.h>
5       #include <sys/types.h>
6
7       int
8       main(int argc, char *argv[])
9       {
10              int fd = open("/tmp/file", O_WRONLY | O_CREAT
                                | O_TRUNC, S_IRWXU);
11              assert(fd > -1 && "Error creating file");
12              int rc = write(fd, "hello world\n", 13);
13              assert(rc == 13 && "Disk full?");
14              close(fd);
15              return 0;
16      }
```

`open()`, `write()`, and `close()` system calls are routed to the part of OS called the file system, which handles the requests

Persistence (Cont.)

- What OS does in order to write to disk?
  - Figure out **where** on disk this new data will reside
  - **Issue I/O** requests to the underlying storage device

- File system handles system crashes during write.
  - **Journaling** or **copy-on-write**
  - Carefully ordering writes to disk

Design Goals

- Build up **abstraction**
  - Make the system convenient and easy to use.
- Provide high **performance**
  - Minimize the overhead of the OS.
  - OS must strive to provide virtualization without excessive overhead.
- **Protection** between applications
  - Isolation: Bad behavior of one does not harm other and the OS itself.

Design Goals (Cont.)

- High degree of **reliability**
  - The OS must also run non-stop.

- Other issues
  - Energy-efficiency
  - Security
  - Mobility

The Abstraction: The Process

Operating System: Three Easy Pieces

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 is performance.

A Process

A process is a running program.

- Comprising of a process:
  - Memory (address space)
    - Instructions
    - Data section
  - Registers (processor architectural state (?))
    - Program counter
    - Stack pointer
    - …

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**
    - 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 (code + static data)*.
   - OS perform the loading process lazily.
     - Loading pieces of code or data 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 → `argc` and the `argv` array of `main()` function

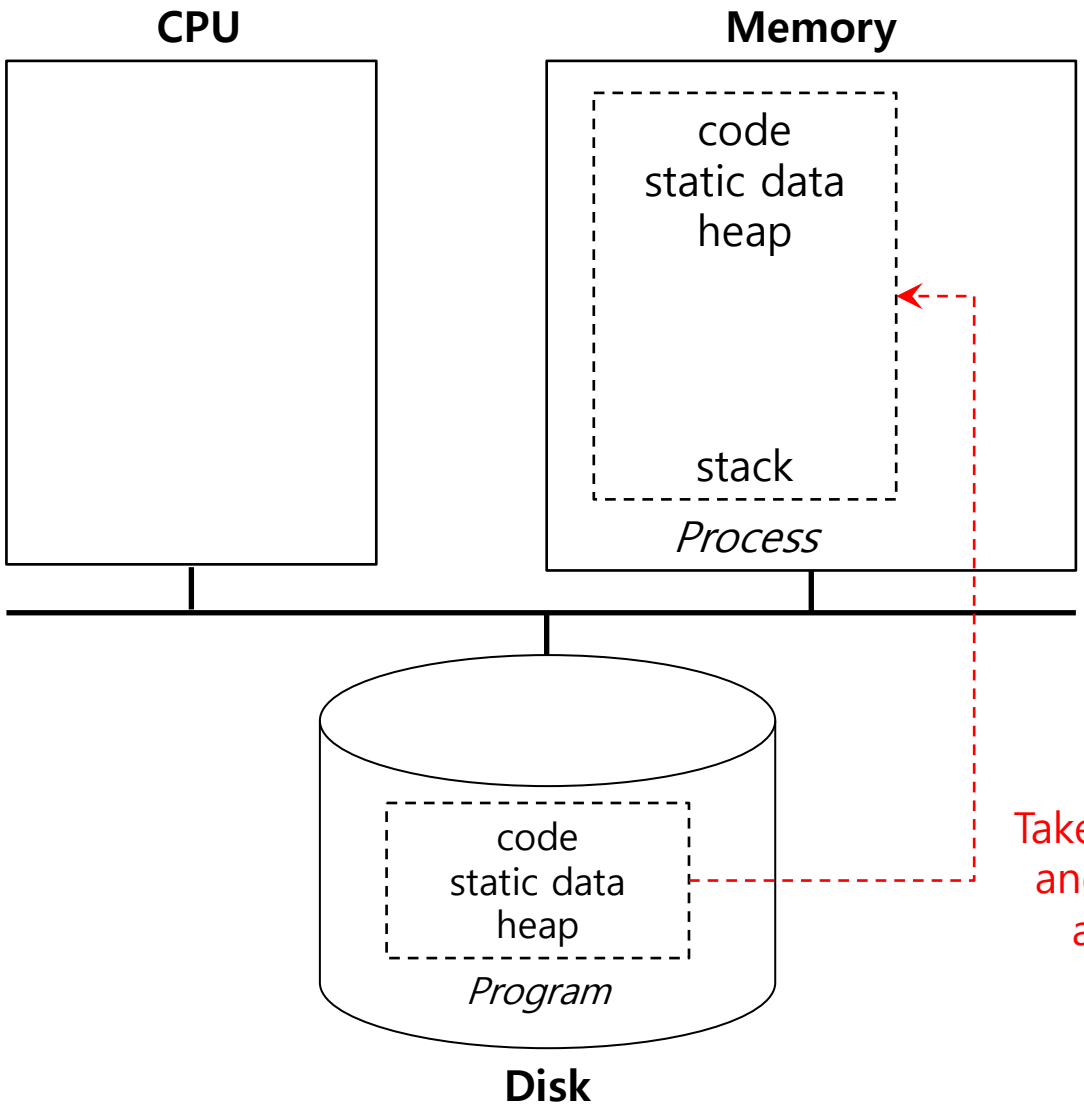
Process Creation (Cont.)

3. The program's **heap** is created.
   - Used for explicitly requested dynamically allocated data.
   - 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.
     - 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

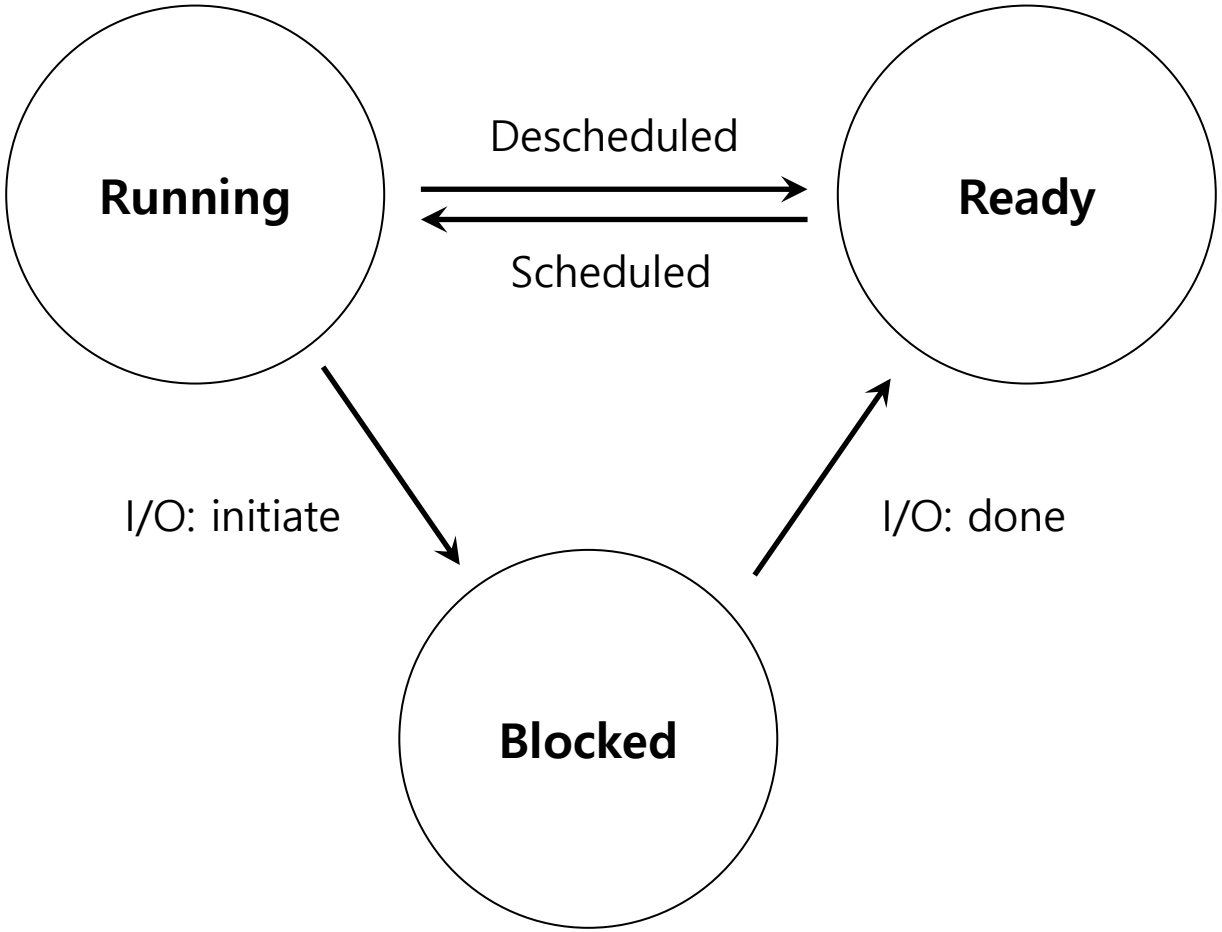


Loading:
Takes on-disk program and reads it into the address space of process

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 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**
    - Ready processes
    - Blocked processes
    - Current running process
  - **Register context**

- PCB(Process Control Block)
  - A C-structure that contains information about each process.

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 };
```

XV6 available in repo CODE/xv6

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
};
```

Mechanism: Limited Direct Execution

Operating System: Three Easy Pieces

How to efficiently virtualize the CPU with control?

- The OS needs to share the physical CPU by time sharing.
- Issue
  - **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 (without limits!)

- 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 (processor must support it)
  - 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 to user program, such as …
  - Accessing the file system
  - Creating and destroying processes
  - Communicating with other processes
  - Allocating more memory

But why they look like a regular procedure call "sometimes" (e.g., libc calls)?

System Call (Cont.)

- **Trap** instruction
  - Jump into the kernel (how to tell where?)
  - Raise (the processor) privilege level to kernel mode
- **Return-from-trap** instruction
  - Return into the calling user program
  - Reduce (the processor) privilege level back to user mode
- **Trap Table**

Limited Direction Execution Protocol

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

OS @ run (kernel mode)	Hardware	Program (user mode)
Create entry for process list 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 **proc kernel stack** move to user mode jump to main	
		Run main() … Call system **trap** into OS

Limited Direction Execution Protocol (Cont.)

OS @ run (kernel mode)	Hardware	Program (user mode)
	(Cont.)	
	save regs to **proc kernel stack** move to kernel mode jump to trap handler	
Handle trap Do work of syscall **return-from-trap**		
	restore regs from **proc 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		

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**
  - A Non-Cooperative Approach: **The OS takes control**

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
    - Try to access memory that it shouldn't be able to access
  - Ex) Early versions of the Macintosh OS, The old Xerox Alto system

A process gets stuck in an infinite loop.
→ Reboot the machine

A Non-Cooperative Approach: OS Takes Control

- **A timer interrupt**
  - During the boot sequence, the OS start the timer (hardware).
  - The timer raise an interrupt every so many milliseconds. (hardware)
  - 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 again on a CPU.

Saving and Restoring Context

- Scheduler makes a decision:
  - Whether to continue running the **current process or** switch to a **different one**.
  - If the decision is made to switch, the OS executes context switch.

Context Switch

- A low-level piece of assembly code
  - **Save a few register values** for the current process onto its kernel stack
    - General purpose registers
    - PC
    - kernel stack pointer
  - **Restore a few** 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
		...
	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)
	(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 …

The xv6 Context Switch Code

```
1 # void swtch(struct context **old, struct context *new);
2 #
3 # Save current register context in old
4 # and then load register context from new.
5 .globl swtch
6 swtch:
7         # Save old registers
8         movl 4(%esp), %eax          # put old ptr into eax
9         popl 0(%eax)                # save the old IP (pop from stack to mem)
10        movl %esp, 4(%eax)          # and stack
11        movl %ebx, 8(%eax)          # and other registers
12        movl %ecx, 12(%eax)
13        movl %edx, 16(%eax)
14        movl %esi, 20(%eax)
15        movl %edi, 24(%eax)
16        movl %ebp, 28(%eax)
17
18        # Load new registers
19        movl 8(%esp), %eax          # put new ptr into eax
20        movl 28(%eax), %ebp         # restore other registers
21        movl 24(%eax), %edi
22        movl 20(%eax), %esi
23        movl 16(%eax), %edx
24        movl 12(%eax), %ecx
25        movl 8(%eax), %ebx
26        movl 4(%eax), %esp          # stack is switched here
27        pushl 0(%eax)               # return addr put in place
28        ret                         # finally return into new ctxt
```

Current xv6 Code

```
# Context switch
#
#   void swtch(struct context **old, struct context *new);
#
# Save current register context in old
# and then load register context from new.

.globl swtch
swtch:
  movl 4(%esp), %eax
  movl 8(%esp), %edx

  # Save old callee-save registers
  pushl %ebp
  pushl %ebx
  pushl %esi
  pushl %edi

  # Switch stacks
  movl %esp, (%eax)
  movl %edx, %esp

  # Load new callee-save registers
  popl %edi
  popl %esi
  popl %ebx
  popl %ebp
  ret
```

No actual change to new `%eip`, because we need to "switch" memory addressing space before (done in the scheduler `switchkvm();`)

In `proc.h`
// Don't need to save `%eax, %ecx, %edx,` because the 46
// x86 convention is that the caller has saved them (I can overwrite them!)

Worried About Concurrency?

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

Scheduling: Introduction

Operating System: Three Easy Pieces

Scheduling: Introduction

- Workload assumptions:
  1. Each job runs for the **same amount of time.**
  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.

Single CPU!!

Scheduling Metrics

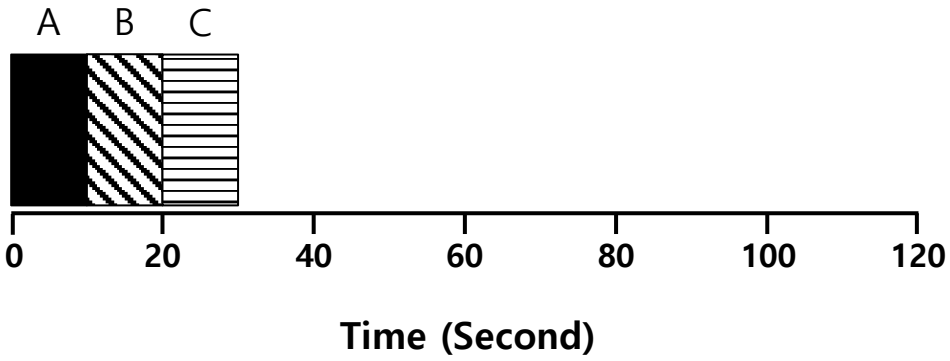
- Performance metric: Turnaround time
  - The time at which **the job completes** minus the time at which **the job arrived** in the system.

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

- 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:
  - A arrived just before B which arrived just before C.
  - Each job runs for 10 seconds.



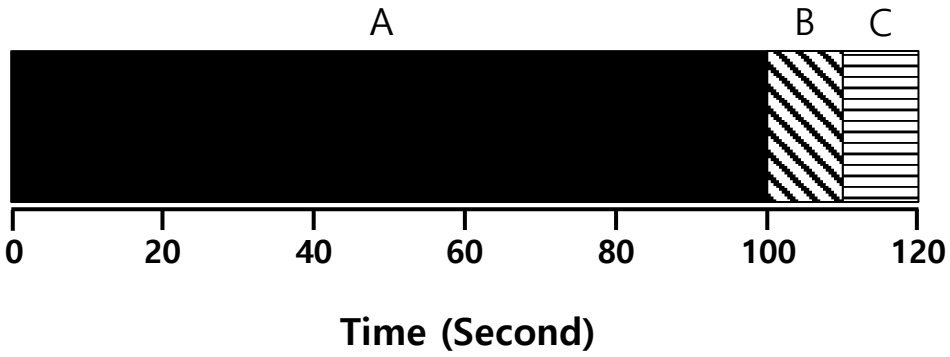
$$Average\ turnaround\ time = \frac{10 + 20 + 30}{3} = 20\ sec$$

Scheduling: Introduction

- Workload assumptions:
  1. Each job runs for the **same amount of time.**
  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.

Why FIFO is not that great? – Convoy effect

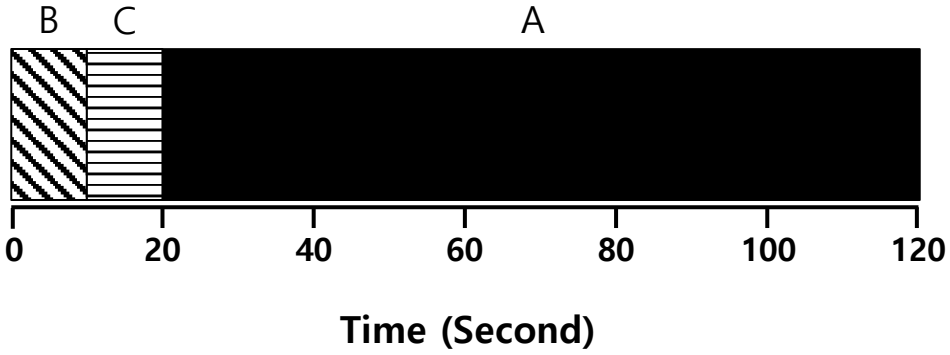
- Let's relax assumption 1: Each job **no longer** runs for the same amount of time.
- Example:
  - A arrived just before B which arrived just before C.
  - A runs for 100 seconds, B and C run for 10 each.



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

Shortest Job First (SJF)

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



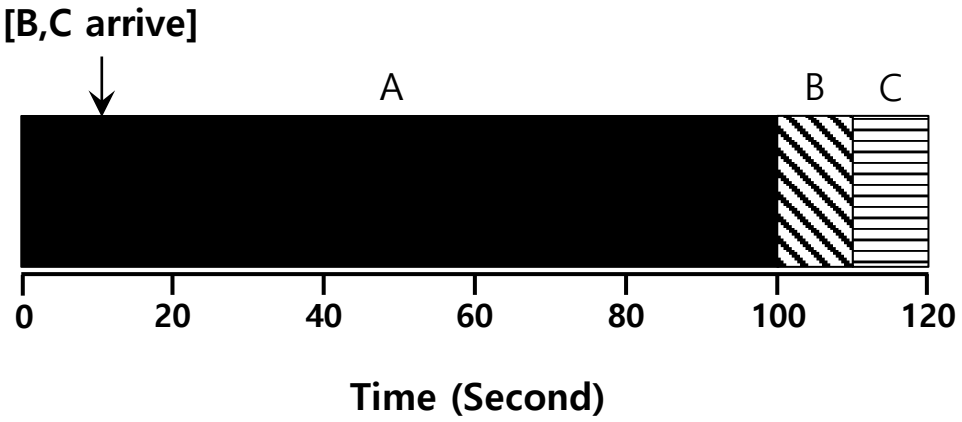
$$Average\ turnaround\ time = \frac{10 + 20 + 120}{3} = 50\ sec$$

Scheduling: Introduction

- Workload assumptions:
  1. Each job runs for the **same amount of time.**
  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.

SJF with Late Arrivals from B and C

- Let's relax assumption 2: 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



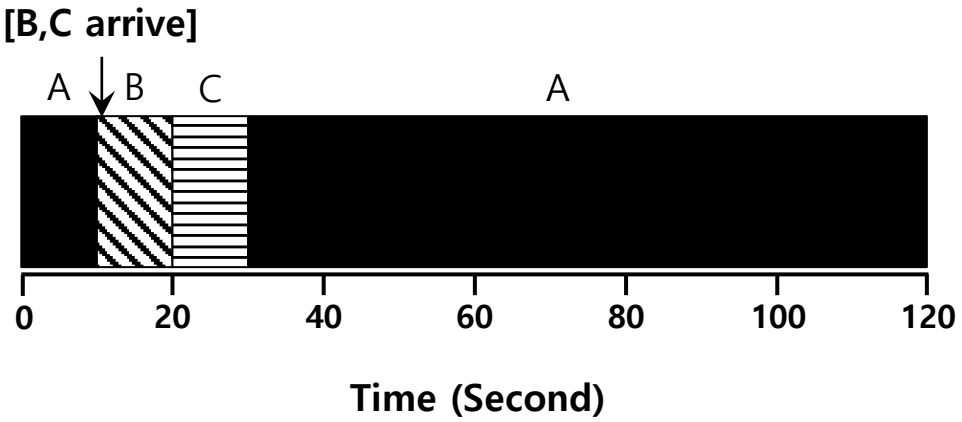
$$Average\ turnaround\ time = \frac{100 + (110 - 10) + (120 - 10)}{3} = 103.33\ sec$$

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 of the remaining jobs and new job
  - Schedule the job which has the lest 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



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

New scheduling metric: Response time

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

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

  - STCF and related disciplines are not particularly good for response time.

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

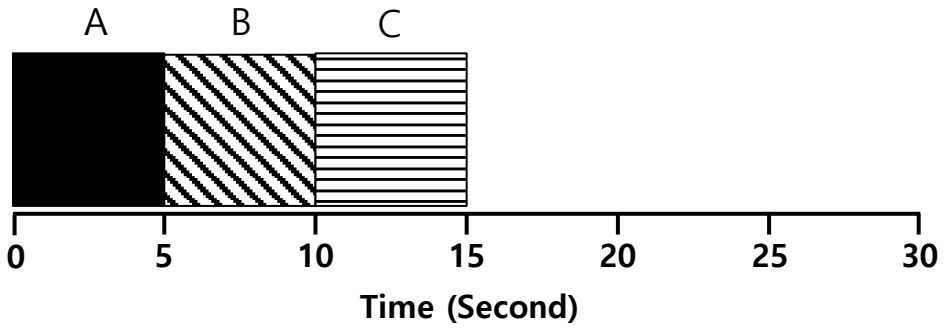
Round Robin (RR) Scheduling

- Time slicing Scheduling
  - Run a job for a time slice 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 the jobs are finished.
  - The length of a time slice must be *a multiple of* the timer-interrupt period.

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

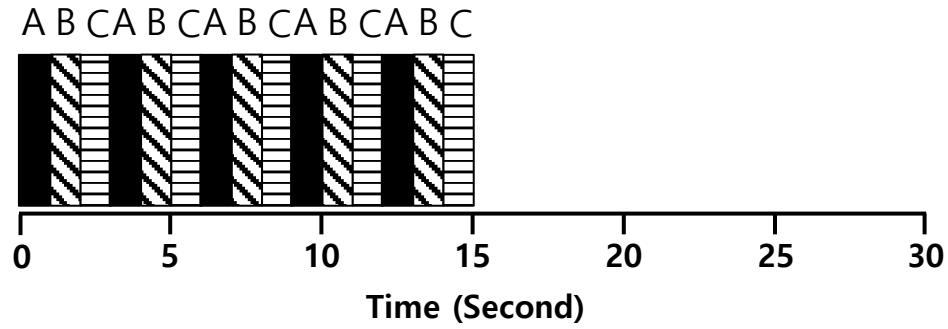
RR Scheduling Example

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



SJF (Bad for Response Time)

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



RR with a time-slice of 1sec (Good for Response Time)

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

The length of the time slice is critical.

- The shorter time slice
  - Better response time
  - The cost of context switching will dominate overall performance.
- The longer time slice
  - Amortize the cost of switching
  - Worse response time

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

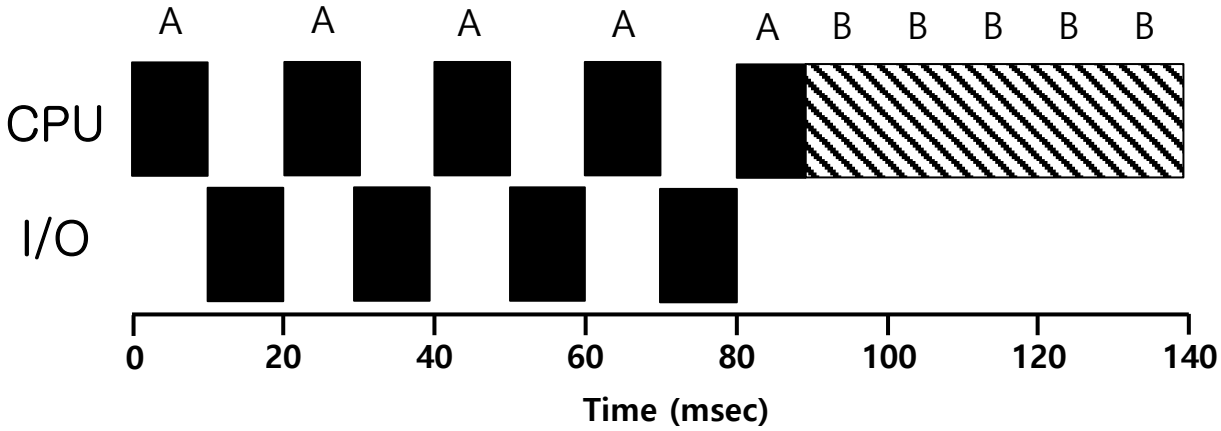
Scheduling: Introduction

- Workload assumptions:
  1. Each job runs for the **same amount of time.**
  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.

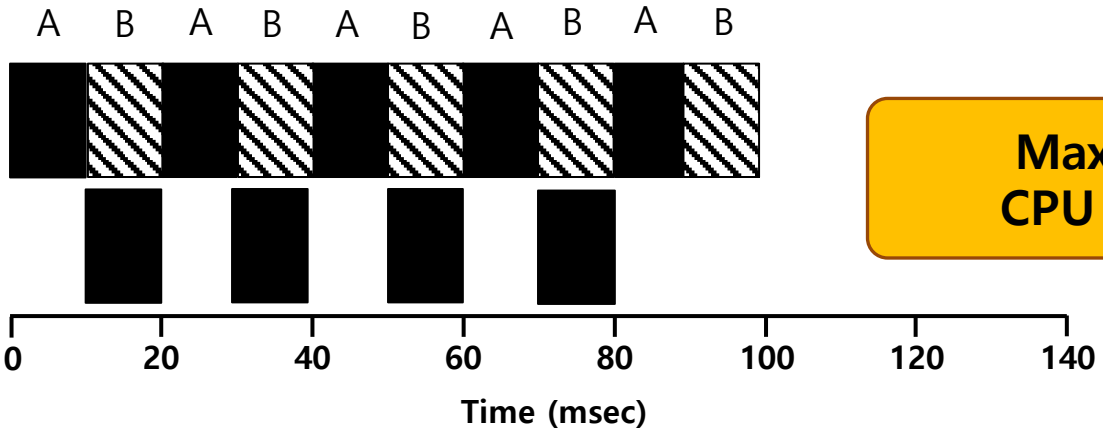
Incorporating I/O

- Let's relax assumption 3: All programs perform I/O
- Example:
  - A and B need 50ms of CPU time each.
  - A runs for 10ms and then issues an I/O request
    - 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 (Cont.)



Poor Use of Resources



Maximize the CPU utilization

Overlap Allows Better Use of Resources

Incorporating I/O (Cont.)

- When a job initiates an I/O request.
  - The job is blocked waiting for I/O completion.
  - The 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 ready state.
- No more Oracle (assumption 4)
  - In general purpose, the OS knows very little about the length of each job. How can build SJF/STCF without a priori knowledge?

Scheduling: Proportional Share

Operating System: Three Easy Pieces

Proportional Share Scheduler

- Fair-share scheduler
  - Guarantee that each job obtain *a certain percentage* of CPU time.
  - Not optimized for turnaround 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.
    - 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 runs it.
- Example
  - There are 100 tickets
    - Process A has 75 tickets: 0 ~ 74
    - Process B has 25 tickets: 75 ~ 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.

The beauty of randomness (in scheduling)

- Deals easily with corner-case situations
  - Others should have a lot of "ifs" to prevent them
- Little state required
  - No need to track the details of each process in the past
- Really fast
  - More speed → more pseudo-randomness (or HW assistance)

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)
    - Process A has 100 tickets
    - Process B has 100 tickets

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

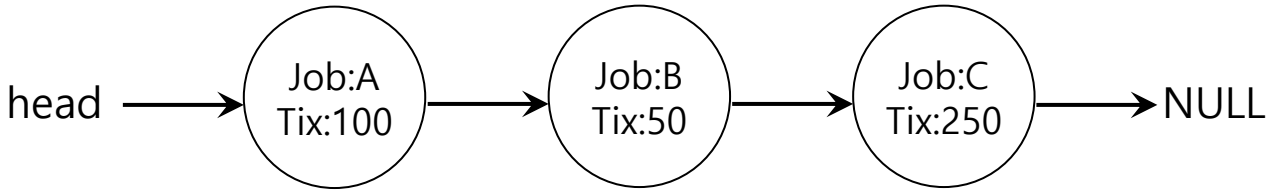
User B → *10* (B's currency) to B1 → *100* (global currency)

Ticket Mechanisms (Cont.)

- Ticket transfer
  - A process can temporarily hand off *its tickets* to another process.
- Ticket inflation
  - A process can temporarily raise or lower the number of tickets is 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:




```
1         // counter: used to track if we've found the winner yet
2         int counter = 0;
3
4         // winner: use some call to a random number generator to
5         // get a value, between 0 and the total # of tickets
6         int winner = getrandom(0, totaltickets);
7
8         // current: use this to walk through the list of jobs
9         node_t *current = head;
10
11        // loop until the sum of ticket values is > the winner
12        while (current) {
13                  counter = counter + current->tickets;
14                  if (counter > winner)
15                            break; // found the winner
16                  current = current->next;
17        }
18        // 'current' is the winner: schedule it...
```

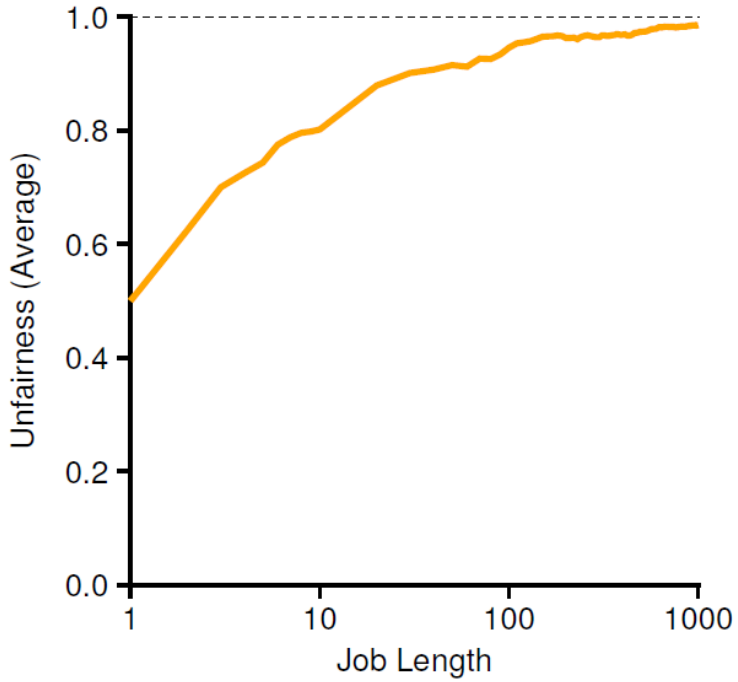
https://stackoverflow.com/questions/2509679/how-to-generate-a-random-integer-number-from-within-a-range

Implementation (Cont.)

- U: unfairness metric
  - The time the first job completes divided by the time that the second job completes.
- Example:
  - 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.

Lottery Fairness Study

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



When the job length is not very long, average unfairness can be quite severe.

Stride Scheduling (deterministic Fair-share scheduler)

- Stride of each process
  - Defined as (one large number) / (the number of tickets of the process)
  - Example: one large number = 10,000
    - Process A has 100 tickets → stride of A is 100
    - Process B has 50 tickets → stride of B is 200
    - Process C has 250 tickets → stride of C is 40

- A process runs, increment a counter(=pass value) for it by its stride.
  - Pick the process to run that has the lowest pass value

```
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

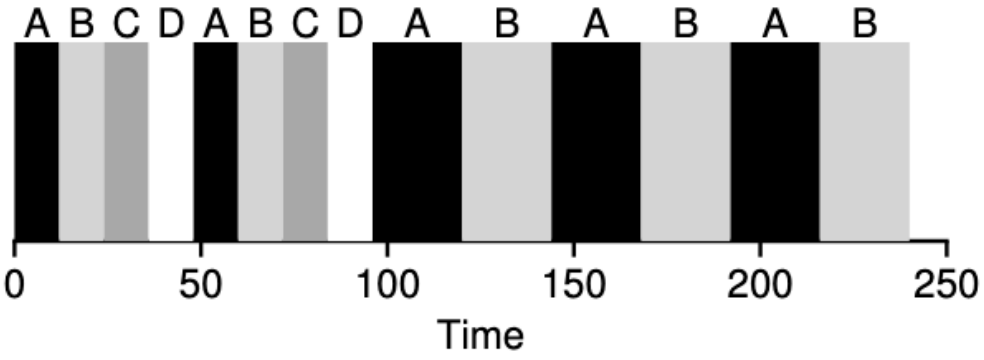
Pass(A) (stride=100)	Pass(B) (stride=200)	Pass(C) (stride=40)	Who Runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	120	C
200	200	160	C
200	200	200	...

**If new job enters with pass value 0,
It will monopolize the CPU!:
Stride scheduler requires global state (in contrast with lottery)**

Linux Completely Fair Scheduler (CFS)

- 5% overall datacenter CPU time wasted in scheduler

- Focus on fairness and minimizing scheduling overhead
  - Keep track of the (virtual) runtime of each process
  - At scheduling time, **chooses** the process with the **lowest virtual run time**
  - Time slice is variable: according number of ready to run processes (from **`sched_latency`** (48 ms) for 1 process to **`min_granularity`** (6 ms) for any number of processes



Niceness and Weights

- Time slice and virtual runtime of the process can be affected by weigh ts (niceness)

$$\texttt{time\_slice}_k = \frac{\texttt{weight}_k}{\sum_{n=0}^{n-1} \texttt{weight}_i} \cdot \texttt{sched\_latency}$$

- Typically, from -20 to 19
- By default, 0

```
static const int prio_to_weight[40] = {
    /* -20 */ 88761, 71755, 56483, 46273, 36291,
    /* -15 */ 29154, 23254, 18705, 14949, 11916,
    /* -10 */  9548,  7620,  6100,  4904,  3906,
    /*  -5 */  3121,  2501,  1991,  1586,  1277,
    /*   0 */  1024,   820,   655,   526,   423,
    /*   5 */   335,   272,   215,   172,   137,
    /*  10 */   110,    87,    70,    56,    45,
    /*  15 */    36,    29,    23,    18,    15,
};
```

Example

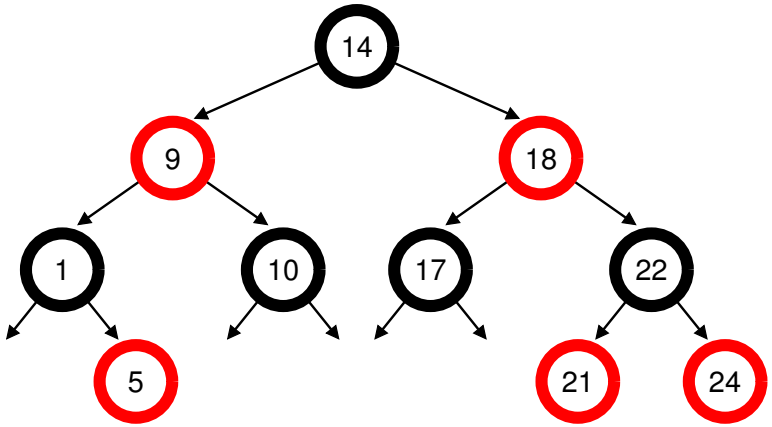
- Two process: A (niceness -5) B (niceness 0)
- $\texttt{weight}_A$=3121, `weightB`=1024
- `time_sliceA`=3/4 (36 ms), `time_sliceB`=1/4 (12 ms) of `sched_latency (48 ms)`
- Also, virtual runtime changes with weights

$$\texttt{vruntime}_i = \texttt{vruntime}_i + \frac{\texttt{weight}_0}{\texttt{weight}_i} \cdot \texttt{runtime}_i$$

- A accumulates virtual runtime at 1/3 of B

Linux Completely Fair Scheduler (CFS)

- Minimal scheduler overhead
  - Data structures should be scalable: No lists
  - CFS uses a balanced tree (red-black tree) of the ready-to-run processes
  - O(log n) insertions and searches



- Many more details
  - I/O is handled faking the `vruntime` of the awaken process to the minimum value in the t ree
  - Heuristics for multi-CPU scheduling (cache affinity, frequency, core complexity…)
  - Cooperative multi-process schedule

The Abstraction: Address Space

Operating System: Three Easy Pieces

Memory Virtualization

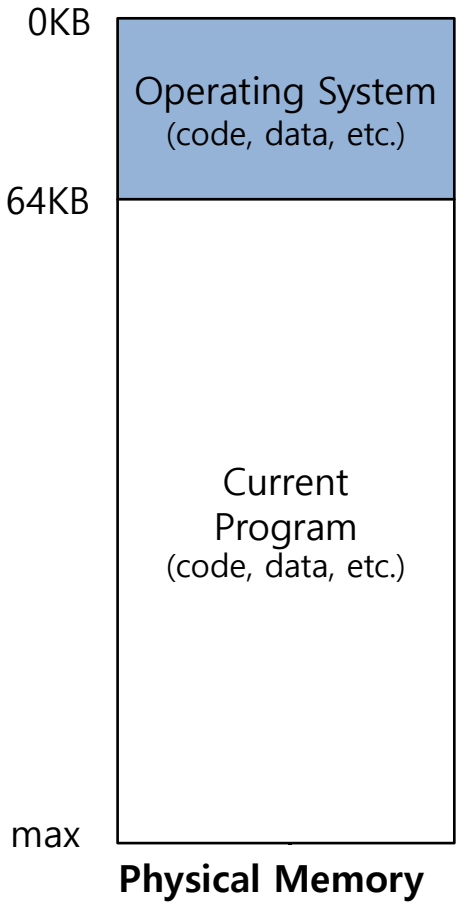
- What is **memory virtualization**?
  - OS virtualizes its physical memory.
  - OS provides an illusion memory space per each process.
  - It seems to be seen like each process uses the whole memory .

Benefit of Memory Virtualization

- Ease of use in programming
- Memory efficiency in terms of time and space
- The guarantee of isolation for processes as well as OS
  - Protection from errant accesses of other processes

OS in The Early System

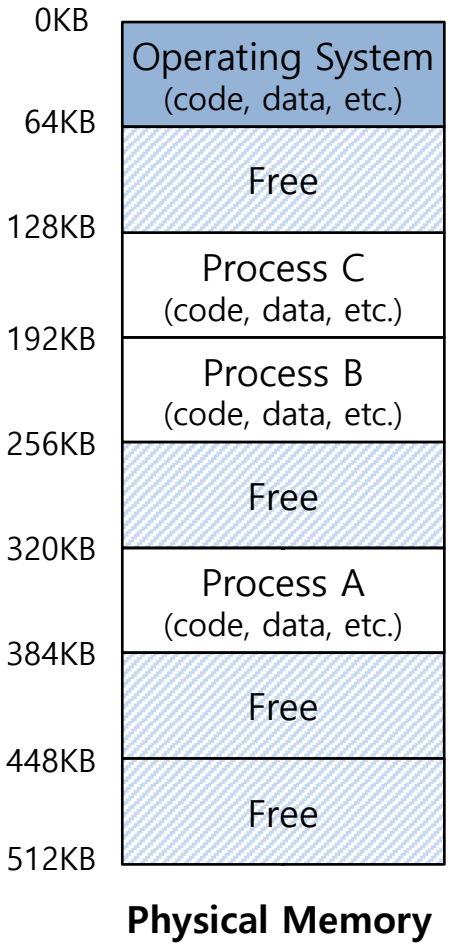
- Load only one process in memory.
  - Poor utilization and efficiency



Perhaps in the future too? -- Unikernels

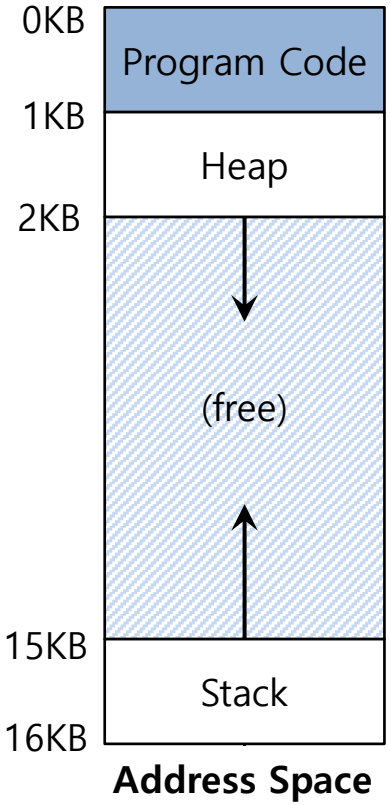
Multiprogramming and Time Sharing

- **Load multiple processes** in memory.
  - Execute one for a short while.
  - Switch processes between them in memory.
  - Increase utilization and efficiency.
- Cause an important **protection issue**.
  - Errant memory accesses from other processes



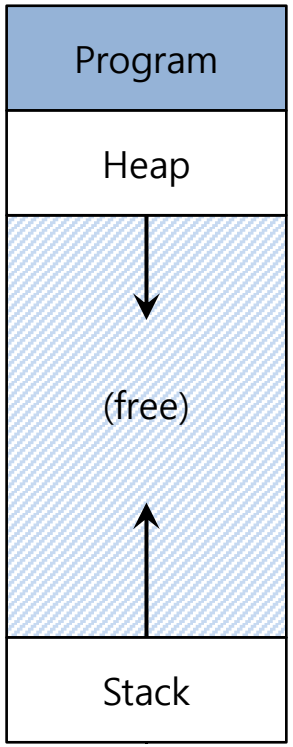
Address Space

- OS creates an **abstraction** of physical memory.
  - The address space contains all about a running process.
  - That is consist of program code, heap, stack and etc.



Address Space(Cont.)

- Program
  - Where instructions and static data live
- Heap
  - Dynamically allocate memory.
    - `malloc/free` in C language
    - `new/delete` in object-oriented language
  - Implicitly handled in (memory) managed languages
- Stack
  - Store return addresses or values.
  - Contain local variables arguments to routines.
  - Implicitly handled in HLL



Address Space

Virtual Address

- **Every address** in a running program is virtual.
  - OS provides the "mechanism" to translate the virtual address to physical address
  - HW assists to make such translation "painless"

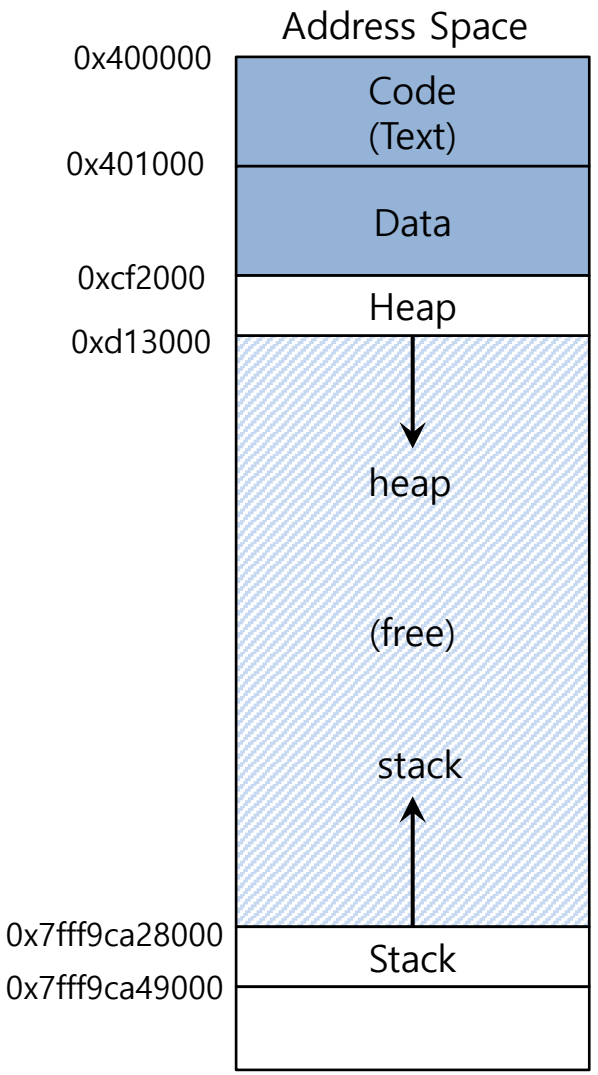
```
#include <stdio.h>
#include <stdlib.h>
int global=1;
int main(int argc, char *argv[])
{
    int x = 3;
    printf("location of code  : %p\n", (void *) main);
    printf("location of data  : %p\n", (void *) &global);
    printf("location of heap  : %p\n", (void *) malloc(1));
    printf("location of stack : %p\n", (void *) &x);

    return x;
}
```

A simple program that prints out addresses

Virtual Address(Cont.)

- The output in 64-bit Linux machine

```
location of code  : 0x40057d
location of data  : 0x401010
location of heap  : 0xcf2010
location of stack : 0x7fff9ca45fcc
```



Goals of VM

- Transparency
  - VM should be invisible to running program
- Efficiency
  - Minimize overhead in terms of speed and space
- Protection
  - Isolate processes (and OS itself) [but allowing selective "communication"]

Paging: Introduction

Operating System: Three Easy Pieces

Concept of Paging

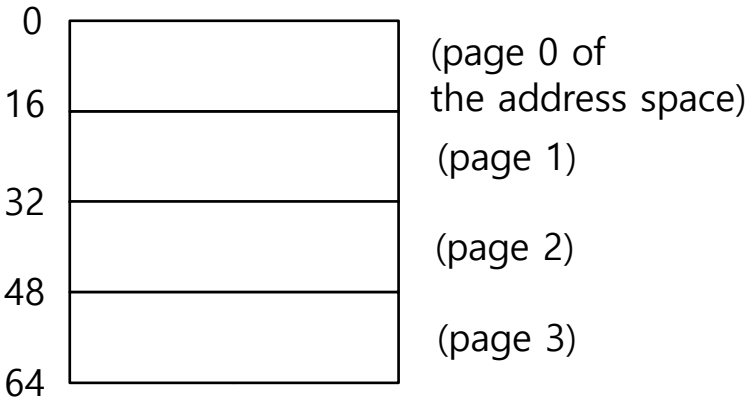
- Paging **splits up** address space into **fixed-zed** unit called a **page**.
  - Segmentation: variable size of logical segments(code, stack, heap, etc.)

- With paging, **physical memory** is also **split** into some number of pages called a **page frame**.

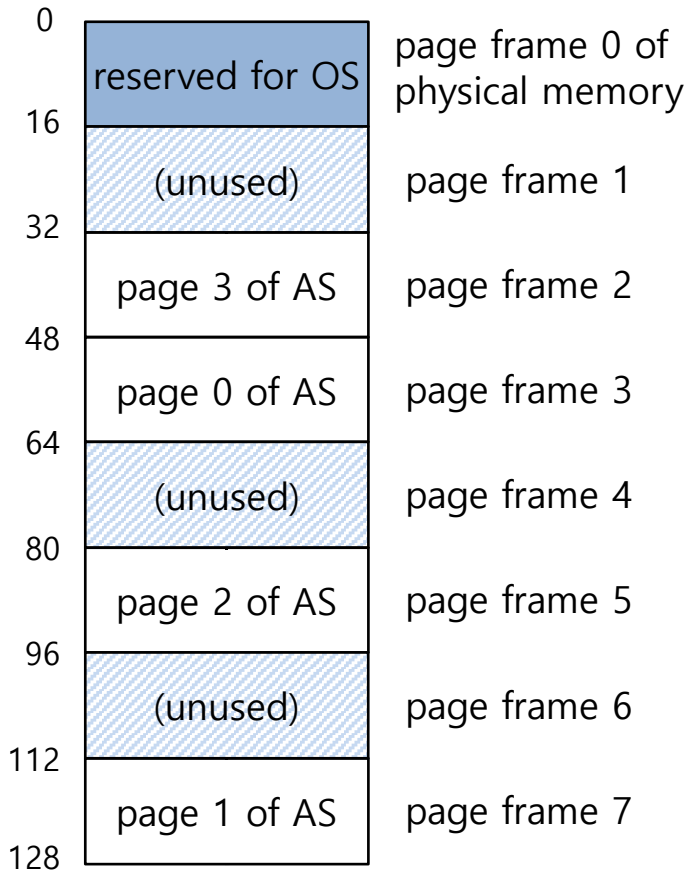
- **Page table** per process is needed **to translate** the virtual address to physical address.

Toy Example: A Simple Paging

- 128-byte physical memory with 16 bytes page frames
- 64-byte address space with 16 bytes pages, 1 byte addressable



A Simple 64-byte Address Space



64-Byte Address Space Placed In Physical Memory

Advantages Of Paging

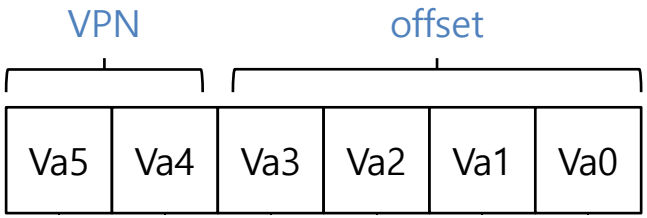
- **Flexibility:** Supporting the abstraction of address space effectively
  - Don't need assumption how heap and stack grow and are used.

- **Simplicity**: ease of free-space management
  - The page in address space and the page frame are the same size.
  - Easy to allocate and keep a free list

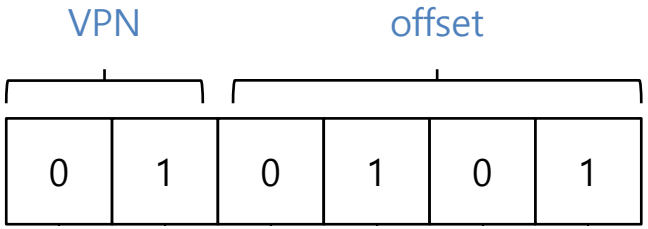
- *Con: the semantic meaning of the content is lost…*

Address Translation

- Two components in the virtual address
  - VPN: virtual page number
  - Offset: offset within the page



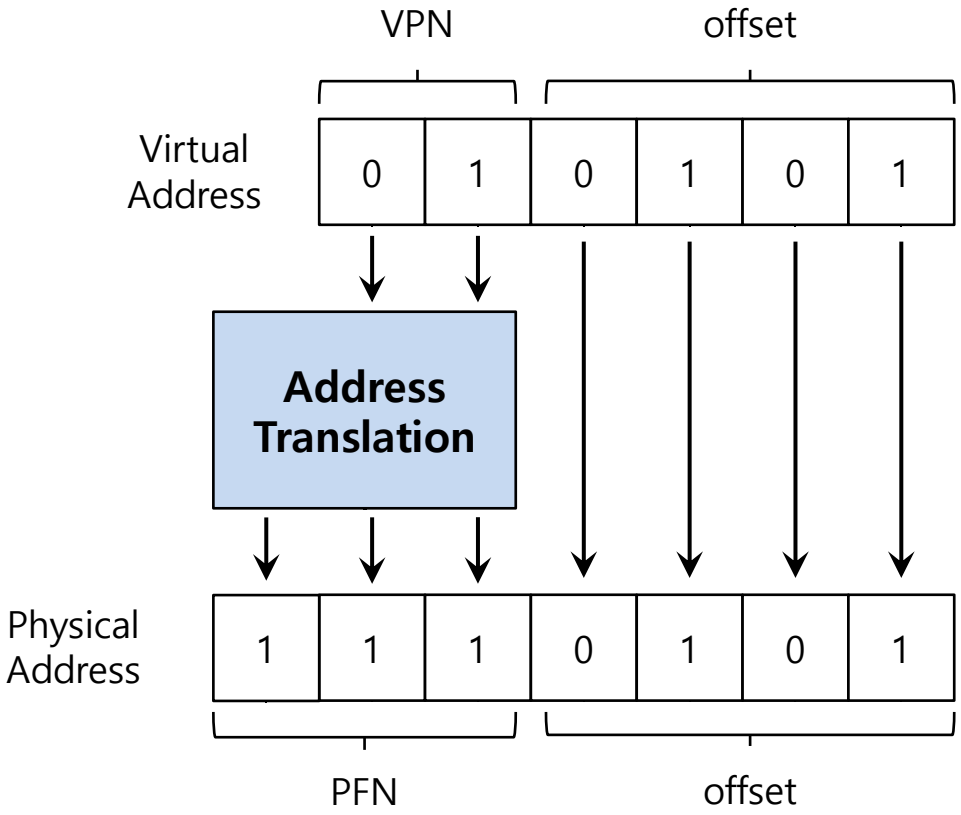
- Example: virtual address 21 in 64-byte address space with 16-Byte pages




```
movl 21, %eax
```

Example: Address Translation

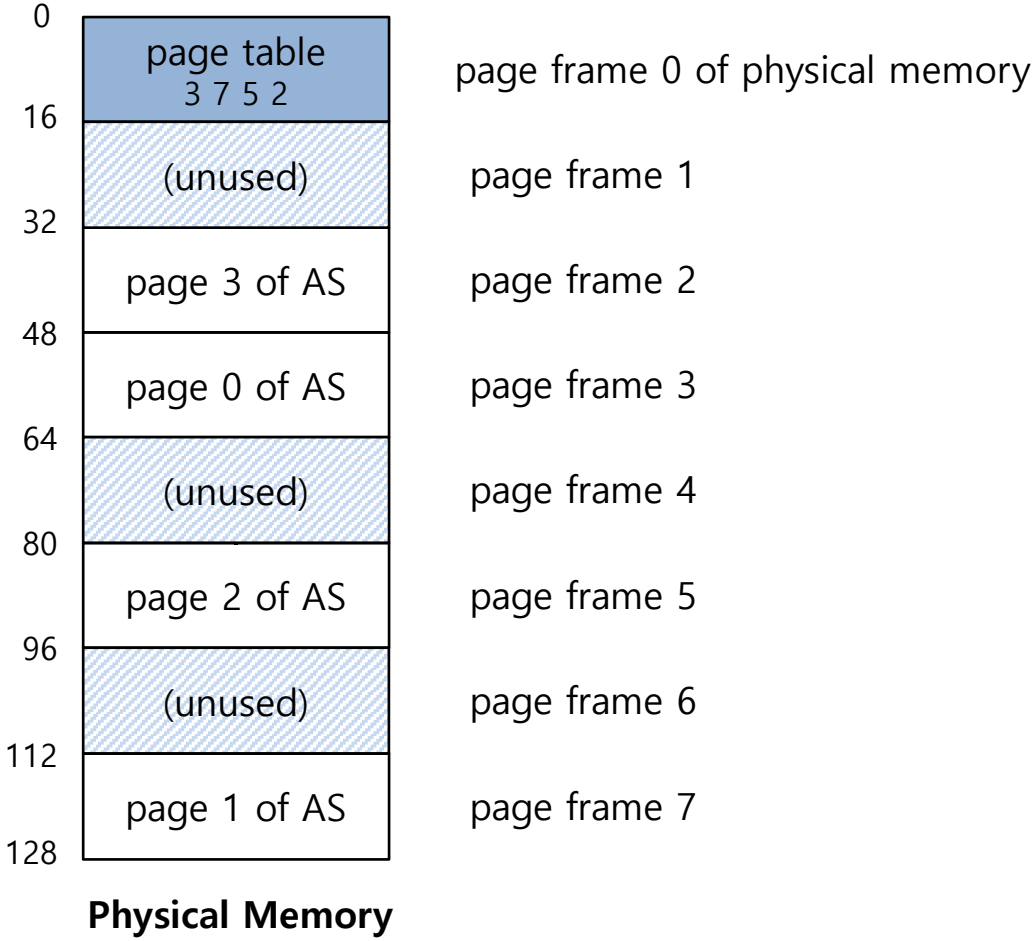
- The virtual address 21 in 64-byte address space with 16-Byte pages



Where Are Page Tables Stored?

- Page tables can get awfully large
  - 32-bit address space with 4-KB pages, 20 bits for VPN
    - $4MB = 2^{20}\ entries * 4\ Bytes\ per\ page\ table\ entry$
- Page tables **for each process** are stored in memory.

Example: Page Table in Kernel Physical Memory



What Is In The Page Table?

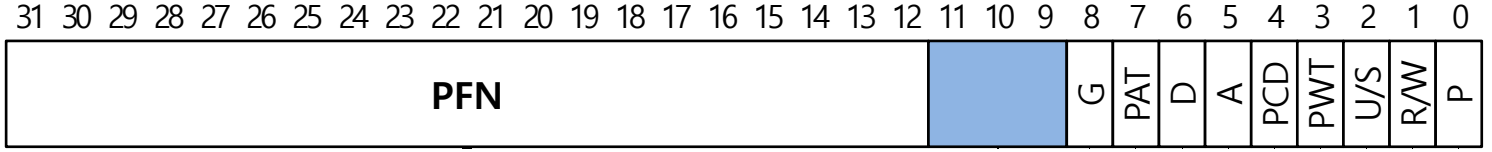
- The page table is just a **data structure** that is used to map the virtual address to physical address.
  - Simplest form: a linear page table, an array

- The OS **indexes** the array by VPN, and looks up the page-table entry.

Common Flags Of Page Table Entry (PTE)

- **Valid Bit**: Indicating whether the particular translation is valid.
- **Protection Bit**: Indicating whether the page could be read from, written to, or executed from
- **Present Bit**: Indicating whether this page is in physical memory or on disk(swapped out)
- **Dirty Bit**: Indicating whether the page has been modified since it was brought into memory
- **Reference Bit(Accessed Bit):** Indicating that a page has been accessed

Example: x86 Page Table Entry



An x86 Page Table Entry(PTE)

- P: present
- R/W: read/write bit
- U/S: supervisor
- A: accessed bit
- D: dirty bit
- PFN: the page frame number
- (PWT, PCD, PAT, and G): how hardware caching should work there

Paging: Too Slow

- To find a location of the desired PTE, the **starting location** of the page table is **needed**.
  - Page tables are too big to be stored in MMU

- For every memory reference, paging requires the OS to perform one **extra memory reference**.

Accessing Memory With Paging

```
1         // Extract the VPN from the virtual address SHIFT=4  VPN_MASK=0x30
2         VPN = (VirtualAddress & VPN_MASK) >> SHIFT
4         // Form the address of the page-table entry (PTE)
5         PTEAddr = PTBR + (VPN * sizeof(PTE))
6
7         // Fetch the PTE ~PTBR[VPN]
8         PTE = AccessMemory(PTEAddr)
9
10        // Check if process can access the page
11        if (PTE.Valid == False):
12                  RaiseException(SEGMENTATION_FAULT)
13        else if (CanAccess(PTE.ProtectBits) == False):
14                  RaiseException(PROTECTION_FAULT)
15        else:
16                  // Access is OK: form physical address and fetch it
17                  offset = VirtualAddress & OFFSET_MASK
18                  PhysAddr = (PTE.PFN << PFN_SHIFT) | offset
19                  Register = AccessMemory(PhysAddr)
```

A Memory Trace

- Example: A Simple Memory Access

```
int array[1000];
...
for (i = 0; i < 1000; i++)
        array[i] = 0;
```

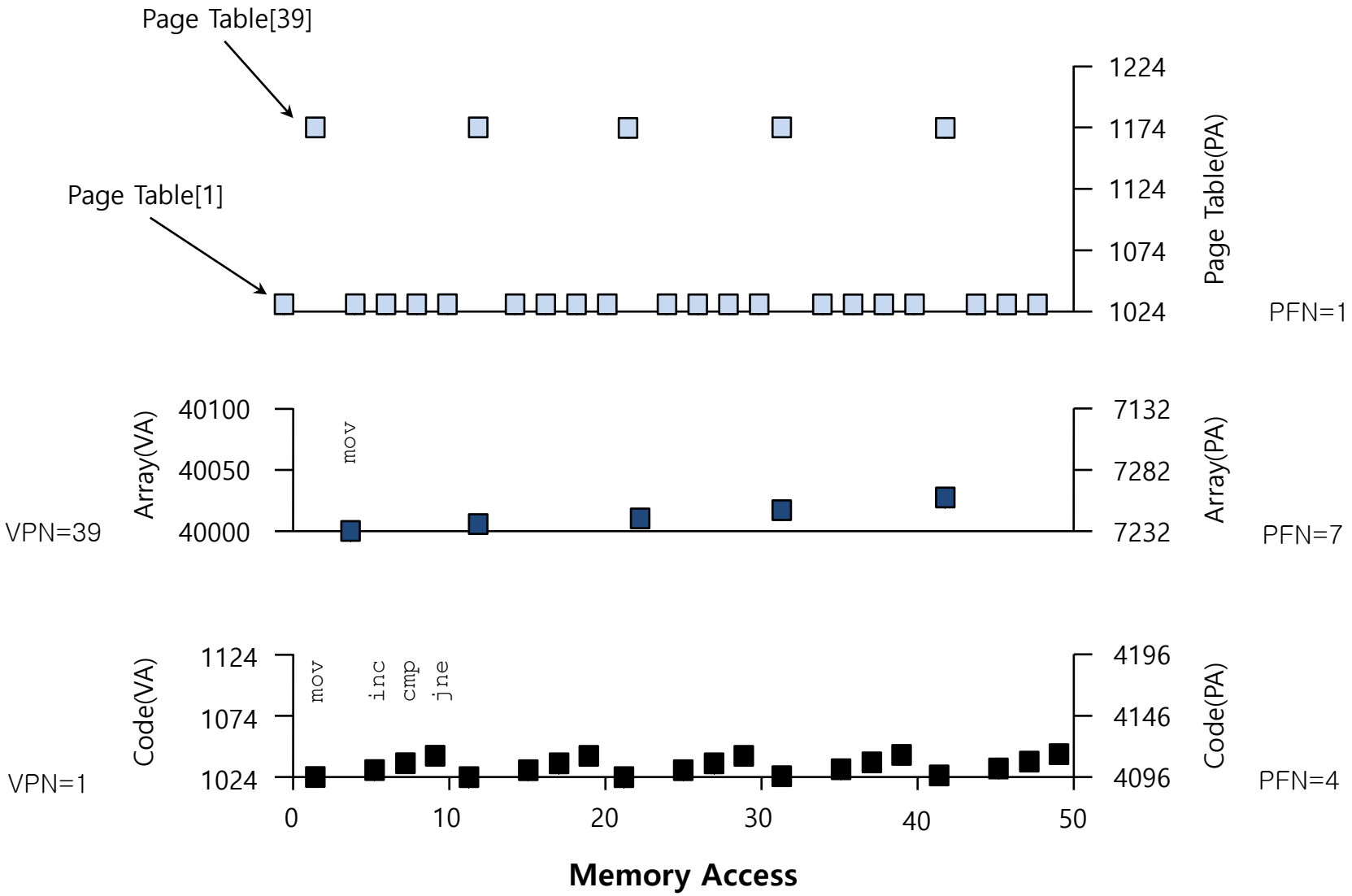
- Compile and execute

```
prompt> gcc -o array array.c -Wall -o
prompt>./array
```

- Resulting Assembly code (`objdump -d`)

```
0x1024 movl $0x0,(%edi,%eax,4)   #Power of CISC! edi+eax*4
0x1028 incl %eax                 #Increase counter
0x102c cmpl $0x03e8,%eax         #Check if last element
0x1030 jne 0x1024                #Implicit (eflags) Zero bit access
```

A Virtual(And Physical) Memory Trace: 64KB VAS, 1KB pages

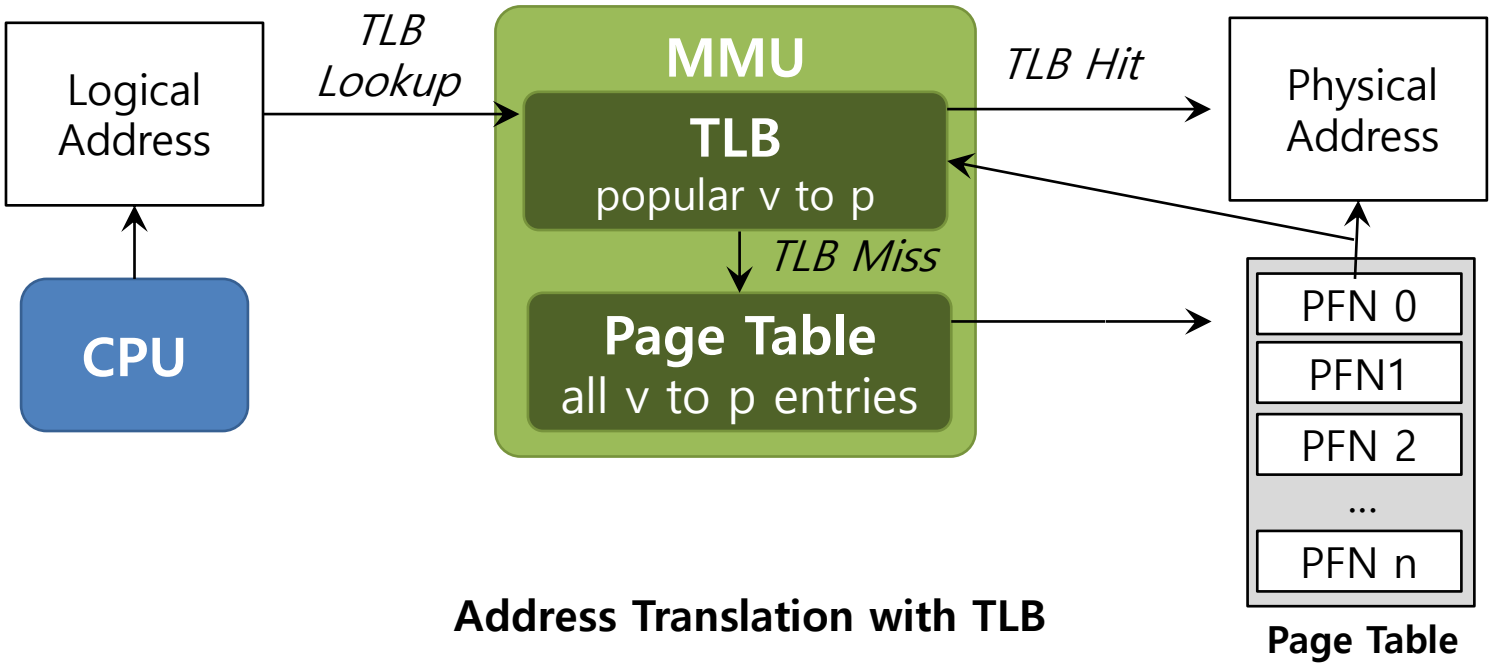


Translation Lookaside Buffers

Operating System: Three Easy Pieces

TLB

- Part of the chip's memory-management unit(MMU).
- A hardware cache of **popular** virtual-to-physical address translation.



Address Translation with TLB

TLB Basic Algorithms

```
1: VPN = (VirtualAddress & VPN_MASK ) >> SHIFT
2: (Success , TlbEntry) = TLB_Lookup(VPN)
3: if(Success == True ){ // TLB Hit
4:    if(CanAccess(TlbEntry.ProtectBit) == True ){
5:        offset = VirtualAddress & OFFSET_MASK
6:        PhysAddr = (TlbEntry.PFN << SHIFT) | Offset
7:        AccessMemory( PhysAddr )
8:     }else RaiseException(PROTECTION_ERROR)
```

- (1 lines) extract the virtual page number (VPN).
- (2 lines) check if the TLB holds the translation for this VPN.
- (5-8 lines) extract the page frame number from the relevant TLB entry, and form the desired physical address and access memory.

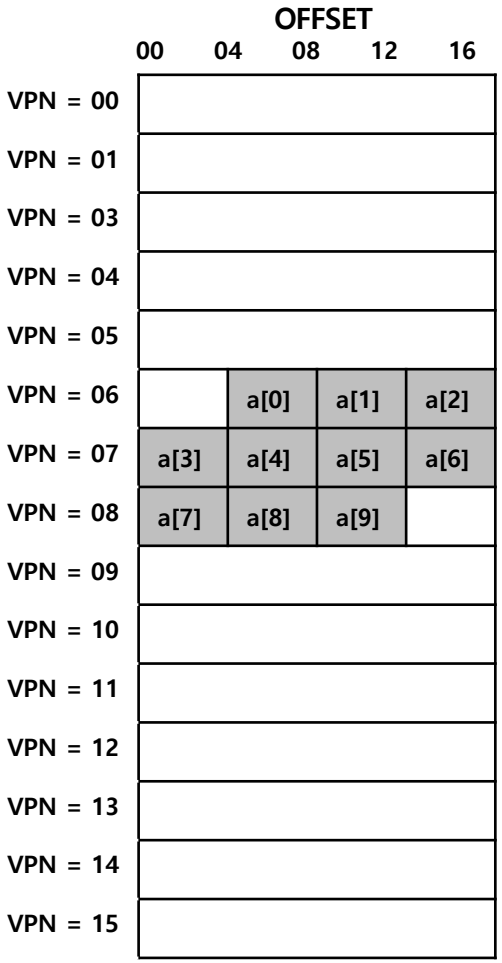
TLB Basic Algorithms (Cont.)

```
11:     }else{ //TLB Miss
12:         PTEAddr = PTBR + (VPN * sizeof(PTE))
13:         PTE = AccessMemory(PTEAddr)
14:         if (PTE.Valid == False) {
15:               RaiseException(SEGMENTATION_FAULT)
16:         }else if (CanAccess(PTE.ProtectBits) == False){
17:               RaiseException(PROTECTION_FAULT)
18:         }else{
19:             TLB_Insert( VPN , PTE.PFN , PTE.ProtectBits)
20:             RetryInstruction()}
21:     }
22:}
```

- (11-13 lines) Accesses the page table to find the translation.
- (13-17 lines) Check if PTE is ok
- (19 lines) updates the TLB with the translation.

Example: Accessing An Array

- How a TLB can improve its performance.



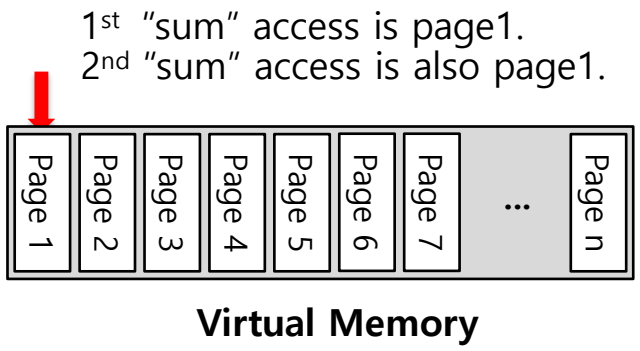

```
0:      int sum = 0 ;
1:      for( i=0; i<10; i++){
2:              sum+=a[i];
3:      }
```

The TLB improves performance due to spatial locality

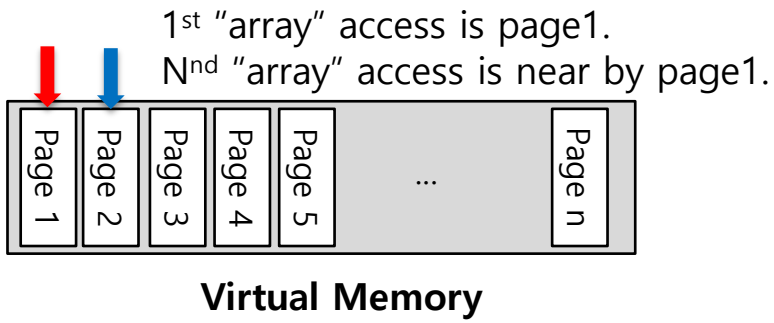
3 misses and 7 hits.
Thus, TLB hit rate is 70%.

Locality

- Temporal Locality
  - An instruction or data item that has been recently accessed will likely be re-accessed soon in the future.



- Spatial Locality
  - If a program accesses memory at address `x`, it will likely soon access memory near `x`.



Who Handles The TLB Miss?

- Hardware handle the TLB miss entirely on **CISC**.
  - The hardware has to know exactly where the page tables are located in memory.
  - The hardware would "walk" the page table (TLB walker), find the correct page-table entry and **extract** the desired translation, **update** and **retry** instruction. This is the previous algorithm.
  - **hardware-managed TLB.**

Who Handles The TLB Miss? (Cont.)

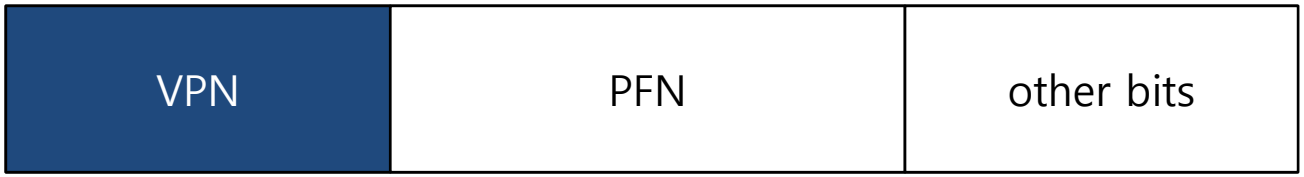
- **RISC** have what is known as a **software-managed TLB.**
  - On a TLB miss, the hardware raises exception(trap handler).
    - **Trap handler is code** within the OS that is written with the express purpose of **handling TLB miss.**

TLB Control Flow algorithm(OS Handled)

```
1:        VPN = (VirtualAddress & VPN_MASK) >> SHIFT
2:        (Success, TlbEntry) = TLB_Lookup(VPN)
3:        if (Success == True){ // TLB Hit
4:                if (CanAccess(TlbEntry.ProtectBits) == True){
5:                        Offset = VirtualAddress & OFFSET_MASK
6:                        PhysAddr = (TlbEntry.PFN << SHIFT) | Offset
7:                        Register = AccessMemory(PhysAddr)}
8:                else{
9:                        RaiseException(PROTECTION_FAULT)}}
10:       else {// TLB Miss
11:                RaiseException(TLB_MISS)}
```

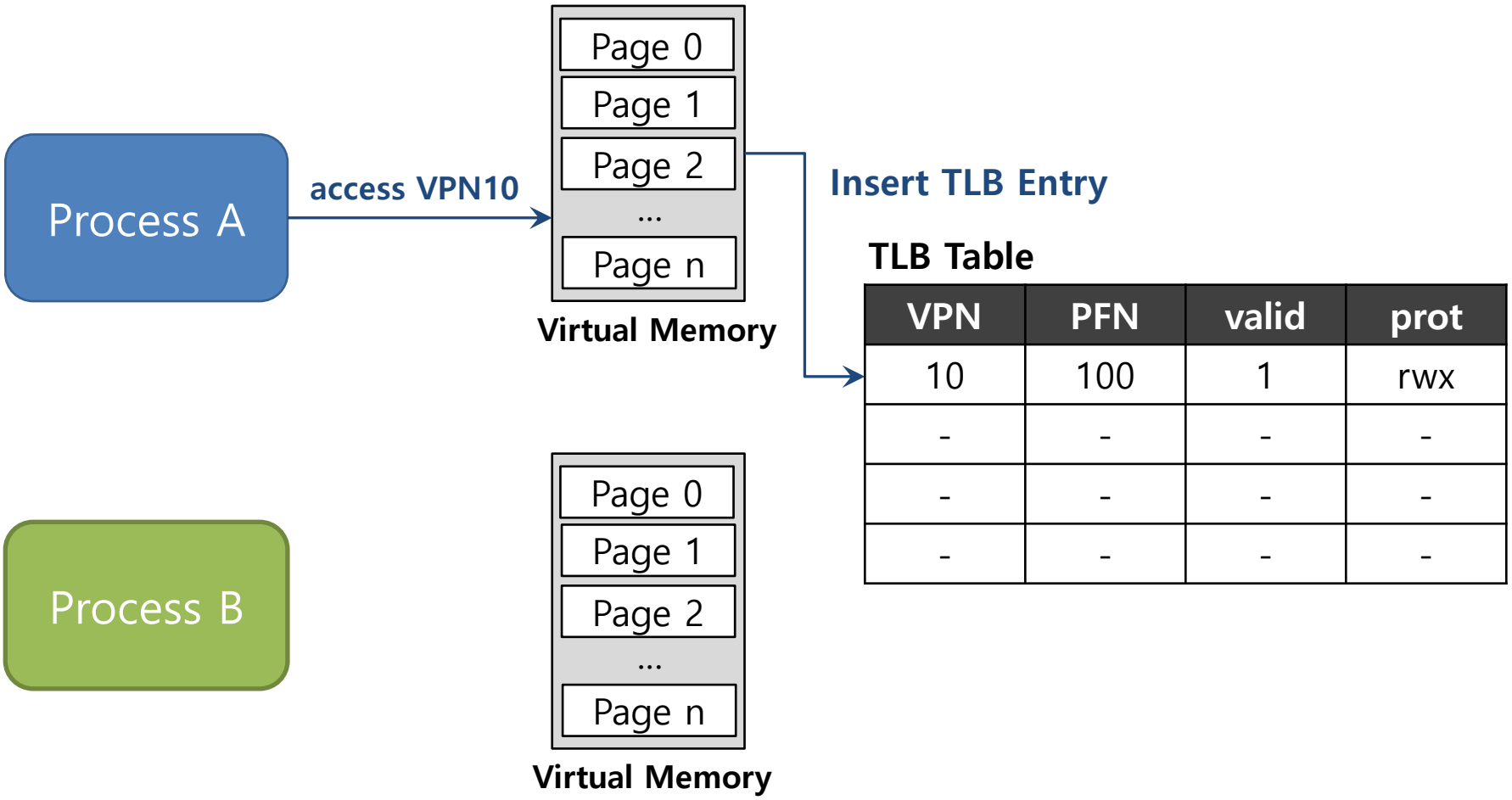
TLB entry

- TLB is managed by **Full Associative** method.
  - A typical TLB might have 32 to 128 entries.
  - Hardware search the entire TLB in parallel to find the desired translation (i.e., a cache without index bit, i.e., tag=VPN)
  - other bits: valid bits , protection bits, address-space identifier, dirty bit



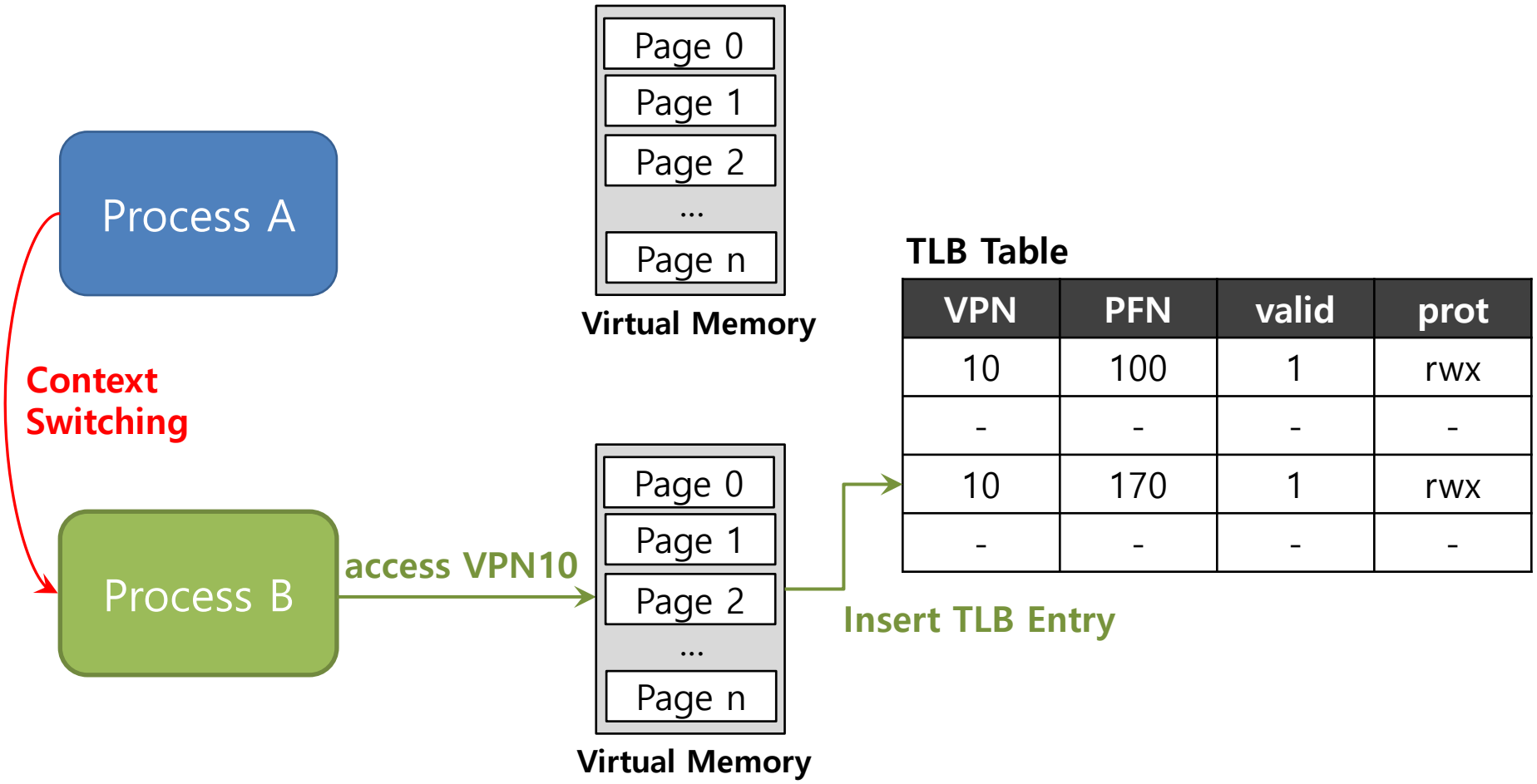
Typical TLB entry look like this

TLB Issue: Context Switching



VPN	PFN	valid	prot
10	100	1	rwx
-	-	-	-
-	-	-	-
-	-	-	-

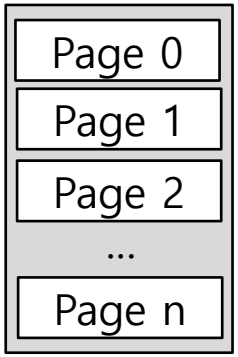
TLB Issue: Context Switching



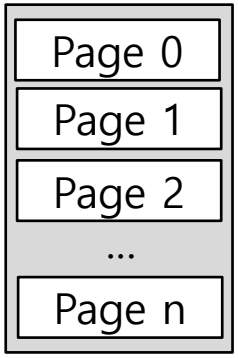
TLB Issue: Context Switching

Process A

Process B



Virtual Memory



Virtual Memory

TLB Table

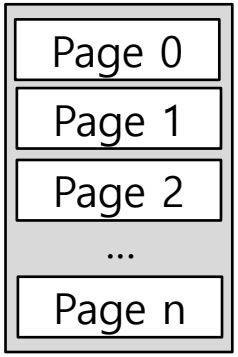
VPN	PFN	valid	prot
10	100	1	rwx
-	-	-	-
10	170	1	rwx
-	-	-	-

Can't Distinguish which entry is meant for which process

To Solve Problem

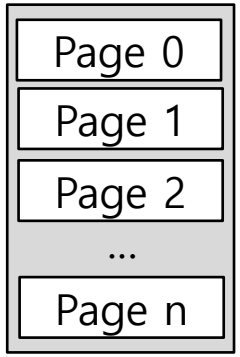
- Provide an address space identifier(ASID) field in the TLB.

Process A



Virtual Memory

Process B



Virtual Memory

TLB Table

VPN	PFN	valid	prot	ASID
10	100	1	rwx	1
-	-	-	-	-
10	170	1	rwx	2
-	-	-	-	-

Another Case

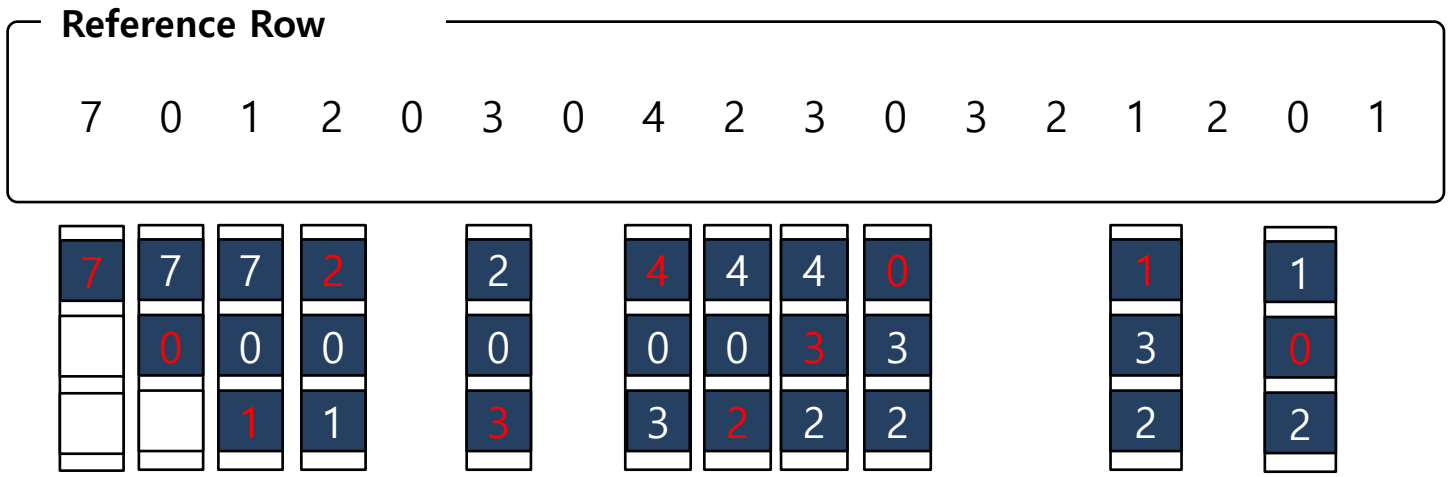
- Two processes share a page.
  - Process 1 is sharing physical page 101 with Process2.
  - P1 maps this page into the 10th page of its address space.
  - P2 maps this page to the 50th page of its address space.

VPN	PFN	valid	prot	ASID
10	101	1	rwx	1
-	-	-	-	-
50	101	1	rwx	2
-	-	-	-	-

Sharing of pages is useful as it reduces the number of physical pages in use.

TLB Replacement Policy

- LRU(Least Recently Used)
  - Evict an entry that has not recently been used.
  - Take advantage of *locality* in the memory-reference stream.



Total 11 TLB miss

TLB Performance Overhead on hits

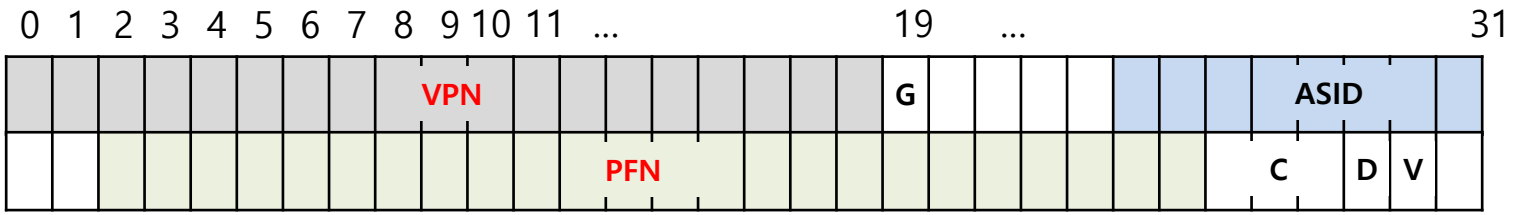
- Zero

- Since Offset VA == Offset PA, if offset is smaller than L1I, L1D way size we can search in L1 and TLB in parallel

- Cache associativity is tunned to this
  - L1 ~32KB, 8-way set associative ~64KB, 16-way set associative
  - Pages >= 4KB

A Real TLB Entry

All 64 bits of this TLB entry(example of MIPS R4000)

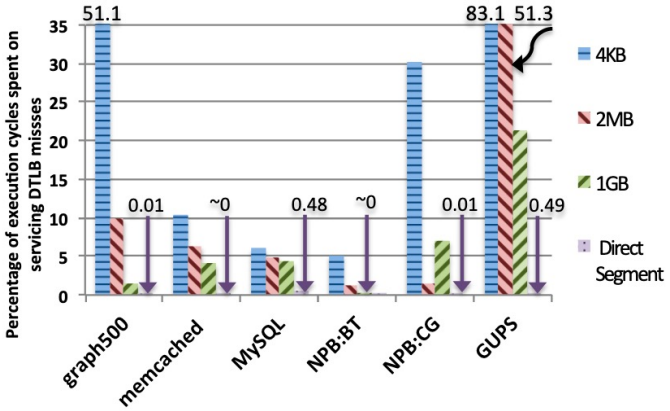


Flag	Content
19-bit VPN	The rest reserved for the kernel.
24-bit PFN	Systems can support with up to 64GB of main memory($2^{24} * 4KB$ pages).
Global bit(G)	Used for pages that are globally-shared among processes (ignore ASID).
ASID	OS can use to distinguish between address spaces.
Coherence bit(C)	determine how a page is cached by the hardware.
Dirty bit(D)	marking when the page has been written.
Valid bit(V)	tells the hardware if there is a valid translation present in the entry.

ISA provides the mechanisms to control the TLB content:
`TLBP` (probe), `TLBR`(read), `TLBWI` (replace index),
`TLBWRI` (replace random)

TLB today

- Applications with very large memory footprint might be heavily impacted by TLB size (i.e., the locality of the code/data is too large exceeding **TLB-coverage**)
  - Data/Instruction Separate TLBs
  - Multiple level TLB
  - Mega pages
  - No TLB ➔ no pages for a fraction of the address space



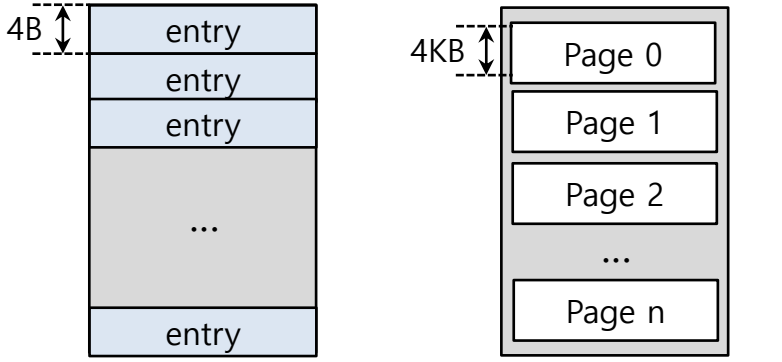
- TLB is an itchy issue for virtualization
  - Complex hardware support required to minimize performance overheads
  - Nested and deep multilevel page tables makes is TLB performance critical

Paging: Smaller Tables

Operating System: Three Easy Pieces

Paging: Linear Tables

- We usually have one page table for **every process** in the system.
  - Assume that 32-bit address space with 4KB pages and 4-byte page-table entry.

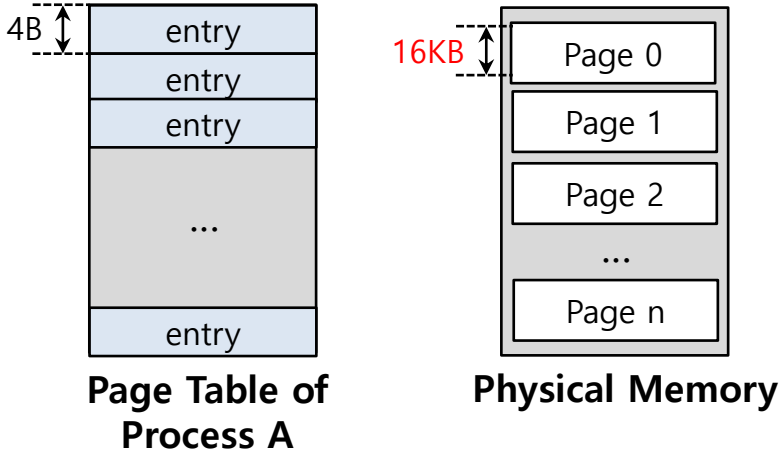


$$\text{Page table size} = \frac{2^{32}}{2^{12}} * 4Byte = 4MByte$$

Page tables are too big and thus consume too much memory.

Paging: Smaller Tables

- Page table are too big and thus consume too much memory.
  - Assume that 32-bit address space with 16KB pages and 4-byte page-table entry.

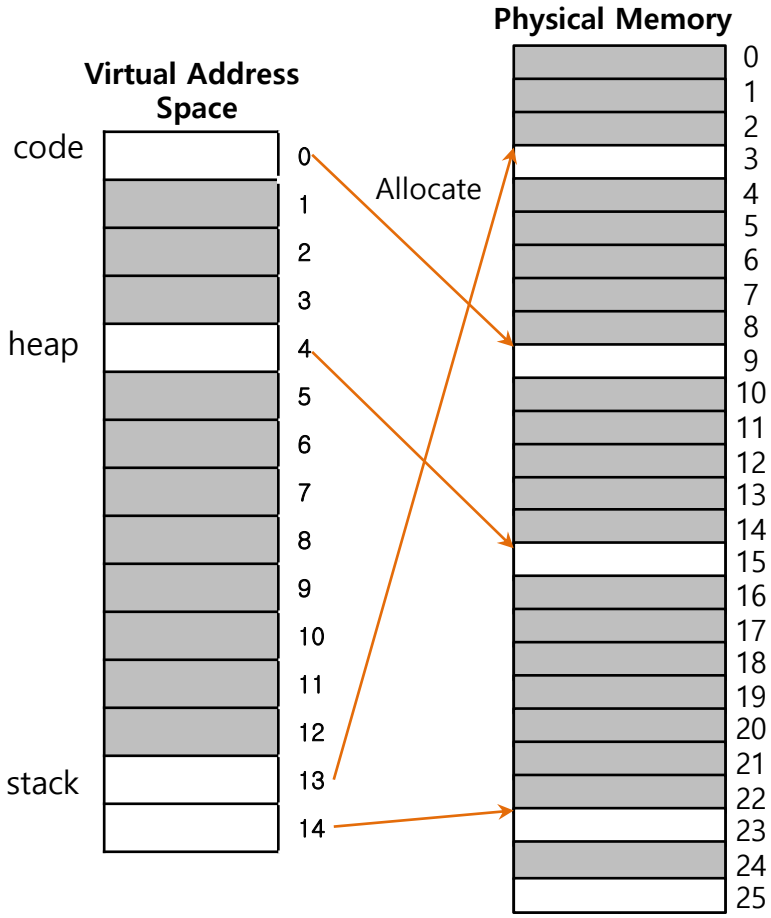


$\frac{2^{32}}{2^{16}} * 4 = 1MB$ **per page table**

But big pages might lead to internal fragmentation.

The Problem

- Single page table for the entries address space of process.



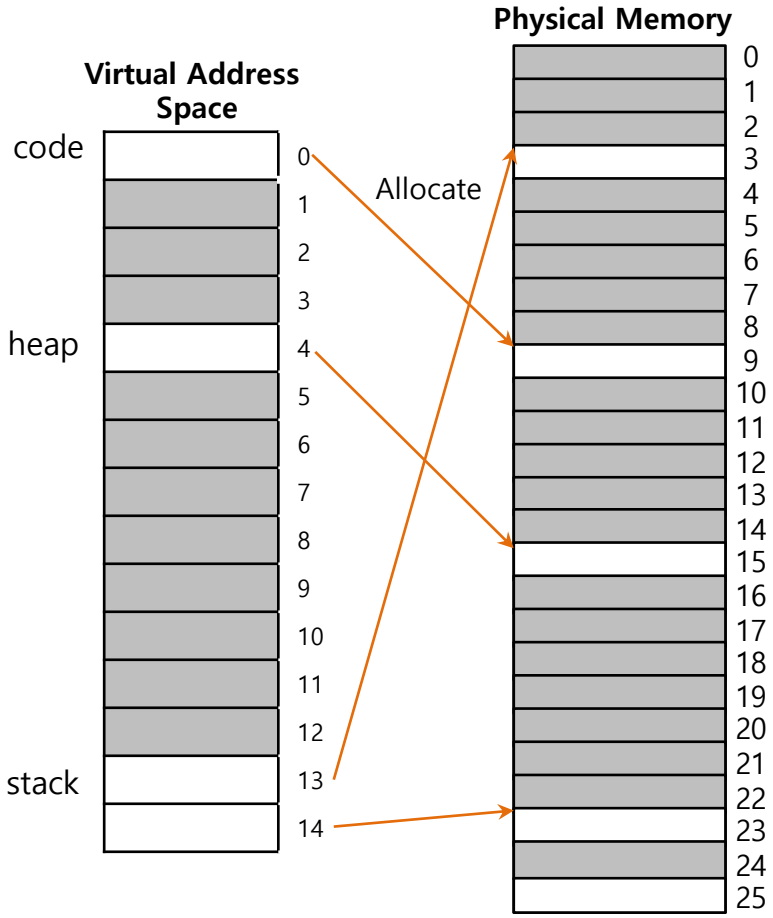
A 16KB Address Space with 1KB Pages

PFN	valid	prot	present	dirty
10	1	r-x	1	0
-	0	-	-	-
-	0	-	-	-
-	0	-	-	-
15	1	rw-	1	1
...	...	...	...	...
-	0	-	-	-
3	1	rw-	1	1
23	1	rw-	1	1

A Page Table For 16KB Address Space

The Problem

- Most of the page table is **unused**, full of invalid entries.



A 16KB Address Space with 1KB Pages

PFN	valid	prot	present	dirty
10	1	r-x	1	0
-	0	-	-	-
-	0	-	-	-
-	0	-	-	-
15	1	rw-	1	1
...	...	...	...	...
-	0	-	-	-
3	1	rw-	1	1
23	1	rw-	1	1

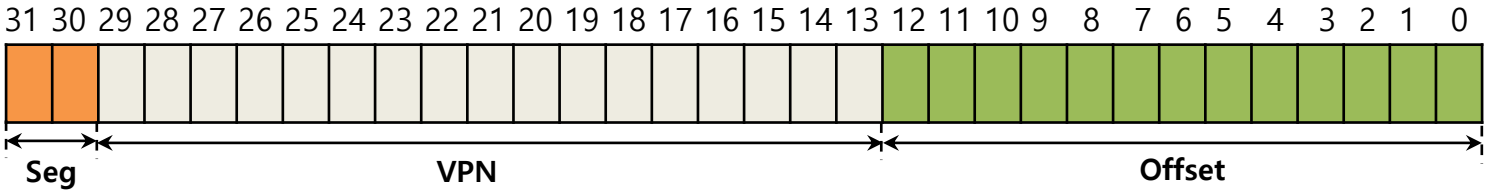
A Page Table For 16KB Address Space

Hybrid Approach to the Problem: Paging and Segments

- In order to reduce the memory overhead of page tables.
  - Using base not to point to the segment itself but rather to hold the physical address of the page table of that segment.
  - The bounds register is used to indicate the end of the page table.

Simple Example of Hybrid Approach

- Each process has three page tables associated with it.
  - When process is running, the base register for each of these segments contains the physical address of a linear page table for that segment.



32-bit Virtual address space with 4KB pages

Seg value	Content
00	unused segment
01	code
10	heap
11	stack

TLB miss on Hybrid Approach

- The hardware get to **physical address** from **page table**.
  - The hardware uses the segment bits(SN) to determine which base and bounds pair to use.
  - The hardware then takes the physical address therein and combines it with the VPN as follows to form the address of the page table entry(PTE) .

```
01:      SN = (VirtualAddress & SEG_MASK) >> SN_SHIFT
02:      VPN = (VirtualAddress & VPN_MASK) >> VPN_SHIFT
03:      AddressOfPTE = Base[SN] + (VPN * sizeof(PTE))
```

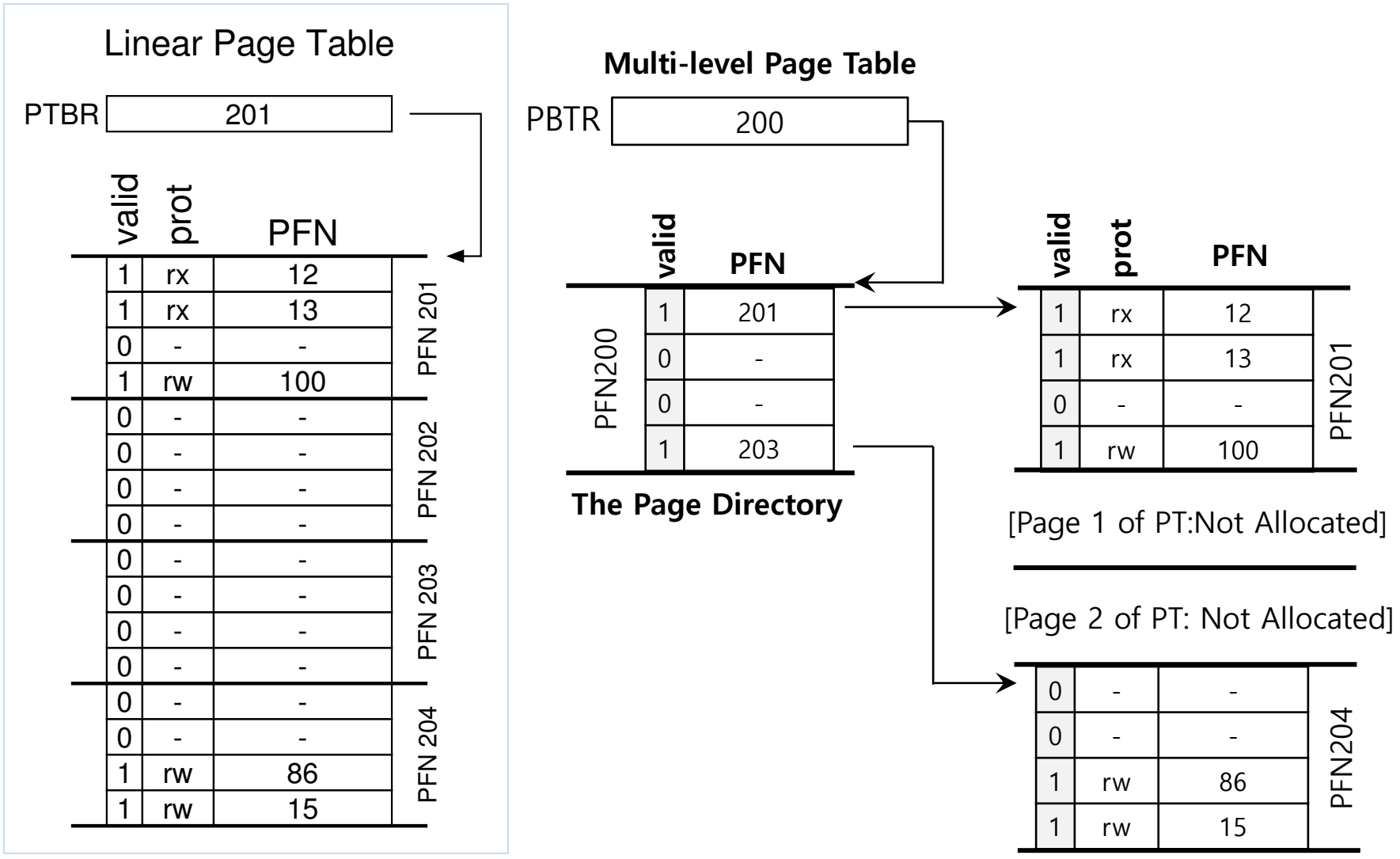
Problem of Hybrid Approach

- Hybrid Approach inherits Segmentation issues
  - If we have a large but sparsely-used heap, we can still end up with a lot of page table waste (most of the free space should be tracked)
  - Causing **external fragmentation** to arise again
  - Page Tables have arbitrary size: it's hard to find space for them (or handle it dynamically)

Multi-level Page Tables

- Turns the linear page table into something like a tree.
  - Chop up the page table into page-sized units.
  - If an entire page of page-table entries is invalid, don't allocate that page of the page table at all.
  - To track whether a page of the page table is valid, use a new structure, called page directory.

Multi-level Page Tables: Page directory



Linear (Left) And Multi-Level (Right) Page Tables

Multi-level Page Tables: Page directory entries

- The page directory contains one entry per page of the page table.
  - It consists of a number of **page directory entries (PDE).**
- PDE (minimally) has a valid bit and page frame number (PFN).

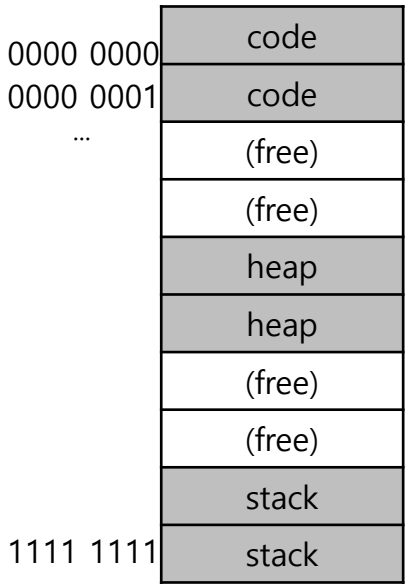
Multi-level Page Tables: Advantage & Disadvantage

- Advantage
  - Only allocates page-table space in proportion to the amount of address space you are using.
  - The OS can grab the next free page when it needs to allocate or grow a page table.

- Disadvantage
  - Multi-level table is a small example of a time-space trade-off.
  - Complexity.

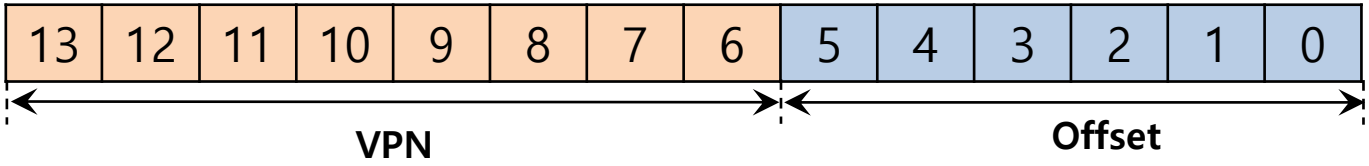
A Detailed Multi-Level Example

- To understand the idea behind multi-level page tables better, let's do an example.



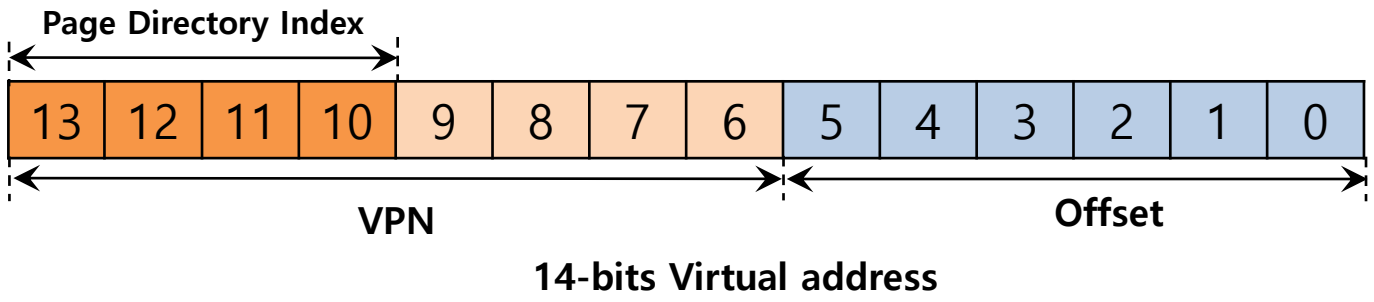
Flag	Detail
Address space	16 KB
Page size	64 byte
Virtual address	14 bit
VPN	8 bit
Offset	6 bit
# Page table entry	$2^8(256)$

A 16-KB Address Space With 64-byte Pages



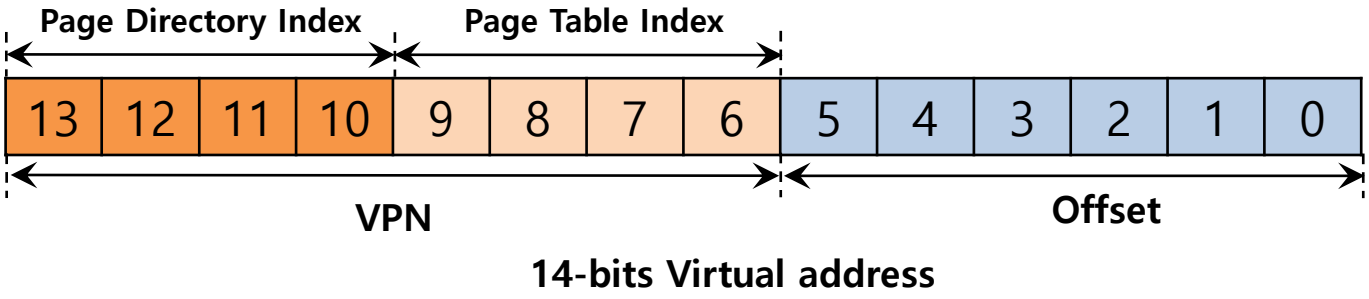
A Detailed Multi-Level Example: Page Directory Idx

- The page directory needs one entry per page of the page table
  - it has 16 entries.
- The PDE is invalid → Raise an exception (The access is invalid)

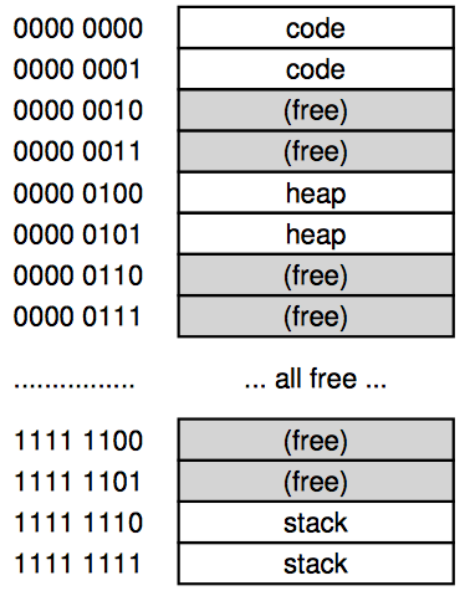


A Detailed Multi-Level Example: Page Table Idx

- The PDE is valid, we have more work to do.
  - To fetch the page table entry(PTE) from the page of the page table pointed to by this page-directory entry.
- This page-table index can then be used to index into the page table itself.



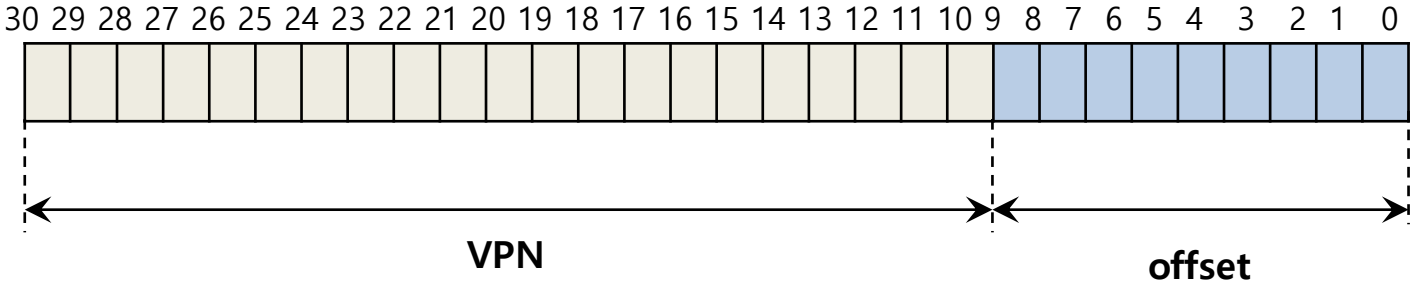
Example



Page Directory		Page of PT (@PFN:100)			Page of PT (@PFN:101)		
PFN	valid?	PFN	valid	prot	PFN	valid	prot
100	1	10	1	r-x	—	0	—
—	0	23	1	r-x	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	80	1	rw-	—	0	—
—	0	59	1	rw-	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	—	0	—
—	0	—	0	—	55	1	rw-
101	1	—	0	—	45	1	rw-

More than Two Levels

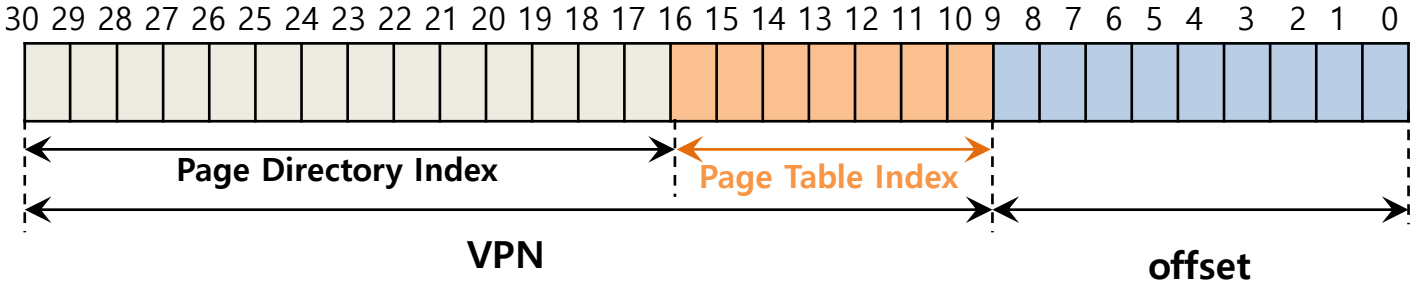
- In some cases, a deeper tree is possible (and needed).



Flag	Detail
Virtual address	30 bit
Page size	512 byte
VPN	21 bit
Offset	9 bit

More than Two Level : Page Table Index

- In some cases, a deeper tree is possible (and needed).



Flag	Detail
Virtual address	30 bit
Page size	512 byte
VPN	21 bit
Offset	9 bit
Page entry per page	128 PTEs

$\log_2 128 = 7$
4bytes per PTE

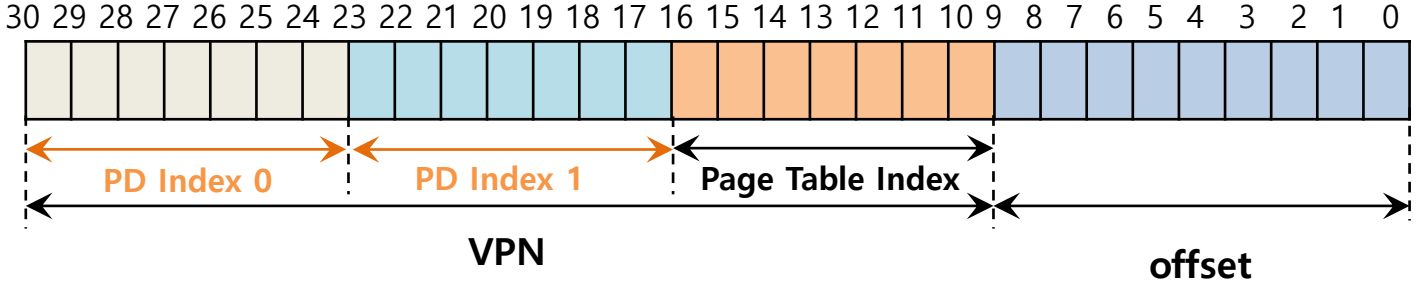
$$PD\ has\ 2^{14}\ entries = 16K \cdot 4 = 64KB$$

More than Two Level : Page Directory Within a Page

- If our page directory has 2^{14}entries, it spans not one page but 128

  assuming size_of(PDE) == size_of(PTE)

- To remedy this problem, we build a **further level** of the tree, by splitting the page directory itself into multiple pages of the page directory.



Multi-level Page Table Control Flow

```
01:      VPN = (VirtualAddress & VPN_MASK) >> SHIFT
02:      (Success,TlbEntry) = TLB_Lookup(VPN)
03:      if(Success == True)        //TLB Hit
04:        if(CanAccess(TlbEntry.ProtectBits) == True)
05:              Offset = VirtualAddress & OFFSET_MASK
06:              PhysAddr = (TlbEntry.PFN << SHIFT) | Offset
07:              Register = AccessMemory(PhysAddr)
08:        else RaiseException(PROTECTION_FAULT);
09:      else // perform the full multi-level lookup
```

- (1 lines) extract the virtual page number(VPN)
- (2 lines) check if the TLB holds the translation for this VPN
- (5-8 lines) extract the page frame number from the relevant TLB entry, and form the desired physical address and access memory

Multi-level Page Table Control Flow

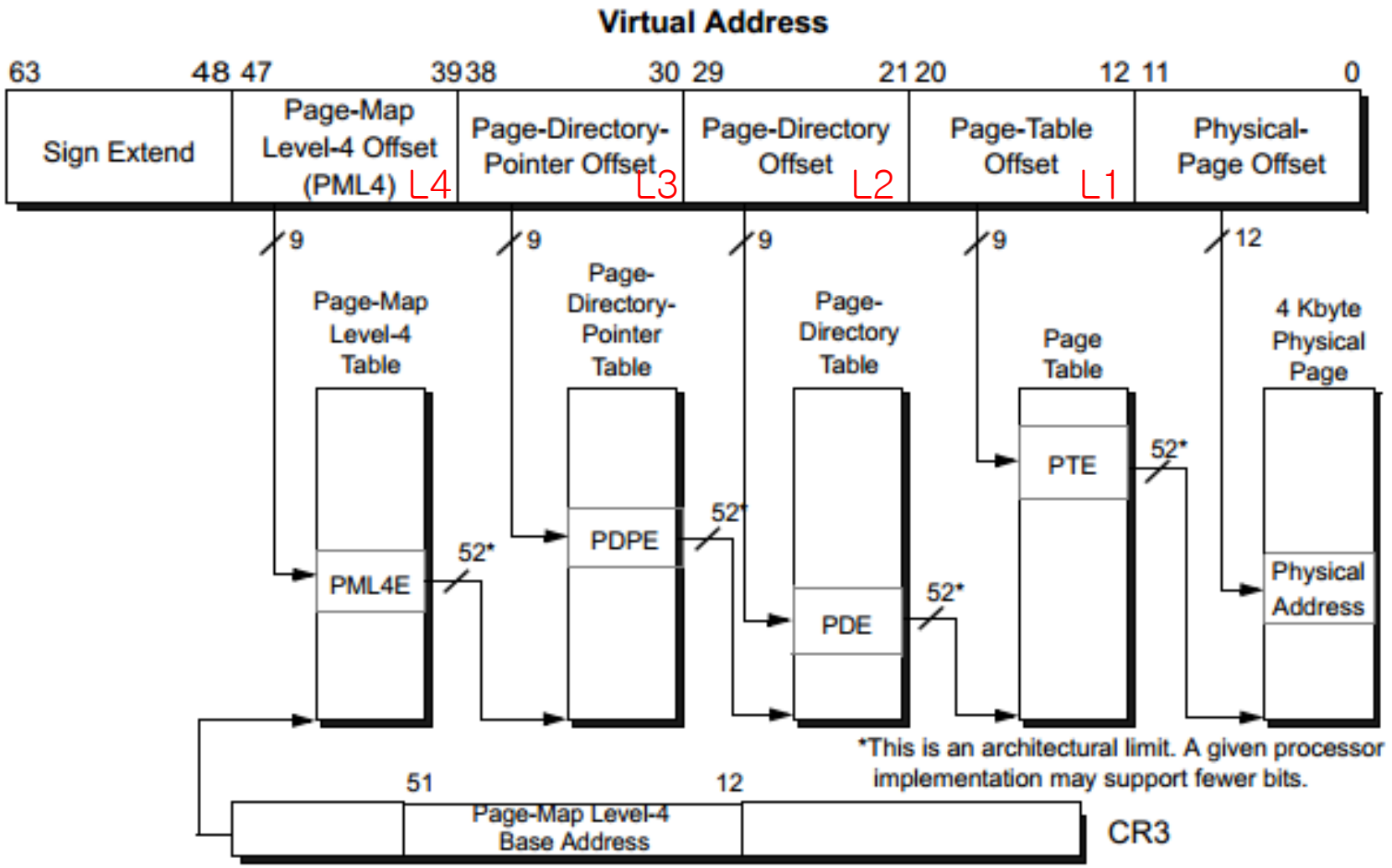
```
11:       else
12:                 PDIndex = (VPN & PD_MASK) >> PD_SHIFT
13:                 PDEAddr = PDBR + (PDIndex * sizeof(PDE))
14:                 PDE = AccessMemory(PDEAddr)
15:                 if(PDE.Valid == False)
16:                           RaiseException(SEGMENTATION_FAULT)
17:                 else // PDE is Valid: now fetch PTE from PT
```

- (11 lines) extract the Page Directory Index(PDIndex)
- (13 lines) get Page Directory Entry(PDE)
- (15-17 lines) Check PDE valid flag. If valid flag is true, fetch Page Table entry from Page Table

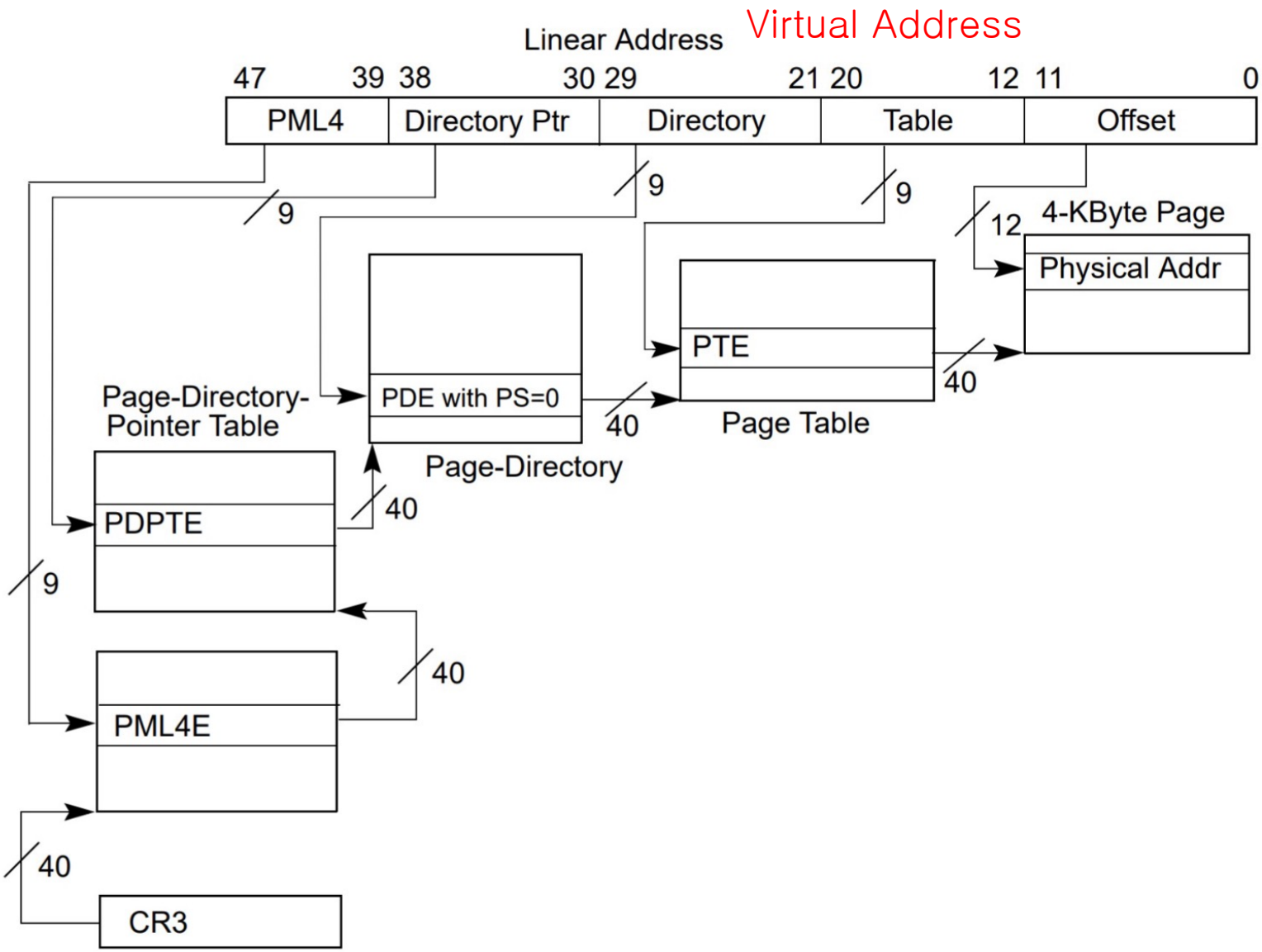
The Translation Process: Remember the TLB

```
18:     PTIndex = (VPN & PT_MASK) >> PT_SHIFT
19:     PTEAddr = (PDE.PFN << SHIFT) + (PTIndex * sizeof(PTE))
20:     PTE = AccessMemory(PTEAddr)
21:     if(PTE.Valid == False)
22:             RaiseException(SEGMENTATION_FAULT)
23:     else if(CanAccess(PTE.ProtectBits) == False)
24:             RaiseException(PROTECTION_FAULT);
25:     else
26:             TLB_Insert(VPN, PTE.PFN , PTE.ProtectBits)
27:             RetryInstruction()
```

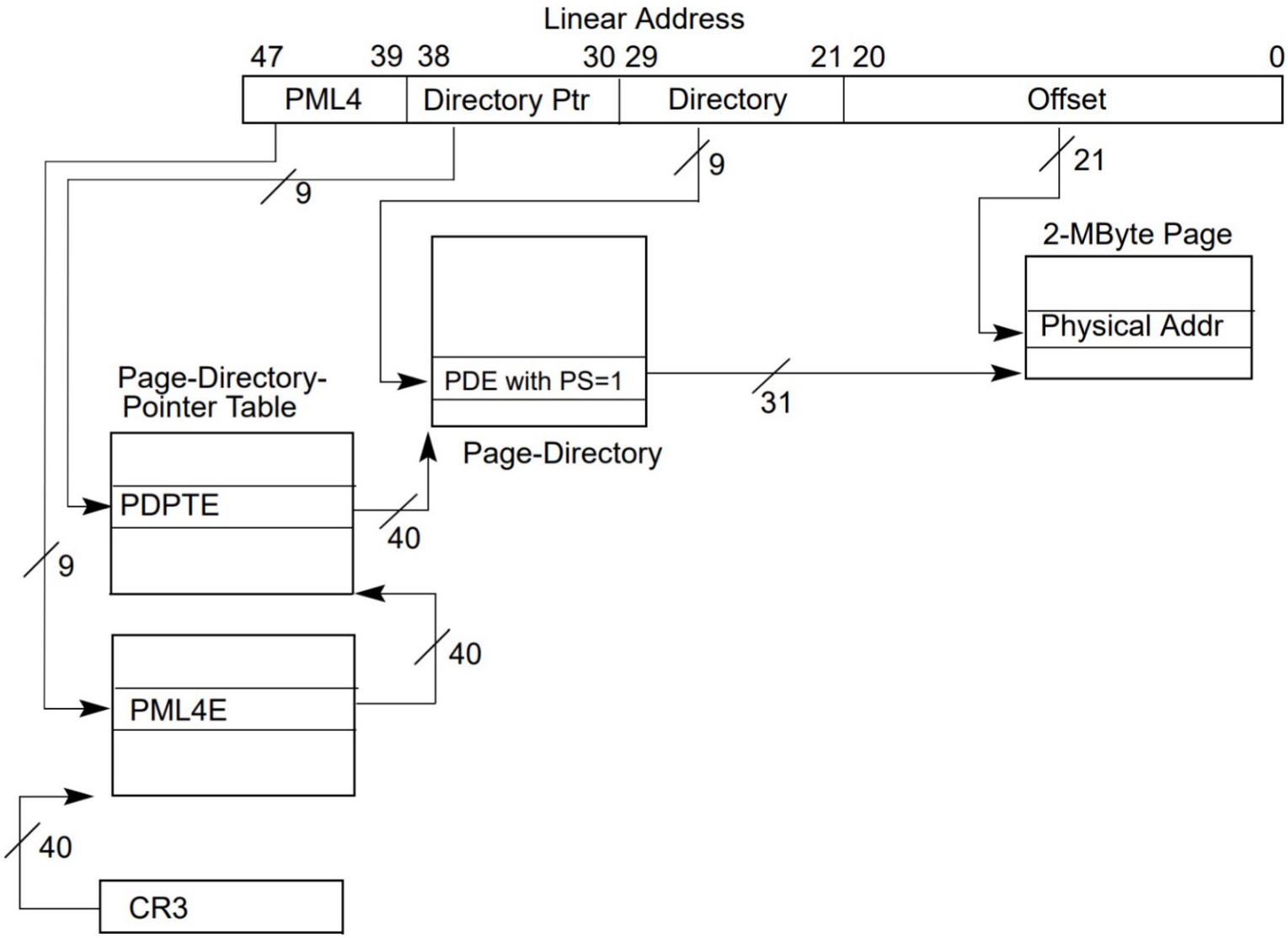
x86-64: from (256TB), to (128 PB)



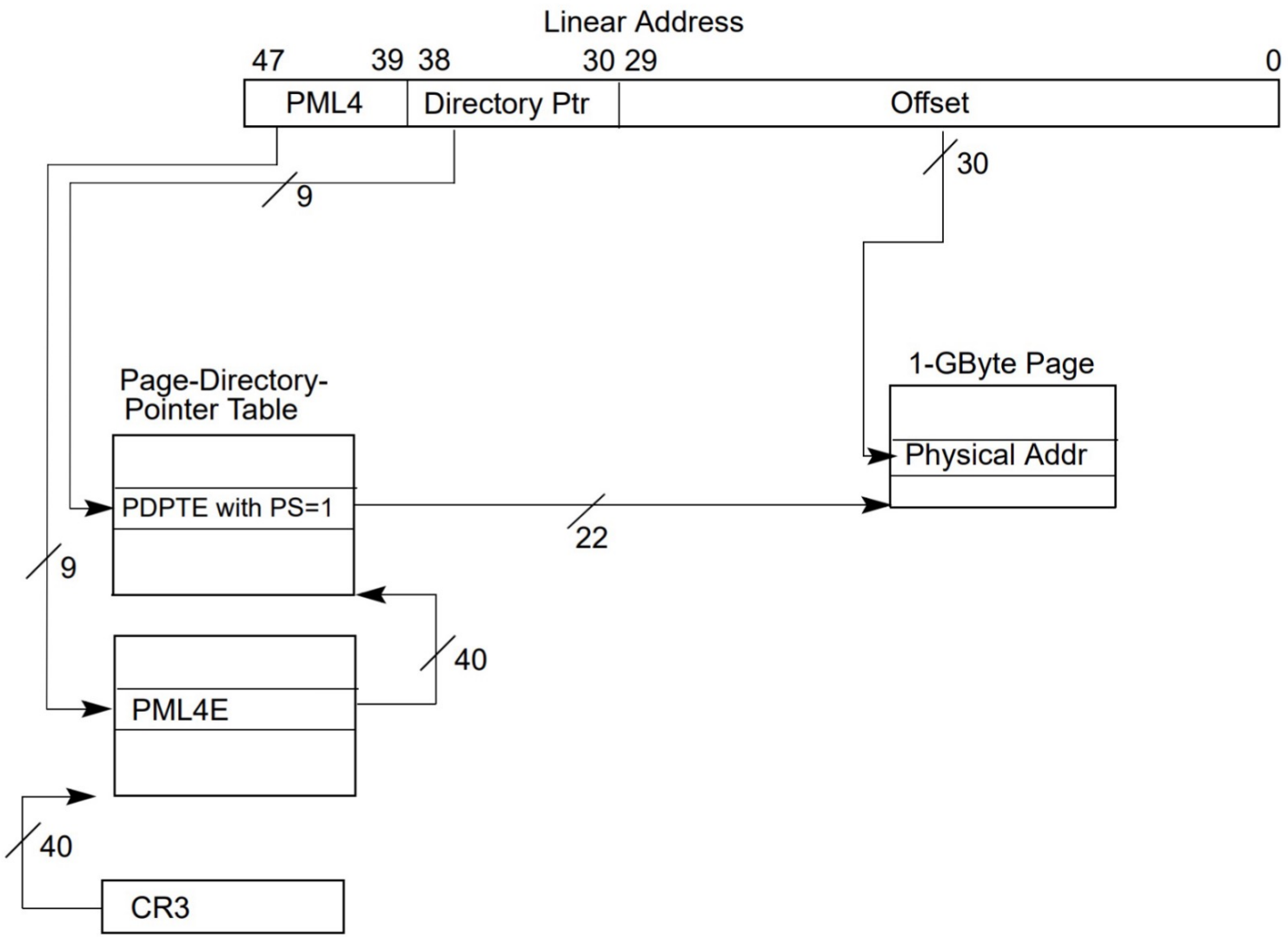
Multilevel Page Tables II (2^{48}B=256TB)



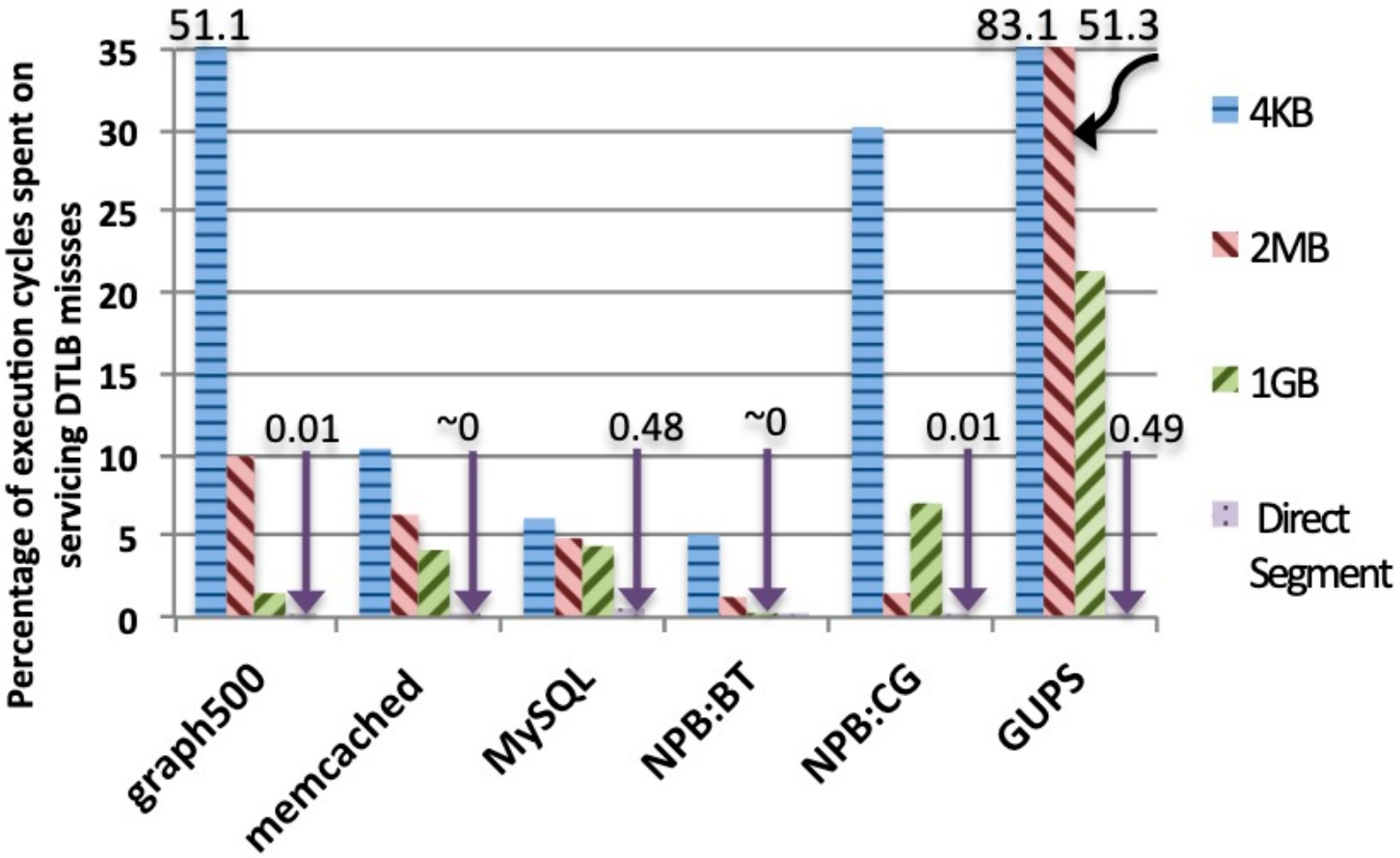
Mega pages (2MB pages)



Giga Pages (1GB Pages)

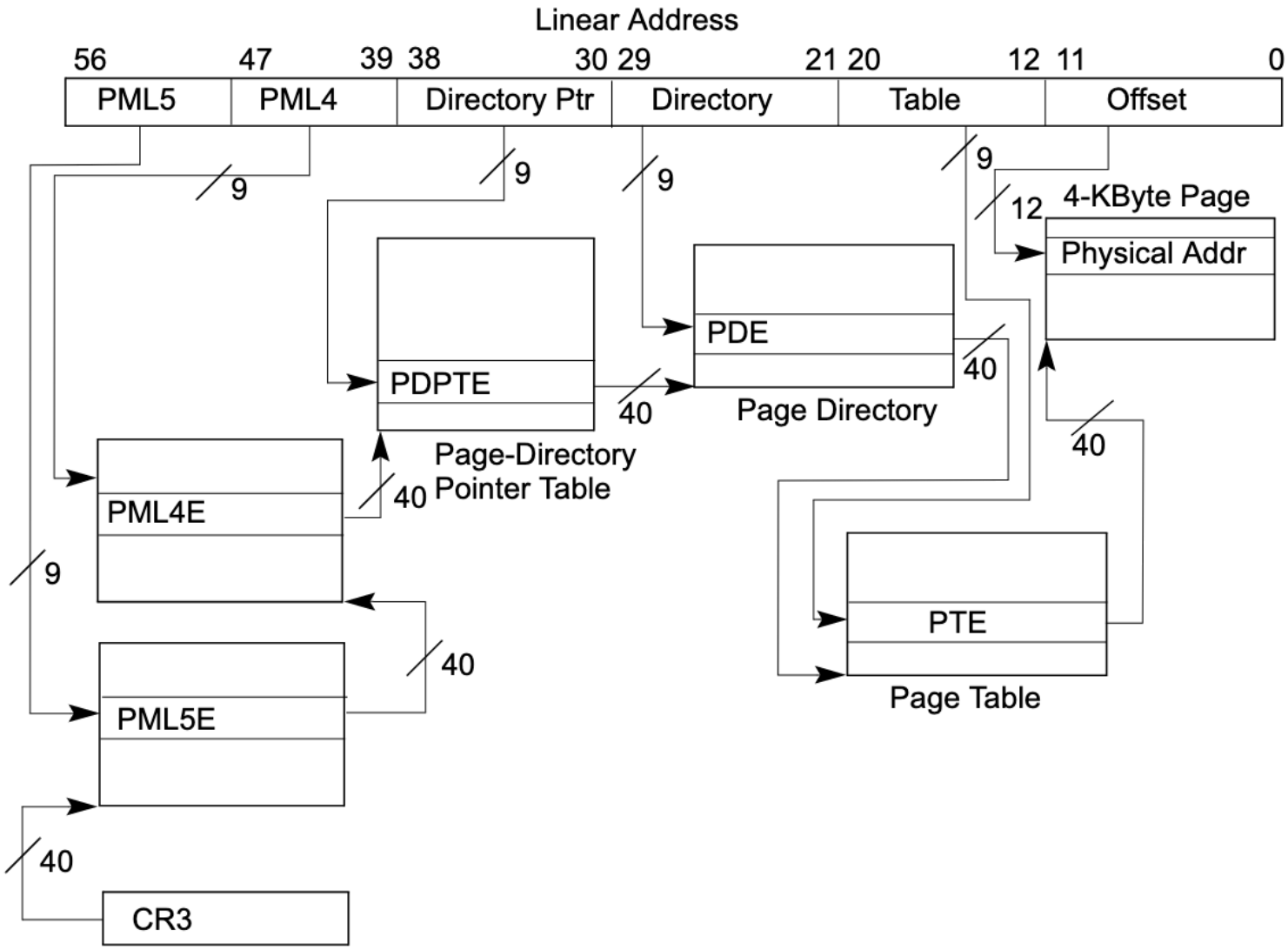


It Matters?



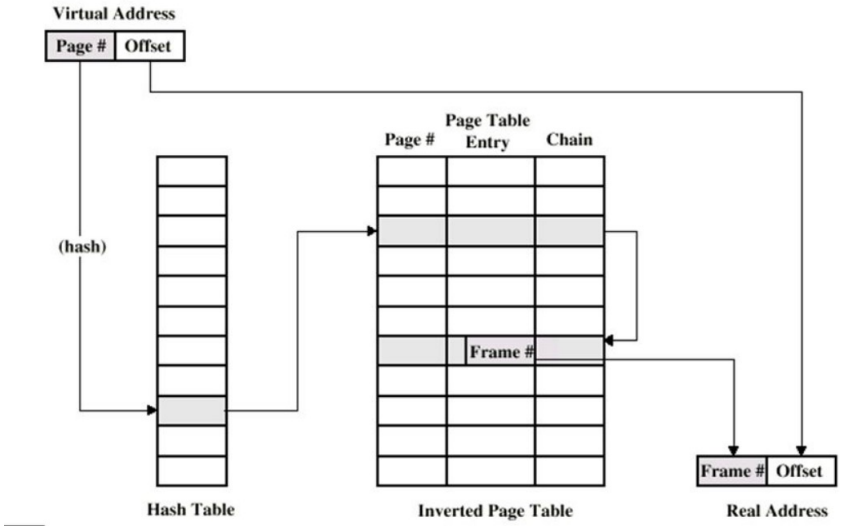
[1] A. Basu, J. Gandhi, J. Chang, M. D. Hill, and M. M. Swift, "Effi cient Virtual Memory for Big Memory Servers", CAL 2013.

Since 2021 (2^{56}B=128PB)



Inverted Page Table

- Keeping a single page table that has an entry for each physical page of the system.
- The entry tells us which process is using this page, and which virtual page of that process maps to this physical page.
- Used with a hashing table (hash anchor table) in order to allow practical implementations



Swapping Page Tables to Disk

- When memory conditions are harsh, kernel allocated pages can be sw apped to disk
- Page tables (a portion of it) might reside only in disk at a given time
- Ignored for sake of simplicity until now (we have no clue about swapp ing yet)

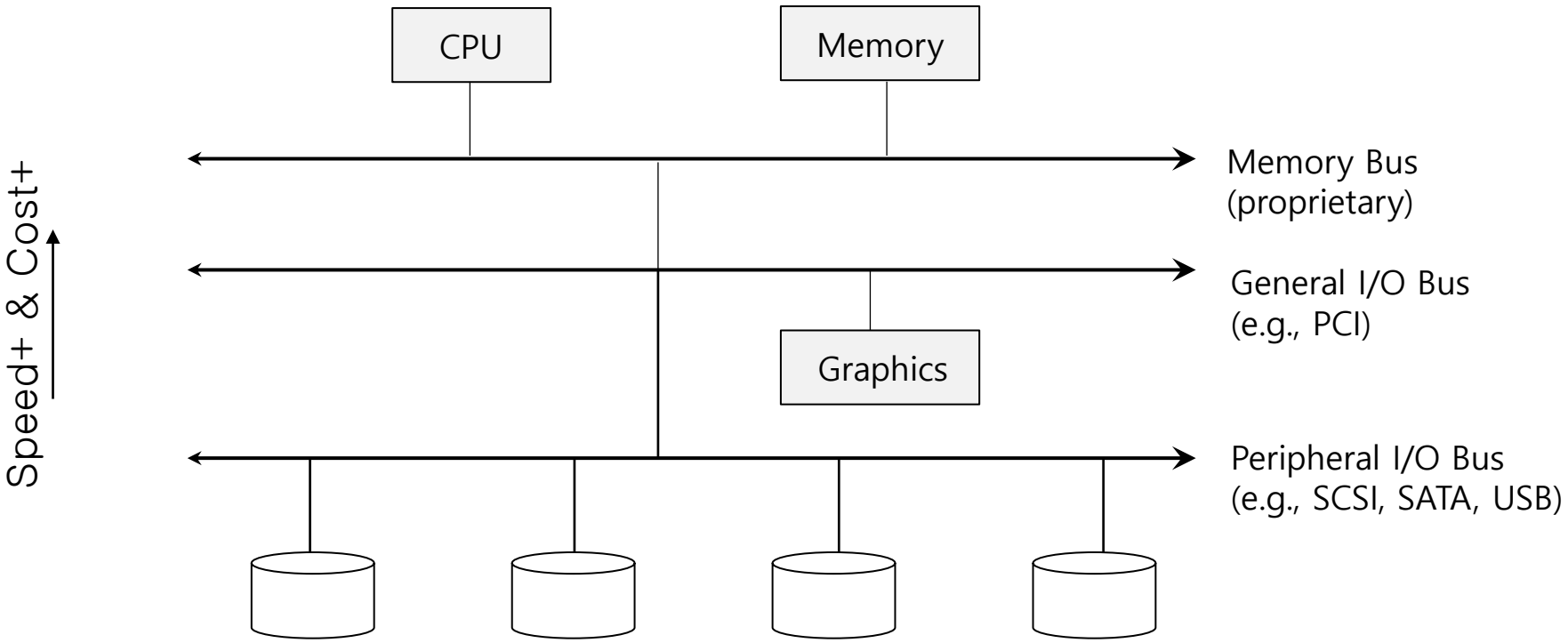
I/O Devices

Operating System: Three Easy Pieces

I/O Devices

- I/O is **critical** to computer system to **interact with systems.**
- Issue :
  - How should I/O be integrated into systems?
  - What are the general mechanisms?
  - How can we make the efficiently?

Structure of input/output (I/O) device



Prototypical System Architecture

CPU is attached to the main memory of the system via some kind of memory bus.

Some devices are connected to the system via a general I/O bus.

Why not a flat design? (like in the early days)

I/O Architecture

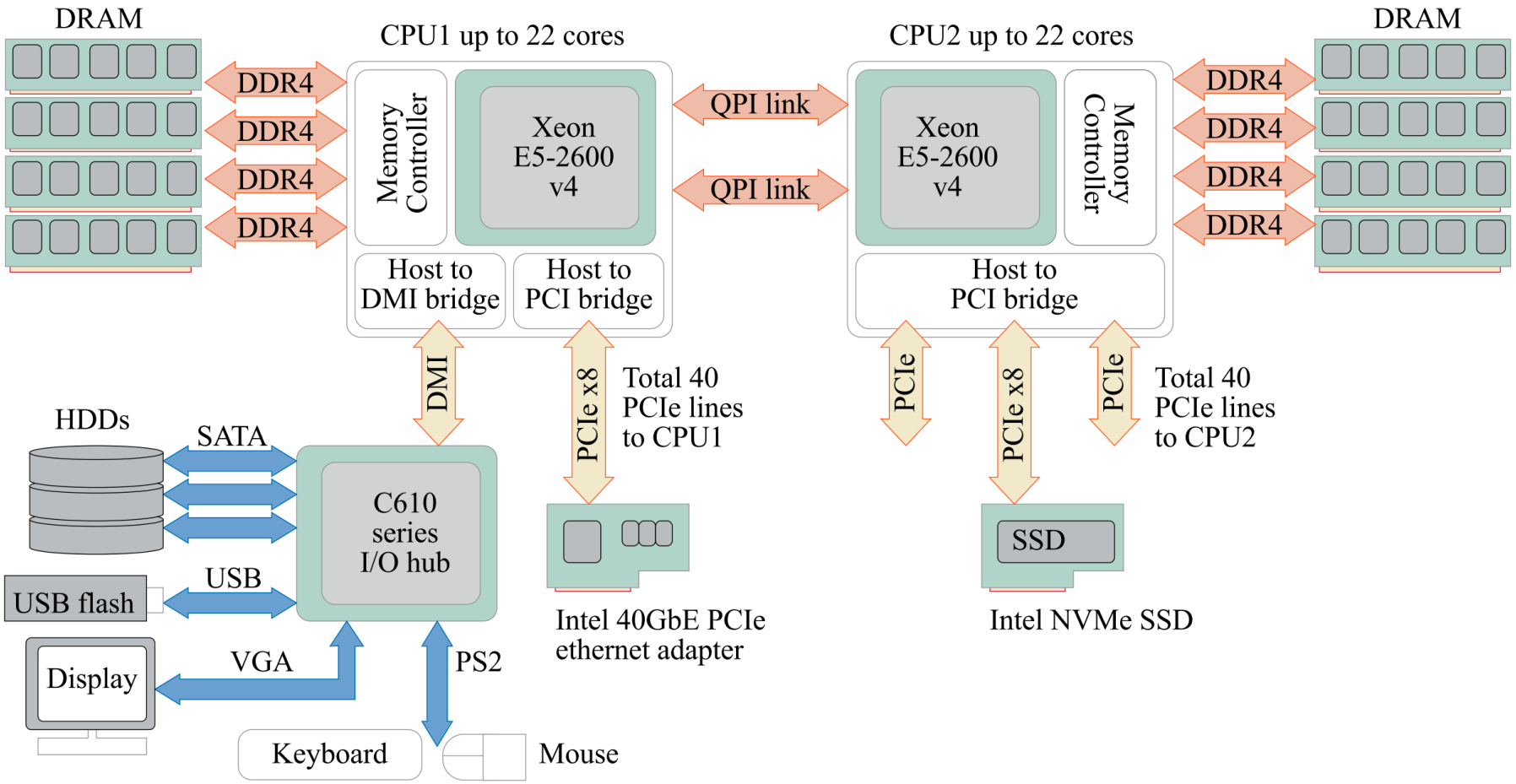
- **Buses**
  - Data paths that provided to enable information between CPU(s), RAM, and I/O devices.

- **I/O bus**
  - Data path that connects a CPU to an I/O device.
  - I/O bus is connected to I/O device by three hardware components: I/O po rts, interfaces and device controllers.

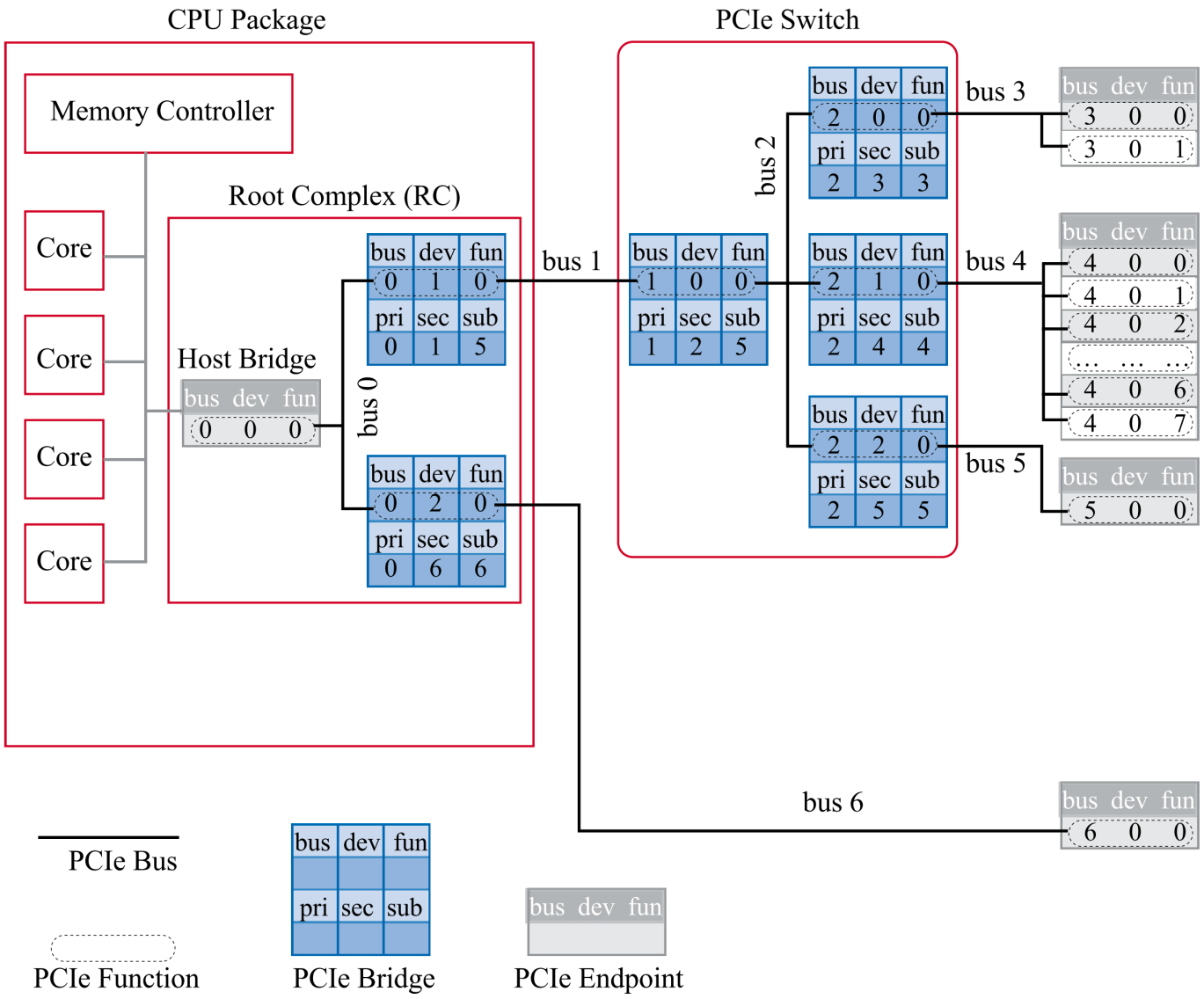
- In current system (due to scalability limitations of the buses) most hig h-speed buses have migrated to **point-to-point networks**

Todays Systems

- Two-socket server with Xeon E5-2600 v4

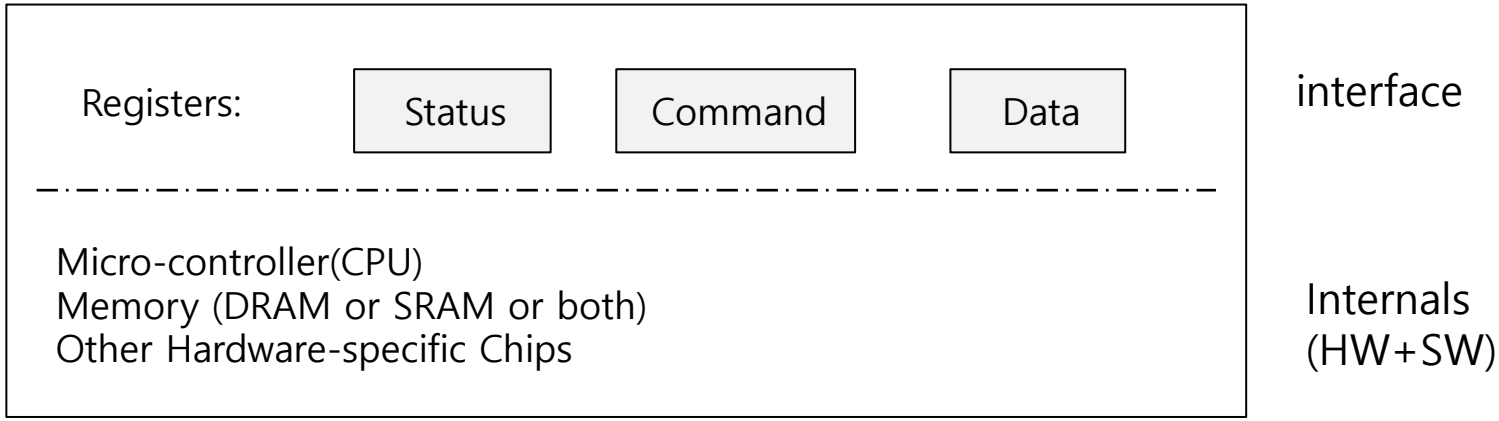


PCIe


CPU Package
Memory Controller
Core
Core
Core
Core
Root Complex (RC)
Host Bridge
bus dev fun
0 0 0
bus 0
bus dev fun
0 1 0
pri sec sub
0 1 5
bus dev fun
0 2 0
pri sec sub
0 6 6
bus 1
PCIe Switch
bus dev fun
1 0 0
pri sec sub
1 2 5
bus 2
bus dev fun
2 0 0
pri sec sub
2 3 3
bus 3
bus dev fun
3 0 0
3 0 1
bus dev fun
2 1 0
pri sec sub
2 4 4
bus 4
bus dev fun
4 0 0
4 0 1
4 0 2
... ...
4 0 6
4 0 7
bus dev fun
2 2 0
pri sec sub
2 5 5
bus 5
bus dev fun
5 0 0
bus 6
bus dev fun
6 0 0
PCIe Bus
PCIe Function
bus dev fun
pri sec sub
PCIe Bridge
bus dev fun
PCIe Endpoint

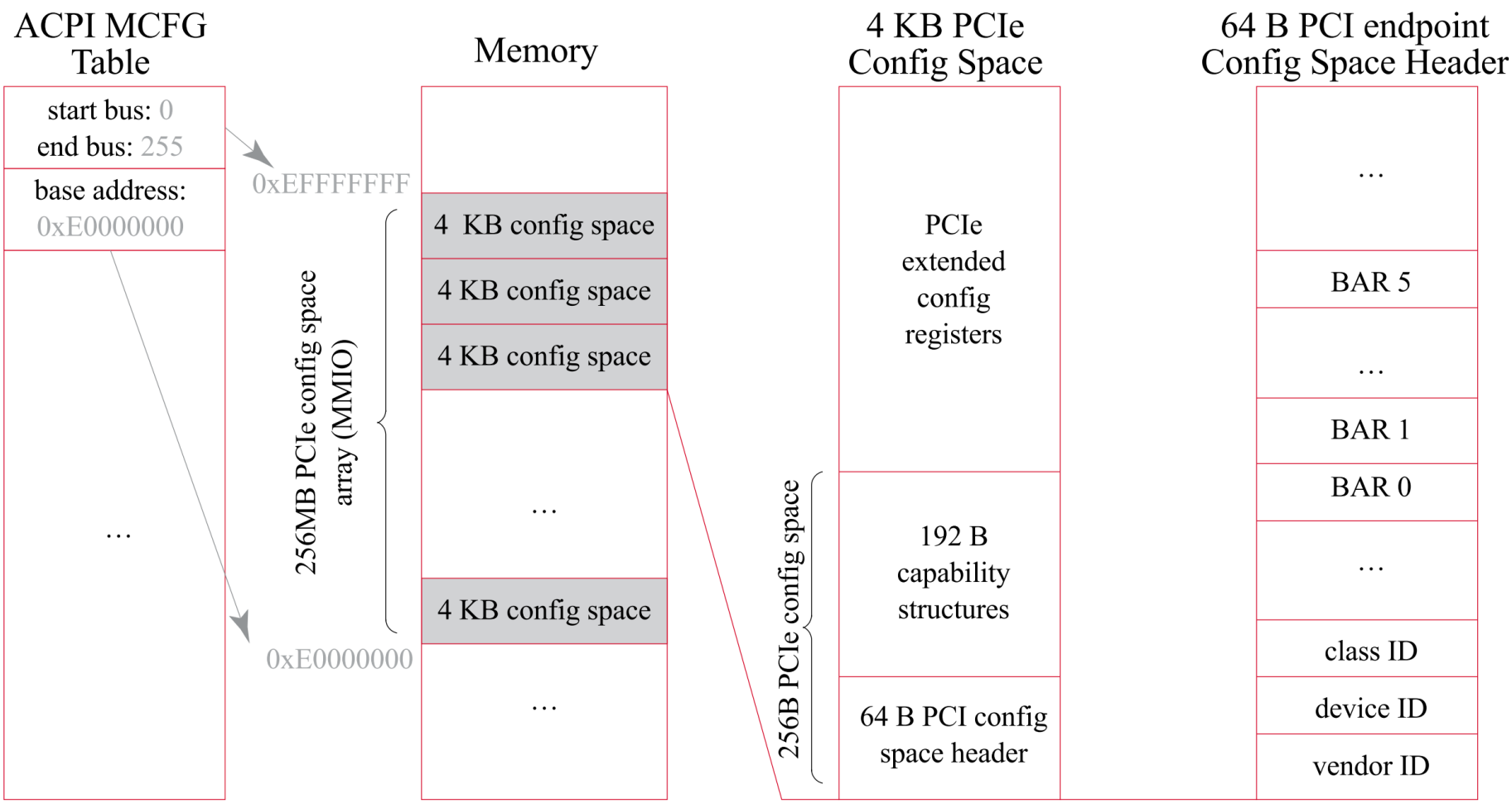
Canonical Device

- Canonical Devices has two important components.
  - **Hardware interface** allows the system software to control its operation.
  - **Internals** which is implementation specific.



Canonical Device

PCIe Devices (the real thing)



Hardware interface of Canonical Device

- **status register**
  - See the current status of the device
- **command register**
  - Tell the device to perform a certain task
- **data register**
  - Pass data to the device, or get data from the device

By reading and writing above three registers,
the operating system can control device behavior.

Hardware interface of Canonical Device (Cont.)

- Typical interaction example (Programmed I/O or PIO)

```
while ( STATUS == BUSY)
    ; //wait until device is not busy
write data to data register
write command to command register
    Doing so starts the device and executes the command
while ( STATUS == BUSY)
    ; //wait until device is done with your request
```

Polling

- Operating system waits until the device is ready by **repeatedly** reading the status register.
  - Positive aspect is simple and working.
  - **However, it wastes CPU time just waiting for the device**.
    - Switching to another ready process is better utilizing the CPU.

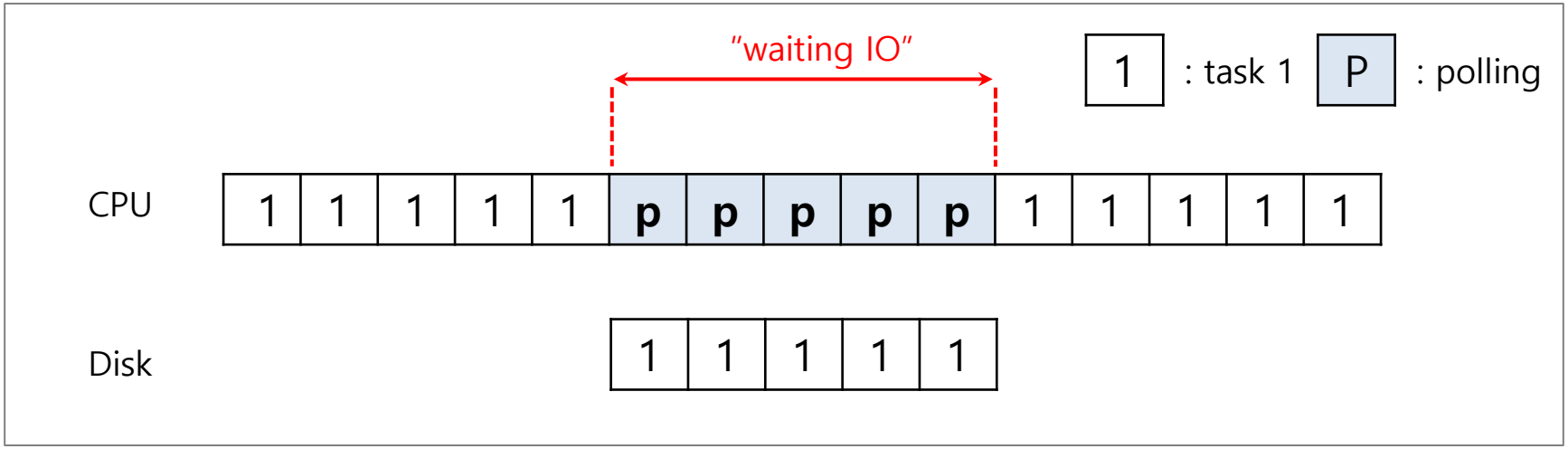


Diagram of CPU utilization by polling

Interrupts

- **Put the I/O request process to sleep** and context switch to another.
- When the device is finished, wake the process waiting for the I/O by **interrupt** (via interrupt handler or *Interrupt Service Routine ISR*)
  - Positive aspect is allowed to **CPU and the disk are properly utilized.**

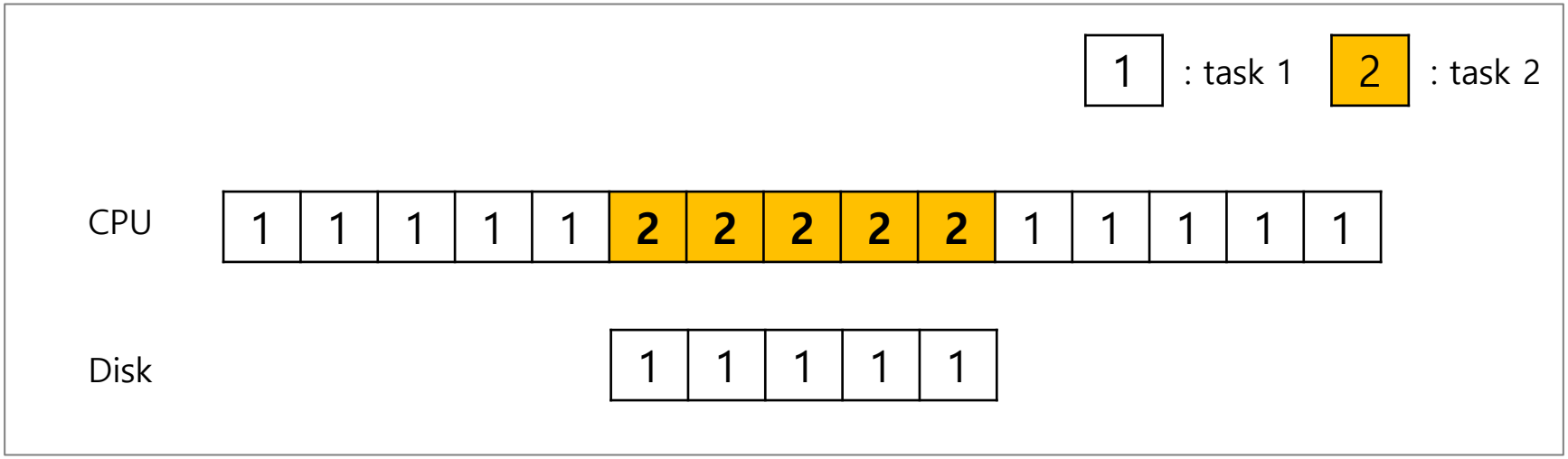


Diagram of CPU utilization by interrupt

Polling vs interrupts

- *However,* **"interrupts is not always the best solution"**
  - If, device performs very quickly (for example, at first poll the operation is done), interrupt will "slow down" the system.
  - Because **context switch is expensive (switching to another process)**

If a device is fast → poll is best.
If it is slow → interrupts is better.

- Hybrid approach
  - If poll too slow go to interrupts
- **Coalescing interrupts**
- Under DDoS attacks go PIO

CPU is once again over-burdened

- CPU **wastes a lot of time** to copy a *large chunk of data* from memory to the device.

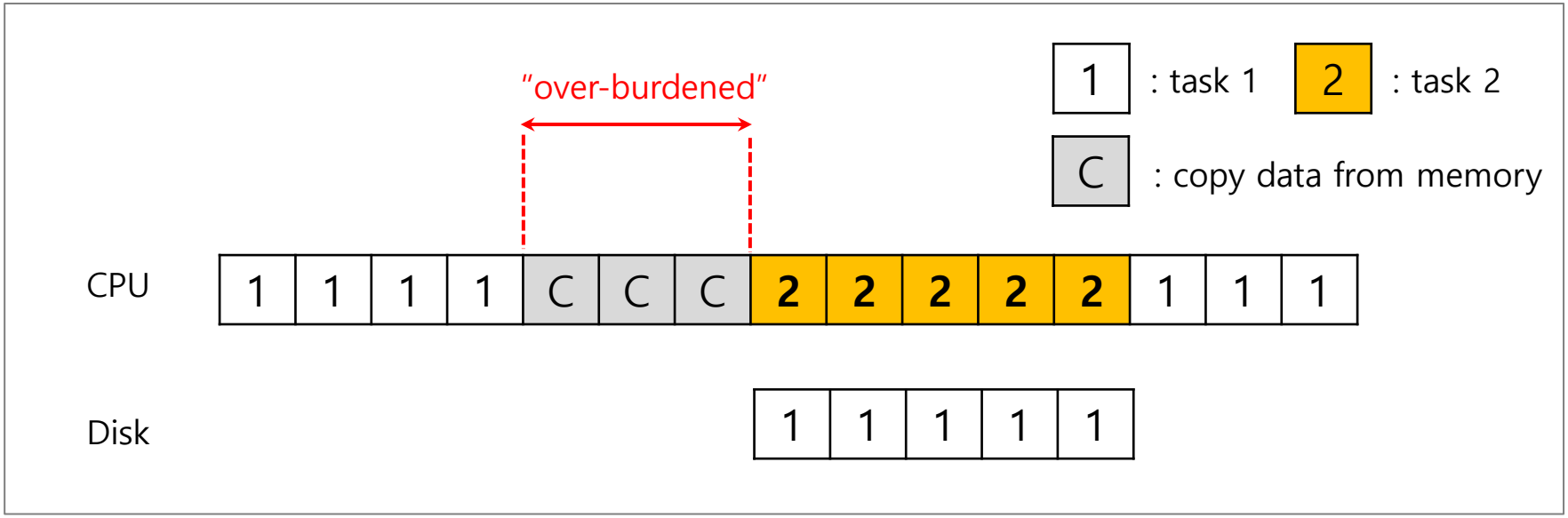


Diagram of CPU utilization

DMA (Direct Memory Access)

- **Copy data** in memory by knowing "where the data lives in memory, & how much data to copy"
- Tell the DMA controller to do the "hard-work"
- When completed, DMA raises an interrupt, I/O begins on Disk.

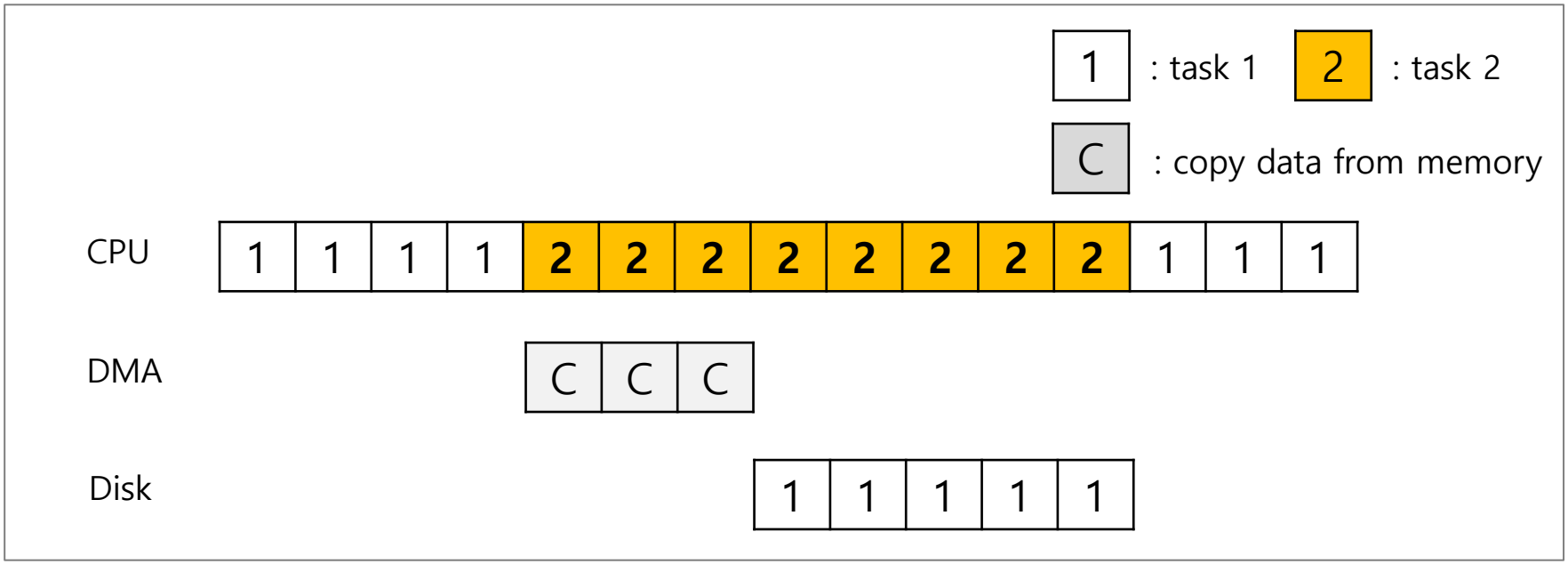


Diagram of CPU utilization by DMA

Device interaction

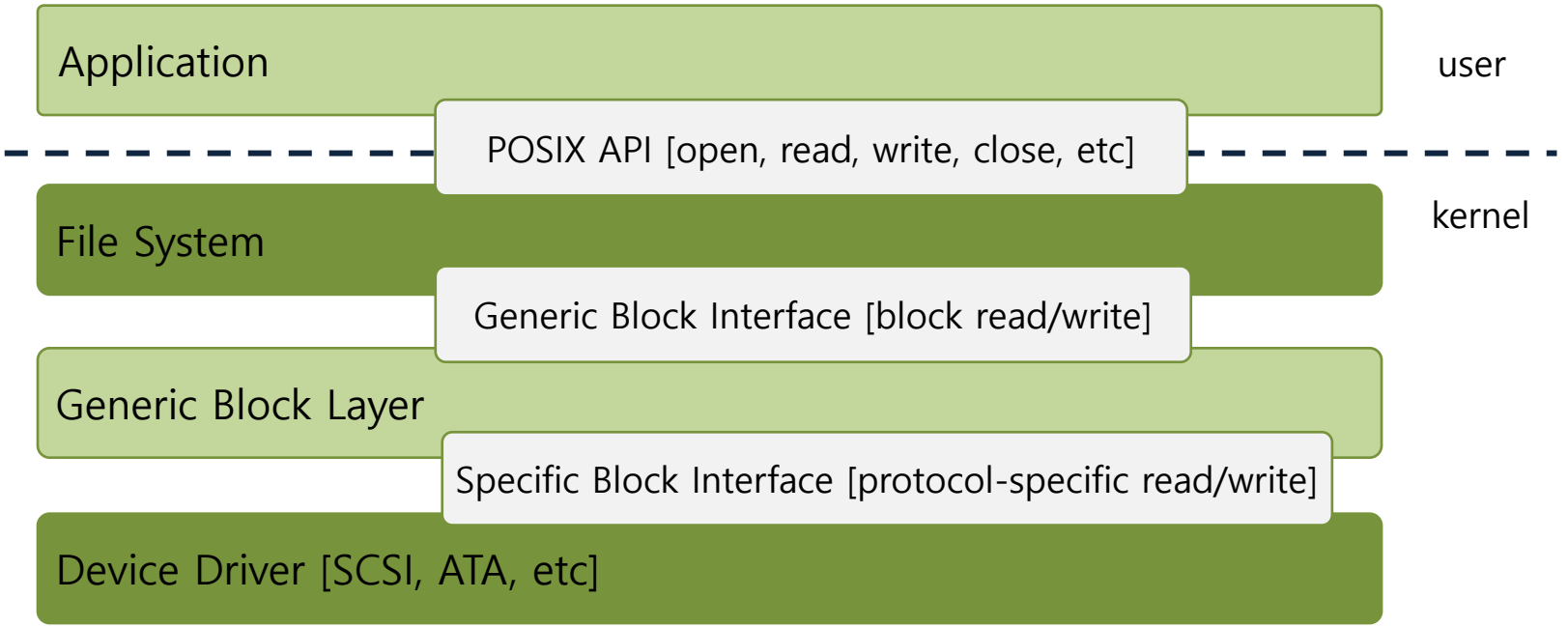
- How the CPU communicates with the **device**?
- Approaches
  - **I/O instructions**: a way for the OS to send data to specific device registers.
    - Ex) `in` and `out` instructions on x86
    - Separate I/O and memory buses in early days
  - **memory-mapped I/O**
    - Device registers available as if they were memory locations.
    - The OS `load` (to read) or `store` (to write) to the device instead of main memory

Fitting Into The OS: The Device Driver

- How the OS interact with **different specific interfaces**?
  - Ex) We'd like to build a file system that worked on top of SCSI disks, IDE disks, USB keychain drivers, and so on.
- **Solution**: **Abstraction**
  - Abstraction encapsulate **any specifics of device interaction**.
  - Only the lowest level should be aware of the specifics: called Device driver

File system Abstraction

- File system **specifics** of which disk class it is using.
  - Ex) It issues **block read** and **write** request to the generic block layer.



The File System Stack

Problem of File system Abstraction

- If there is a device having many special capabilities, these capabilities **will go unused** in the generic interface layer.
  - Ex) SCSI devices have a **rich error reporting** that are mostly **unused** in Linux because IDE/ATA had very limited capabilities

- **Over 70% of OS** code is found in device drivers.
  - Any device drivers are needed because you might plug it to your system.
  - They are primary contributor to **kernel crashes**, making **more bugs**.
  - **Driver signing** in current windows system has improved its resiliency greatly

Case Study: A Simple IDE Disk Driver (xv6 uses QEMU IDE)

- Four types of register
  - Control, command block, status and error
  - Mapped to I/O addresses
  - `in` and `out` I/O instruction
- Book code doesn't not match with current version
- *Integrated Drive Electronics* (IDE) was developed in 1987
- Current xv6-riscv uses virtio disks

- Control Register:

  Address 0x3F6 = 0x80 (0000 1RE0): R=reset, E=0 means "enable interrupt"

- Command Block Registers:

  Address 0x1F0 = Data Port

  Address 0x1F1 = Error

  Address 0x1F2 = Sector Count

  Address 0x1F3 = LBA low byte (Logical Block Address)

  Address 0x1F4 = LBA mid byte

  Address 0x1F5 = LBA hi byte

  Address 0x1F6 = 1B1D TOP4LBA: B=LBA, D=drive

  Address 0x1F7 = Command/status

- Status Register (Address 0x1F7):

7	6	5	4	3	2	1	0
BUSY	READY	FAULT	SEEK	DRQ	CORR	IDDEX	ERROR

- Error Register (Address 0x1F1): (check when Status ERROR==1)

7	6	5	4	3	2	1	0
BBK	UNC	MC	IDNF	MCR	ABRT	T0NF	AMNF

  - BBK = Bad Block
  - UNC = Uncorrectable data error
  - MC = Media Changed
  - IDNF = ID mark Not Found
  - MCR = Media Change Requested
  - ABRT = Command aborted
  - T0NF = Track 0 Not Found
  - AMNF = Address Mark Not Found

- **Wait for drive to be ready**. Read Status Register (0x1F7) until drive is not busy and READY.
- **Write parameters to command registers**. Write the sector count, logical block address (LBA) of the sectors to be accessed, and drive number (master=0x00 or slave=0x10, as IDE permits just two drives) to command registers (0x1F2-0x1F6).
- **Start the I/O**. by issuing read/write to command register. Write READ—WRITE command to command register (0x1F7).
- **Data transfer (for writes)**: Wait until drive status is READY and DRQ (drive request for data); write data to data port.
- **Handle interrupts**. In the simplest case, handle an interrupt for each sector transferred; more complex approaches allow batching and thus one final interrupt when the entire transfer is complete.
- **Error handling.** After each operation, read the status register. If the ERROR bit is on, read the error register for details.

xv6: I/O buffer (node struct)

```
struct buf {          //chunk of 512B to read/write
   int flags;
   uint dev;
   uint sector;
   struct buf *prev; // LRU cache list
   struct buf *next;
   struct buf *qnext; // disk queue
   uchar data[512];
};
#define B_BUSY  0x1  // buffer is locked by some process #d
efine B_VALID 0x2  // buffer has been read from disk #defin
e B_DIRTY 0x4  // buffer needs to be written to disk
```

xv6 code: Queues request (if IDE not avail) or issue the req.

```
void ide_rw(struct buf *b) {
   acquire(&ide_lock);
   for (struct buf **pp = &ide_queue; *pp; pp=&(*pp)->qnext)
   ;                                  // walk queue (beware 2nd term)
   *pp = b;                           // add request to end
   if (ide_queue == b)                // if q was empty (only has b)
      ide_start_request(b);           // send req to disk
   while ((b->flags & (B_VALID|B_DIRTY)) != B_VALID)
      sleep(b, &ide_lock); // wait for completion and rel. lock
   release(&ide_lock);
}
```

xv6 code: intercedes with the driver

```
static void ide_start_request(struct buf *b) {
    ide_wait_ready();
    outb(0x3f6, 0);                         // generate interrupt
    outb(0x1f2, 1);                         // how many sectors to read/write?
    outb(0x1f3, b->sector & 0xff);          // LBA goes here ...
    outb(0x1f4, (b->sector >> 8) & 0xff); // ... and here
    outb(0x1f5, (b->sector >> 16) & 0xff); // ... and here!
    outb(0x1f6, 0xe0 | ((b->dev & 1)<<4) | ((b->sector>>24) & 0x0f)); //M or S?
    if(b->flags & B_DIRTY){
        outb(0x1f7, IDE_CMD_WRITE);         // this is a WRITE 0x20 (ide.c)
        outsl(0x1f0, b->data, 512/4);       // transfer data too!
    } else {
        outb(0x1f7, IDE_CMD_READ);          // this is a READ (no data) 0x30(ide.c)
    }
}
```

Ports and Outs/ins

```
static inline void
outb(ushort port, uchar data)
{
  asm volatile("out %0,%1" : : "a" (data), "d" (port));
}
```

```
static inline void
outsl(int port, const void *addr, int cnt)
{
  asm volatile("cld; rep outsl" :
               "=S" (addr), "=c" (cnt) :
               "d" (port), "0" (addr), "1" (cnt) :
               "cc");
}
```

```
static inline uchar
inb(ushort port)
{
  uchar data;

  asm volatile("in %1,%0" : "=a" (data) : "d" (port));
  return data;
}
```

xv6 code: just check the device is ready and not busy

```
static int ide_wait_ready() {
        while (((int r = inb(0x1f7)) & IDE_BSY) ||
                !(r & IDE_DRDY))
        ; // loop until drive isn't busy
}
```

Device should be initialized somewhere else (at boot)

xv6 code: interrupt handler

```
void ide_intr() { //called from traps()
   struct buf *b;
   acquire(&ide_lock);
   //take b as the first element in the ide_queue (not shown)
   if (!(b->flags & B_DIRTY) && ide_wait_ready(1) >= 0)
      insl(0x1f0, b->data, 512/4); // if READ: get data
   b->flags |=  B_VALID;
   b->flags &= ~B_DIRTY;
   wakeup(b); // wake waiting process (equivalent to signal)
   if ((ide_queue = b->qnext) != 0) // start next request
      ide_start_request(ide_queue); // (if one exists)
   release(&ide_lock);
}
```

Sleep & wakeup

```
// Atomically release lock and sleep on chan.
// Reacquires lock when awakened.
void
sleep(void *chan, struct spinlock *lk)
{
  if(proc == 0)
    panic("sleep");

  if(lk == 0)
    panic("sleep without lk");

  // Must acquire ptable.lock in order to
  // change p->state and then call sched.
  // Once we hold ptable.lock, we can be
  // guaranteed that we won't miss any wakeup
  // (wakeup runs with ptable.lock locked),
  // so it's okay to release lk.
  if(lk != &ptable.lock){  //DOC: sleeplock0
    acquire(&ptable.lock);  //DOC: sleeplock1
    release(lk);
  }

  // Go to sleep.
  proc->chan = chan;
  proc->state = SLEEPING;
  sched();

  // Tidy up.
  proc->chan = 0;

  // Reacquire original lock.
  if(lk != &ptable.lock){  //DOC: sleeplock2
    release(&ptable.lock);
    acquire(lk);
  }
}
```

```
// Wake up all processes sleeping on chan.
// The ptable lock must be held.
static void
wakeup1(void *chan)
{
  struct proc *p;

  for(p = ptable.proc; p < &ptable.proc[NPROC]; p++)
    if(p->state == SLEEPING && p->chan == chan)
      p->state = RUNNABLE;
}

// Wake up all processes sleeping on chan.
void
wakeup(void *chan)
{
  acquire(&ptable.lock);
  wakeup1(chan);
  release(&ptable.lock);
}
```

Current xv6 code (kernel/ide.c)

```
// Sync buf with disk.
// If B_DIRTY is set, write buf to disk, clear B_DIRTY, set B_VALID.
// Else if B_VALID is not set, read buf from disk, set B_VALID.
void
iderw(struct buf *b)
{
  struct buf **pp;

  if(!(b->flags & B_BUSY))
    panic("iderw: buf not busy");
  if((b->flags & (B_VALID|B_DIRTY)) == B_VALID)
    panic("iderw: nothing to do");
  if(b->dev != 0 && !havedisk1)
    panic("iderw: ide disk 1 not present");

  acquire(&idelock);

  // Append b to idequeue.
  b->qnext = 0;
  for(pp=&idequeue; *pp; pp=&(*pp)->qnext)
    ;
  *pp = b;

  // Start disk if necessary.
  if(idequeue == b)
    idestart(b);

  // Wait for request to finish.
  // Assuming will not sleep too long: ignore proc->killed.
  while((b->flags & (B_VALID|B_DIRTY)) != B_VALID){
    sleep(b, &idelock);
  }

  release(&idelock);
}
```

```
// Start the request for b.  Caller must hold idelock.
static void
idestart(struct buf *b)
{
  if(b == 0)
    panic("idestart");

  idewait(0);
  outb(0x3f6, 0);  // generate interrupt
  outb(0x1f2, 1);  // number of sectors
  outb(0x1f3, b->sector & 0xff);
  outb(0x1f4, (b->sector >> 8) & 0xff);
  outb(0x1f5, (b->sector >> 16) & 0xff);
  outb(0x1f6, 0xe0 | ((b->dev&1)<<4) | ((b->sector>>24)&0x0f));
  if(b->flags & B_DIRTY){
    outb(0x1f7, IDE_CMD_WRITE);
    outsl(0x1f0, b->data, 512/4);
  } else {
    outb(0x1f7, IDE_CMD_READ);
  }
}
```

Current xv6 code (kernel/ide.c)

```
// Wait for IDE disk to become ready.
static int
idewait(int checkerr)
{
  int r;

  while(((r = inb(0x1f7)) & (IDE_BSY|IDE_DRDY)) != IDE_DRDY)
    ;
  if(checkerr && (r & (IDE_DF|IDE_ERR)) != 0)
    return -1;
  return 0;
}

void
ideinit(void)
{
  int i;

  initlock(&idelock, "ide");
  picenable(IRQ_IDE);
  ioapicenable(IRQ_IDE, ncpu - 1);
  idewait(0);

  // Check if disk 1 is present
  outb(0x1f6, 0xe0 | (1<<4));
  for(i=0; i<1000; i++){
    if(inb(0x1f7) != 0){
      havedisk1 = 1;
      break;
    }
  }

  // Switch back to disk 0.
  outb(0x1f6, 0xe0 | (0<<4));
}
```

```
case T_IRQ0 + IRQ_IDE:
  ideintr();
  lapiceoi();
  break;
```

```
// Interrupt handler.
void
ideintr(void)
{
  struct buf *b;

  // Take first buffer off queue.
  acquire(&idelock);
  if((b = idequeue) == 0){
    release(&idelock);
    // cprintf("spurious IDE interrupt\n");
    return;
  }
  idequeue = b->qnext;

  // Read data if needed.
  if(!(b->flags & B_DIRTY) && idewait(1) >= 0)
    insl(0x1f0, b->data, 512/4);

  // Wake process waiting for this buf.
  b->flags |= B_VALID;
  b->flags &= ~B_DIRTY;
  wakeup(b);

  // Start disk on next buf in queue.
  if(idequeue != 0)
    idestart(idequeue);

  release(&idelock);
}
```