

# Operating Systems

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December 20, 2020

## Textbooks

- [1] TANENBAUM A S. *Modern Operating Systems*. 3rd ed. Prentice Hall Press, 2007.
- [2] Silberschatz, Galvin, Gagne. *Operating System Concepts Essentials*. 1st ed. John Wiley & Sons, 2011.
- [3] BOVET D, CESATI M. *Understanding The Linux Kernel*. 3rd ed. OReilly, 2005.
- [4] VENKATESH B, ANGRAVE L, et Al. *CS241 System Programming Coursebook*. University of Illinois, 2019.

# Course Web Links

Course web site <https://cs6.swfu.edu.cn/moodle>

Lecture slides [https://cs6.swfu.edu.cn/~wx672/lecture\\_notes/os/slides/](https://cs6.swfu.edu.cn/~wx672/lecture_notes/os/slides/)

Source code [https://cs6.swfu.edu.cn/~wx672/lecture\\_notes/os/src/](https://cs6.swfu.edu.cn/~wx672/lecture_notes/os/src/)

Lab instructions [https://cs6.swfu.edu.cn/~wx672/lecture\\_notes/os/lab.html](https://cs6.swfu.edu.cn/~wx672/lecture_notes/os/lab.html)

Sample lab report [https://cs6.swfu.edu.cn/~wx672/lecture\\_notes/os/sample-report/](https://cs6.swfu.edu.cn/~wx672/lecture_notes/os/sample-report/)

System Programming <https://github.com/angrave/SystemProgramming/wiki>

Beej's Guides <http://beej.us/guide/>



# Homework

## Weekly tech question

1. What was I trying to do?
2. How did I do it? (steps)
3. The expected output? The real output?
4. How did I try to solve it? (steps, books, web links)
5. How many hours did I struggle on it?

|m <https://cs6.swfu.edu.cn/moodle/mod/forum/view.php?id=53>

✉ [wx672ster+os@gmail.com](mailto:wx672ster+os@gmail.com)

E Preferably in English

✍ in [stackoverflow](#) style

OR simply show me the tech questions you asked on any website

# Part I

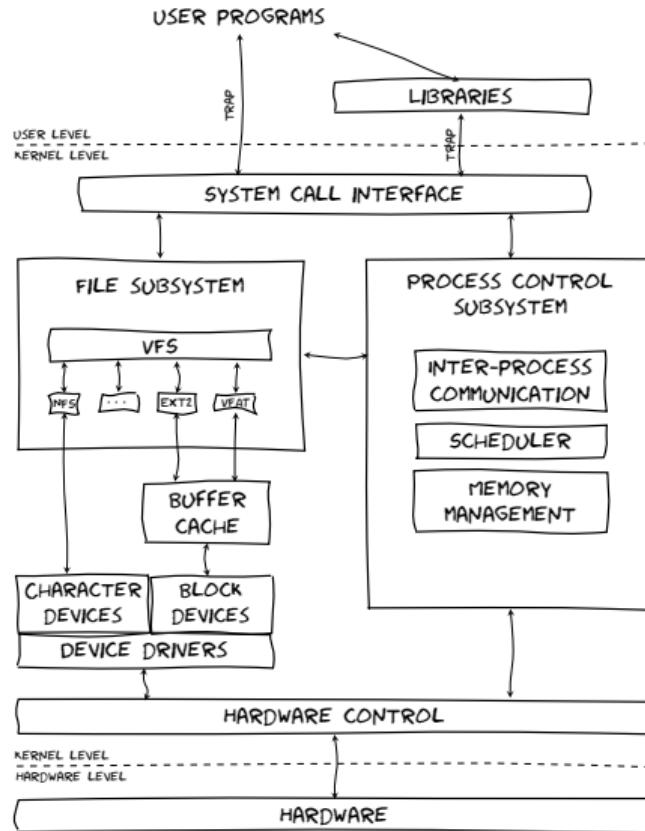
## Introduction

# 1 What's an Operating System

# What's an Operating System?

- ▶ “*Everything a vendor ships when you order an operating system*”
- ▶ It’s the program that runs all the time
- ▶ It’s a **resource manager**
  - Each program gets time with the resource
  - Each program gets space on the resource
- ▶ It’s a **control program**
  - Controls execution of programs to prevent errors and improper use of the computer
- ▶ No universally accepted definition

# What's in the OS?



# Choosing an OS

Do you fear technology?

Is your daddy rich?

Yes ↗ No ↘

Do you care about freedom/privacy?



Do you have a life?

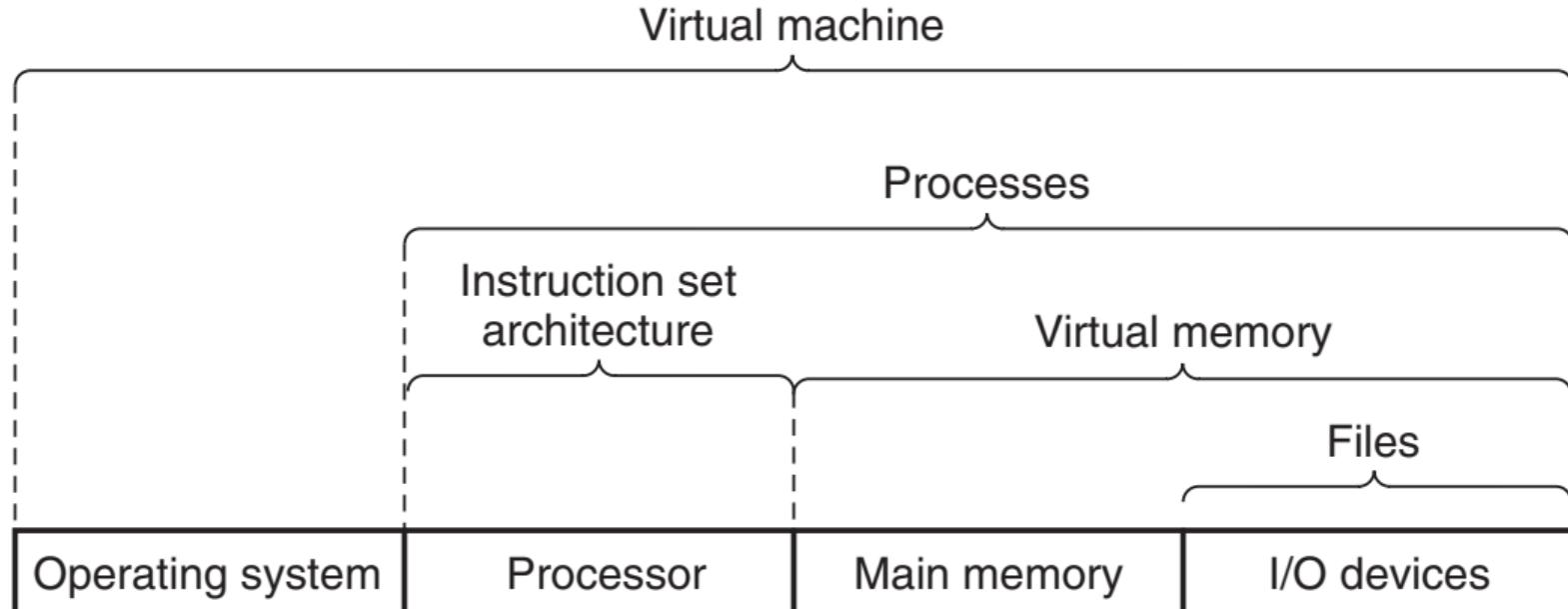
Yes ↗ No ↘

Yes ↗ No ↘



# Abstractions

To hide the complexity of the actual implementations



# System Goals

## Convenient vs. Efficient

- ▶ Convenient for the user — for PCs
- ▶ Efficient — for mainframes, multiusers
- ▶ UNIX
  - Started with keyboard + printer, none paid to convenience
  - Now, still concentrating on efficiency, with GUI support

# History of Operating Systems

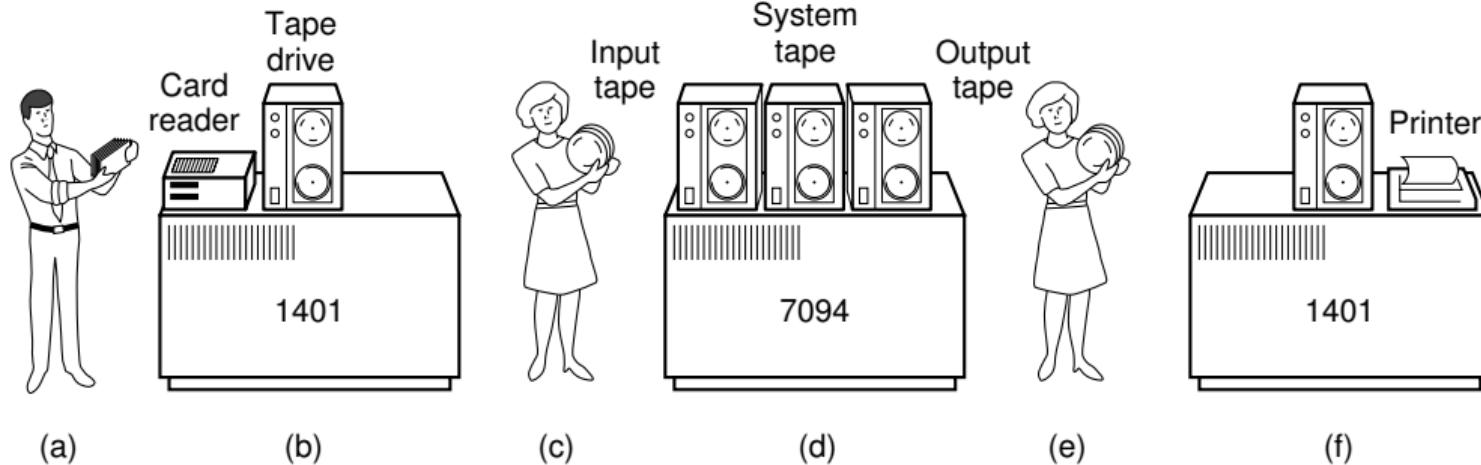


Fig. 1-2. An early batch system. (a) Programmers bring cards to 1401. (b) 1401 reads batch of jobs onto tape. (c) Operator carries input tape to 7094. (d) 7094 does computing. (e) Operator carries output tape to 1401. (f) 1401 prints output.

1945 - 1955 First generation

- vacuum tubes, plug boards

1955 - 1965 Second generation

- transistors, batch systems

1965 - 1980 Third generation

- ICs and multiprogramming

1980 - present Fourth generation

- personal computers

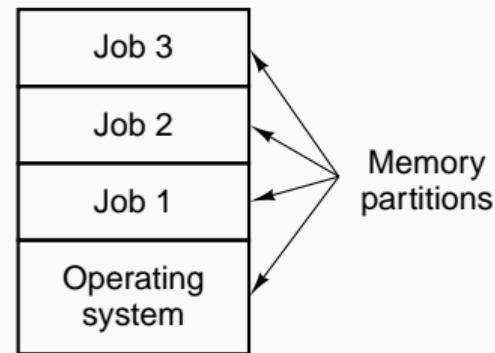
Multi-programming is the first instance where the OS must make decisions for the users

Job scheduling — decides which job should be loaded into the memory.

Memory management — because several programs in memory at the same time

CPU scheduling — choose one job among all the jobs are ready to run

Process management — make sure processes don't offend each other



# The Operating System Zoo

- ▶ Mainframe OS
- ▶ Server OS
- ▶ Multiprocessor OS
- ▶ Personal computer OS
- ▶ Real-time OS
- ▶ Embedded OS
- ▶ Smart card OS

## 2 OS Services

# OS Services

Like a government

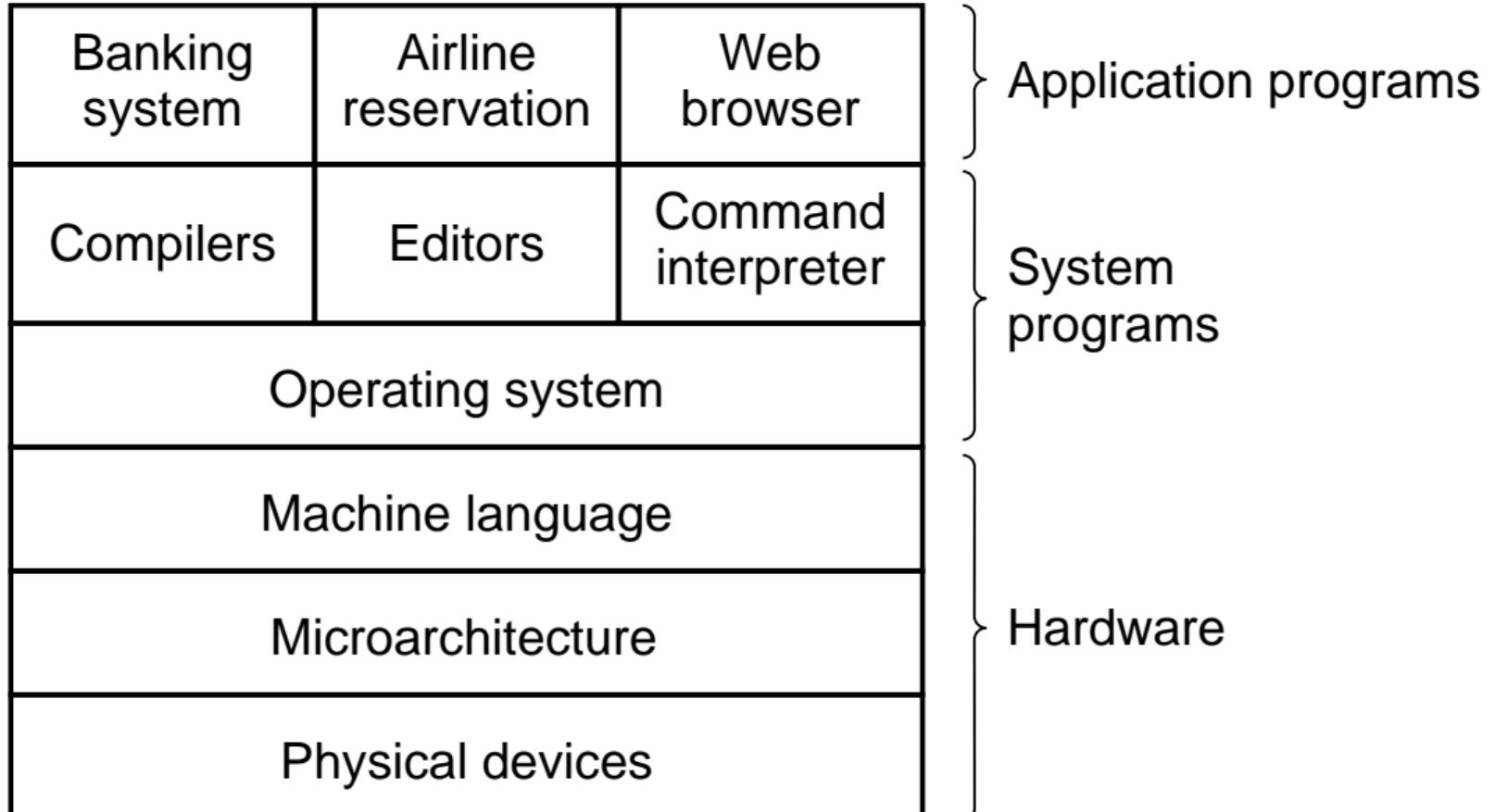
## Helping the users:

- ▶ User interface
- ▶ Program execution
- ▶ I/O operation
- ▶ File system manipulation
- ▶ Communication
- ▶ Error detection

## Keeping the system efficient:

- ▶ Resource allocation
- ▶ Accounting
- ▶ Protection and security

# A Computer System



### 3 Hardware

# CPU Working Cycle



1. Fetch the first instruction from memory
2. Decode it to determine its type and operands
3. execute it

## Special CPU Registers

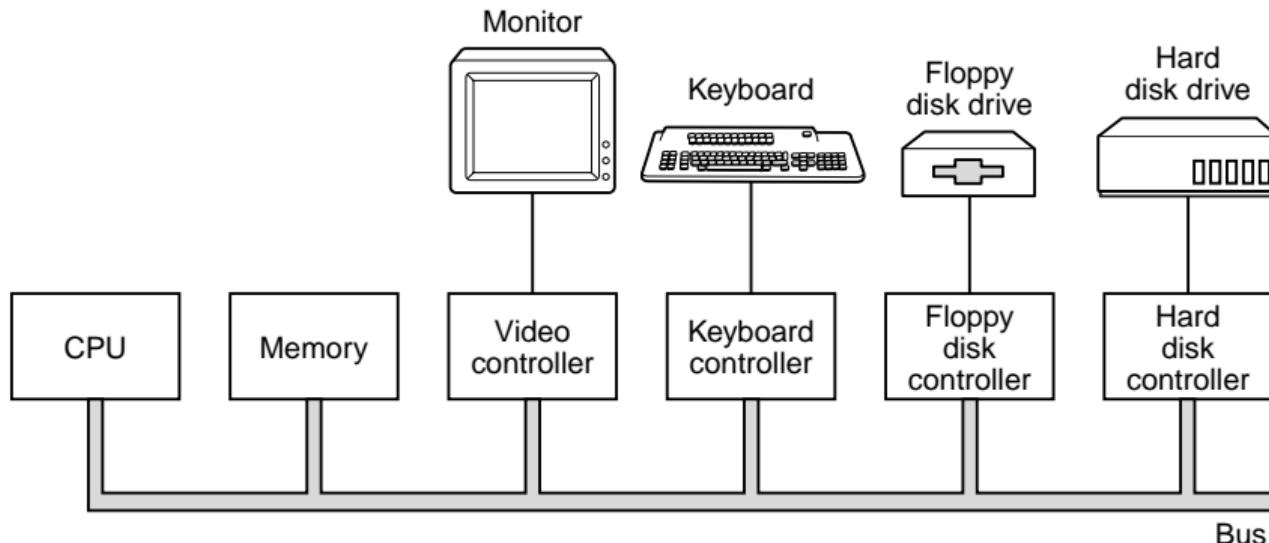
Program counter (PC): keeps the memory address of the next instruction to be fetched

Stack pointer (SP): ➔ the top of the current stack in memory

Program status (PS): holds

- condition code bits
- processor state

# System Bus



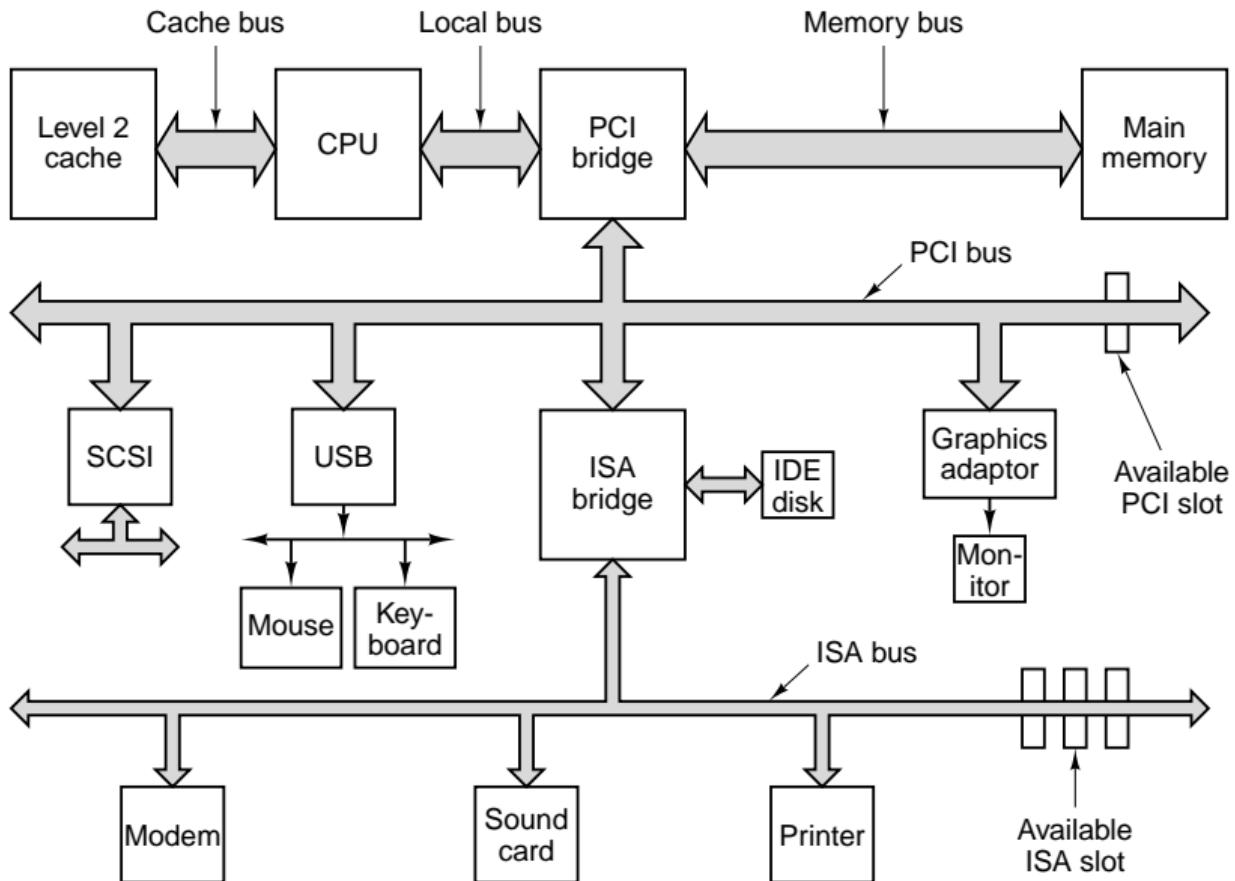
**Address Bus:** specifies the memory locations (addresses) for the data transfers

**Data Bus:** holds the data transferred. Bidirectional

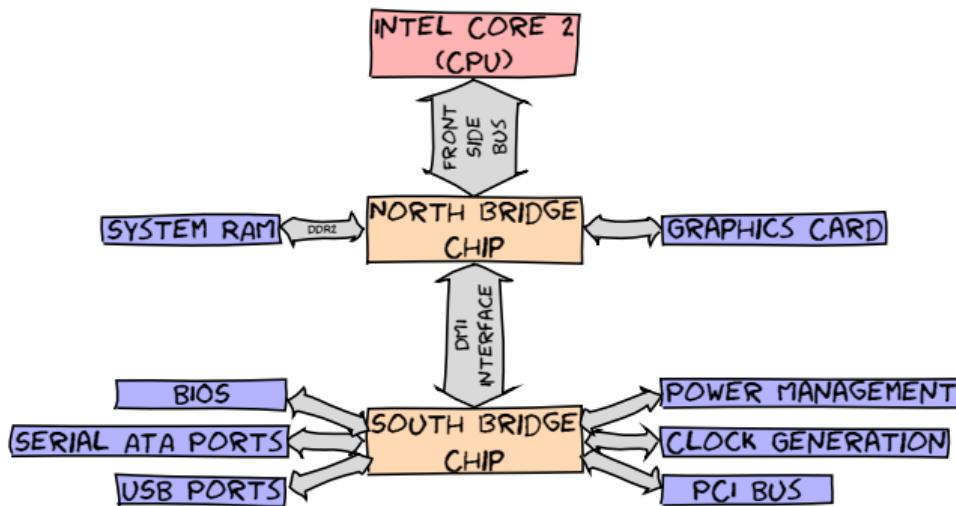
**Control Bus:** contains various lines used to route timing and control signals throughout the system

## Controllers and Peripherals

- ▶ Peripherals are real devices controlled by controller chips
- ▶ Controllers are processors like the CPU itself, have control registers
- ▶ Device driver writes to the registers, thus control it
- ▶ Controllers are connected to the CPU and to each other by a variety of buses



# Motherboard Chipsets



## The northbridge

1. receives a physical memory request
2. decides where to route it
  - to RAM? to video card? to ...?
  - decision made via the **memory address map**

- ▶ The CPU doesn't know what it's connected to
  - CPU test bench? network router? toaster? brain implant?
- ▶ The CPU talks to the outside world through its pins
  - some pins to transmit the physical memory address
  - other pins to transmit the values
- ▶ The CPU's gateway to the world is the [front-side bus](#)

### Intel Core 2 QX6600

- ▶ 33 pins to transmit the physical memory address
  - so there are  $2^{33}$  choices of memory locations
- ▶ 64 pins to send or receive data
  - so data path is 64-bit wide, or 8-byte chunks

This allows the CPU to physically address 64GB of memory ( $2^{33} \times 8B$ )

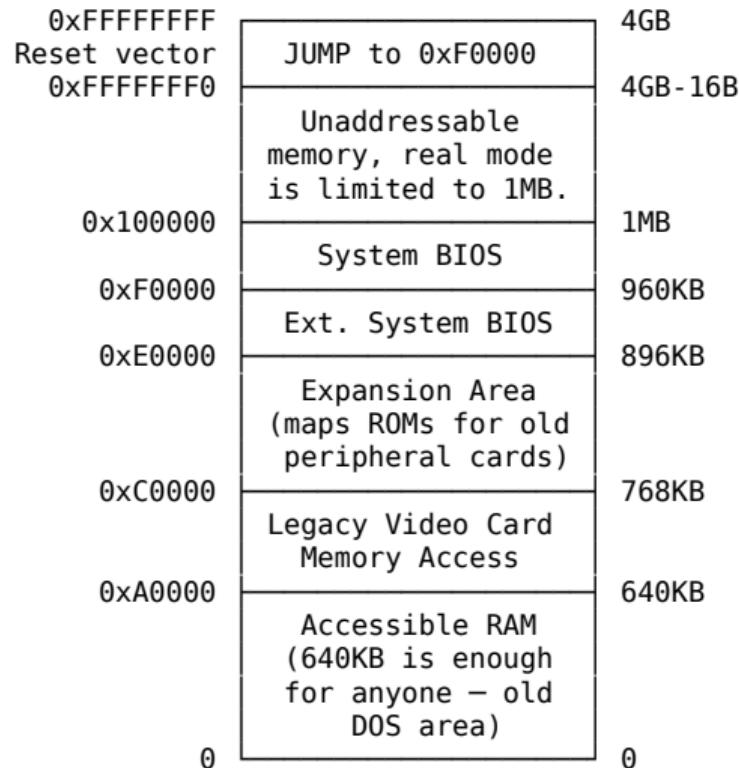
## Some physical memory addresses are mapped away!

- ▶ only the addresses, not the spaces
- ▶ Memory holes
  - 640KB ~ 1MB
  - /proc/iomem

## Memory-mapped I/O

- ▶ BIOS ROM
- ▶ video cards
- ▶ PCI cards
- ▶ ...

This is why 32-bit OSes have problems using 4 gigs of RAM.

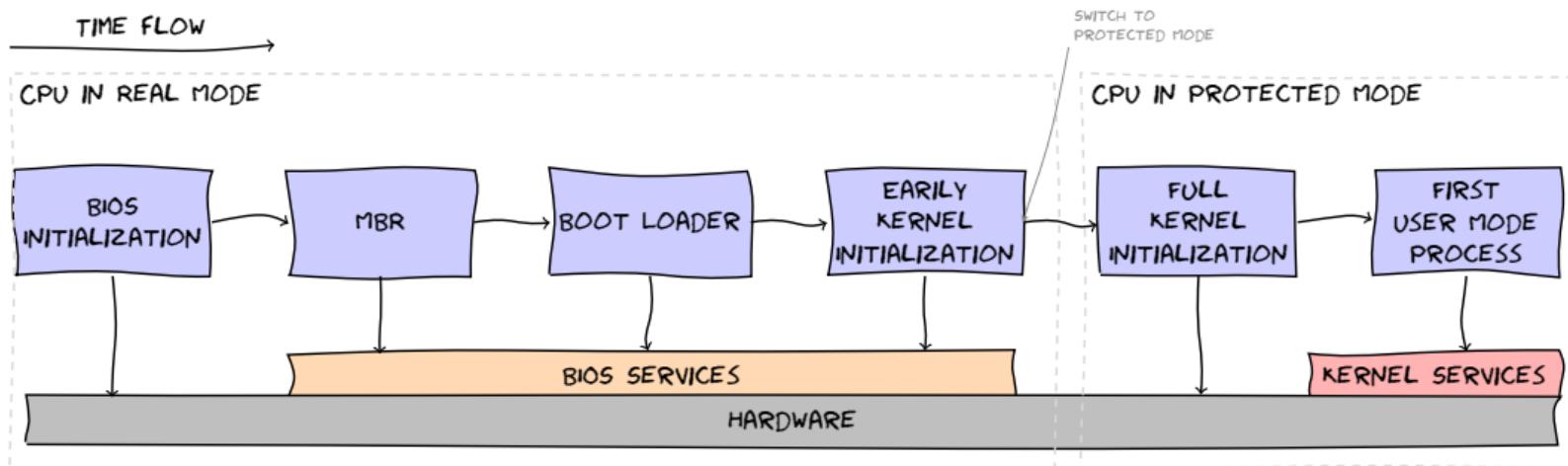


## 4 Bootstrapping

# Bootstrapping

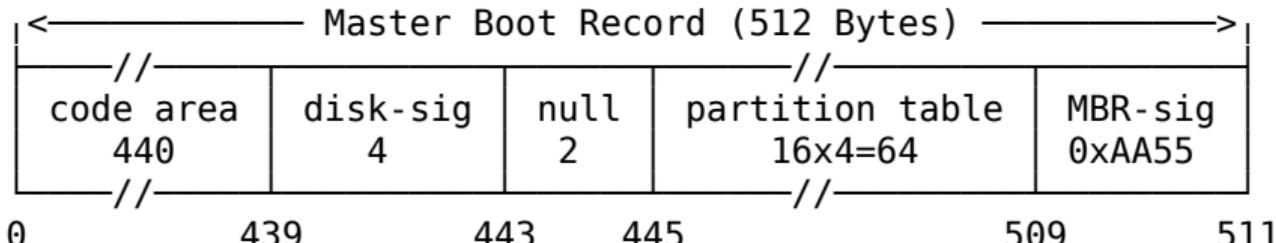
Can you pull yourself up by your own bootstraps?

A computer cannot run without first loading software but must be running before any software can be loaded.



# Intel x86 Bootstrapping

1. BIOS (0xffffffff0)
  - ➡ POST ➡ HW init ➡ Find a boot device (FD,CD,HD...) ➡ Copy sector zero (MBR) to RAM (0x00007c00)
2. MBR – the first 512 bytes, contains
  - ▶ Small code (< 446 Bytes), e.g. GRUB stage 1, for loading GRUB stage 2
  - ▶ the primary partition table ( $16 \times 4 = 64$  Bytes)
  - ▶ its job is to load the second-stage boot loader.
3. GRUB stage 2 — load the OS kernel into RAM
4. ⚙ startup
5. init — the first user-space program



```
$ sudo dd -n512 /dev/sda
```

## 5 Interrupt

## Why Interrupt?

While a process is reading a disk file, can we do...

```
1  while(!done_reading_a_file())
2  {
3      let_CPU_wait();
4      /* or... */
5      lend_CPU_to_others();
6  }
7  operate_on_the_file();
```

## Modern OS are Interrupt Driven

HW INT by sending a signal to CPU

SW INT by executing a **system call**

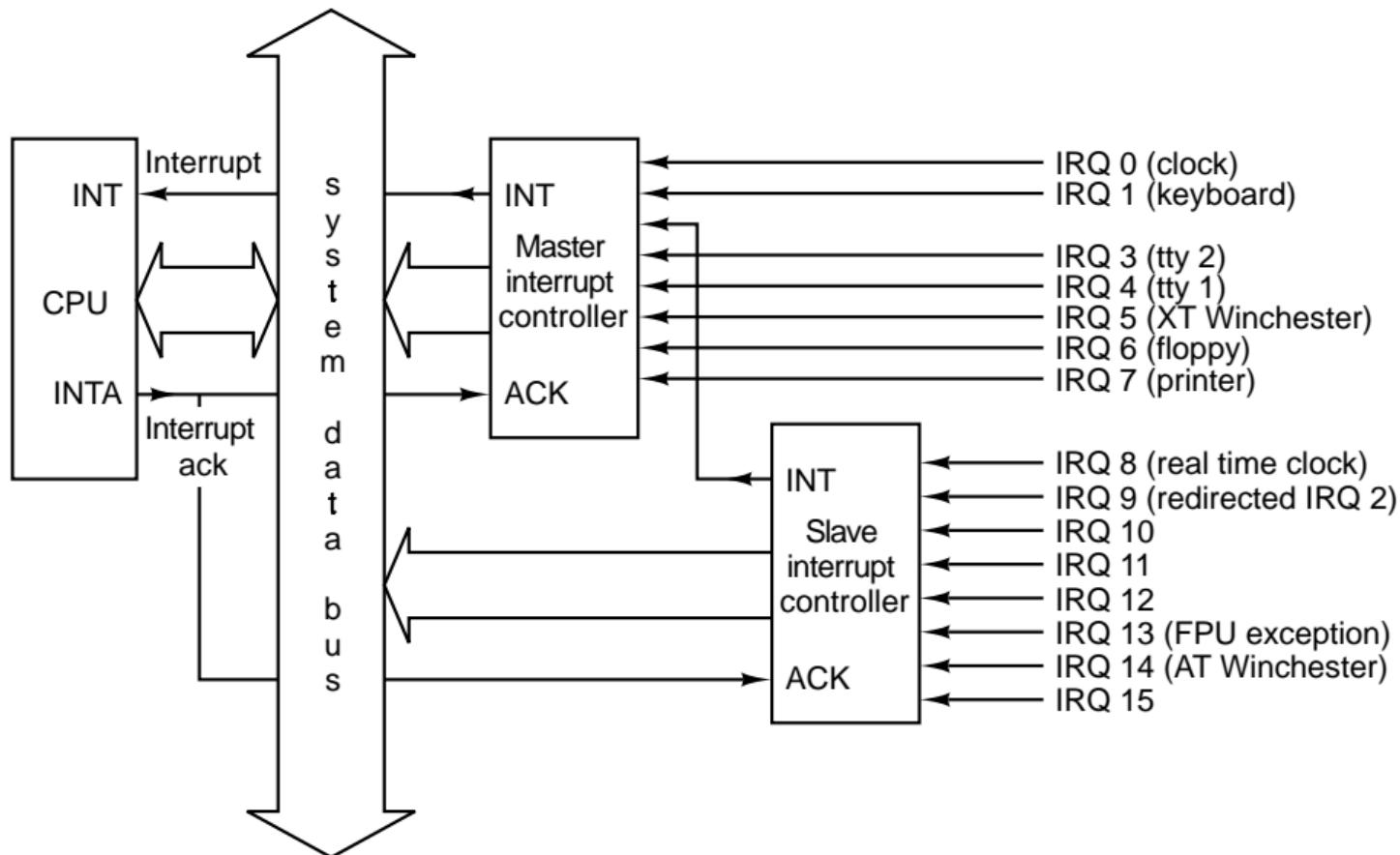
Trap (exception) is a software-generated INT caused by an error or by a specific request from an user program

Interrupt vector is an array of pointers → the memory addresses of **interrupt handlers**. This array is indexed by a unique device number

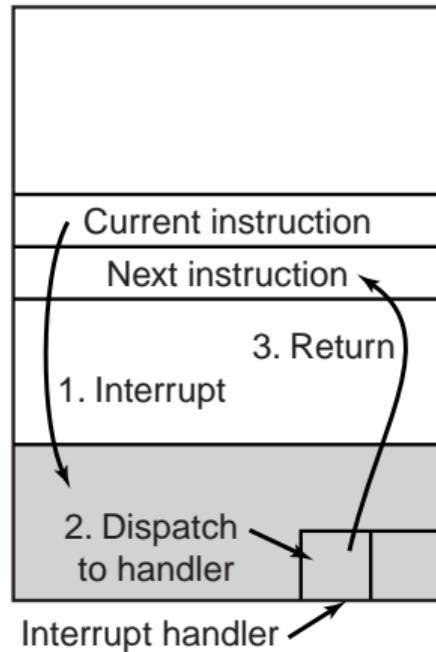
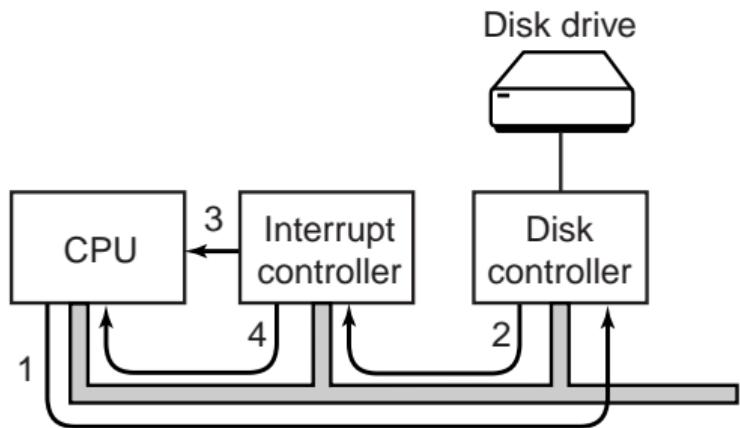
\$ less /proc/devices

\$ less /proc/interrupts

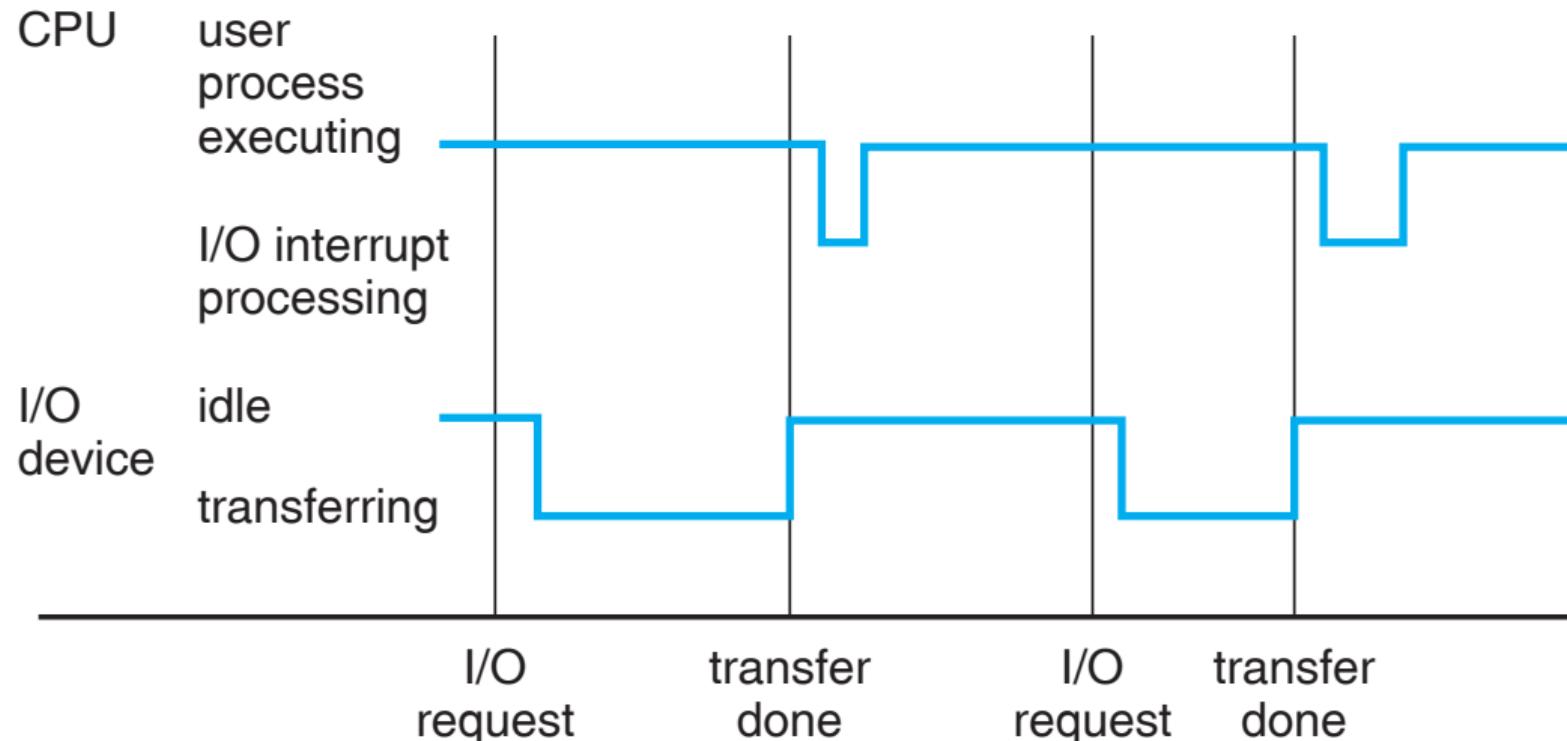
# Programmable Interrupt Controllers



# Interrupt Processing



## Interrupt Timeline



## 6 System Calls

# System Calls

## A System Call

- ▶ is how a program requests a service from an OS kernel
- ▶ provides the interface between a process and the OS

```
$ man 2 intro
```

```
$ man 2 syscalls
```

### Process management

Call	Description
pid = fork()	Create a child process identical to the parent
pid = waitpid(pid, &statloc, options)	Wait for a child to terminate
s = execve(name, argv, environp)	Replace a process' core image
exit(status)	Terminate process execution and return status

### File management

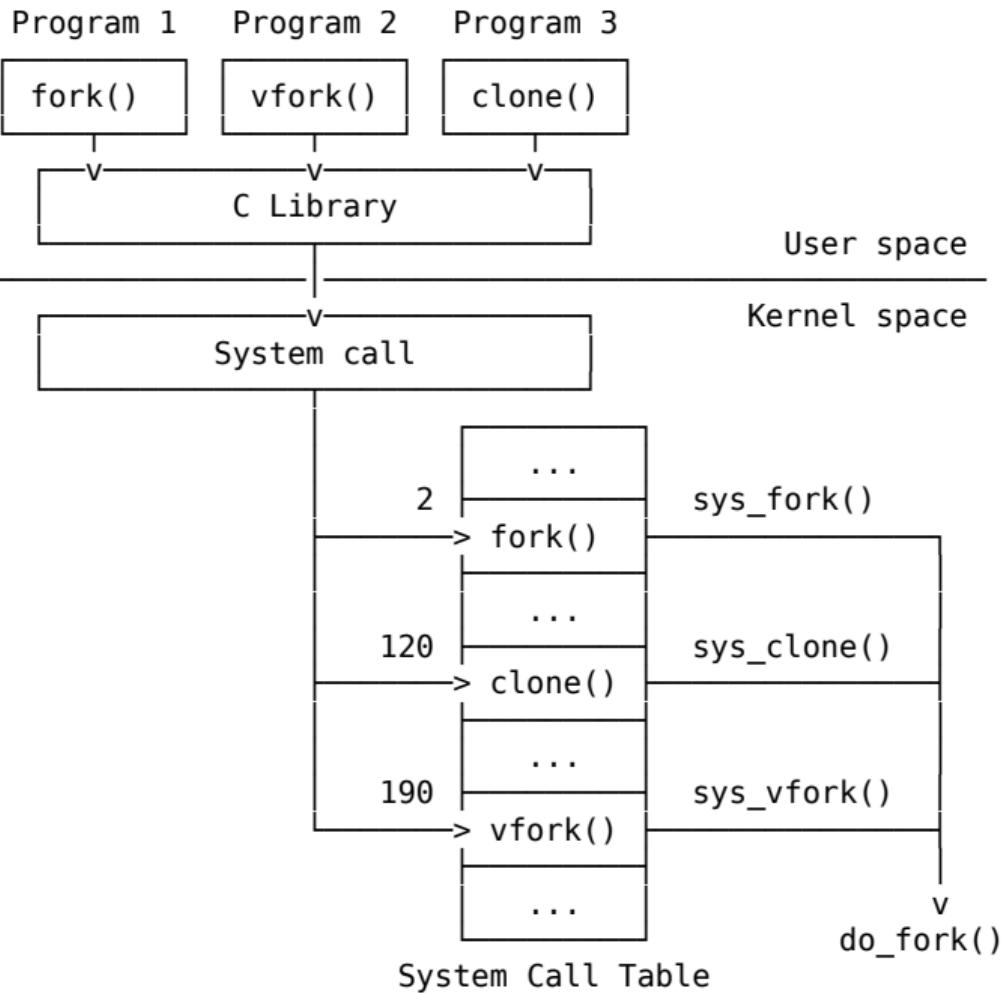
Call	Description
fd = open(file, how, ...)	Open a file for reading, writing or both
s = close(fd)	Close an open file
n = read(fd, buffer, nbytes)	Read data from a file into a buffer
n = write(fd, buffer, nbytes)	Write data from a buffer into a file
position = lseek(fd, offset, whence)	Move the file pointer
s = stat(name, &buf)	Get a file's status information

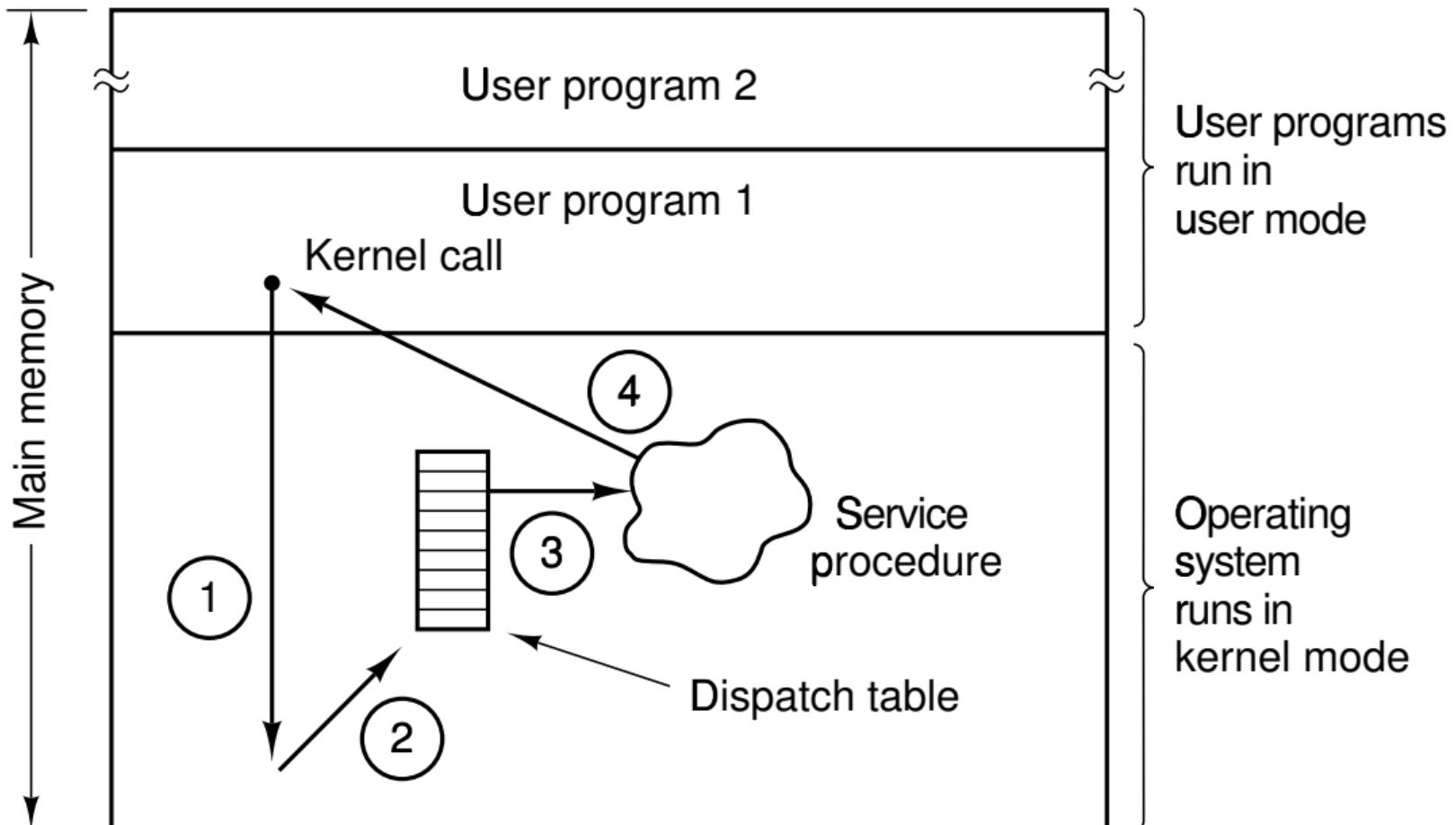
### Directory and file system management

Call	Description
s = mkdir(name, mode)	Create a new directory
s = rmdir(name)	Remove an empty directory
s = link(name1, name2)	Create a new entry, name2, pointing to name1
s = unlink(name)	Remove a directory entry
s = mount(special, name, flag)	Mount a file system
s = umount(special)	Unmount a file system

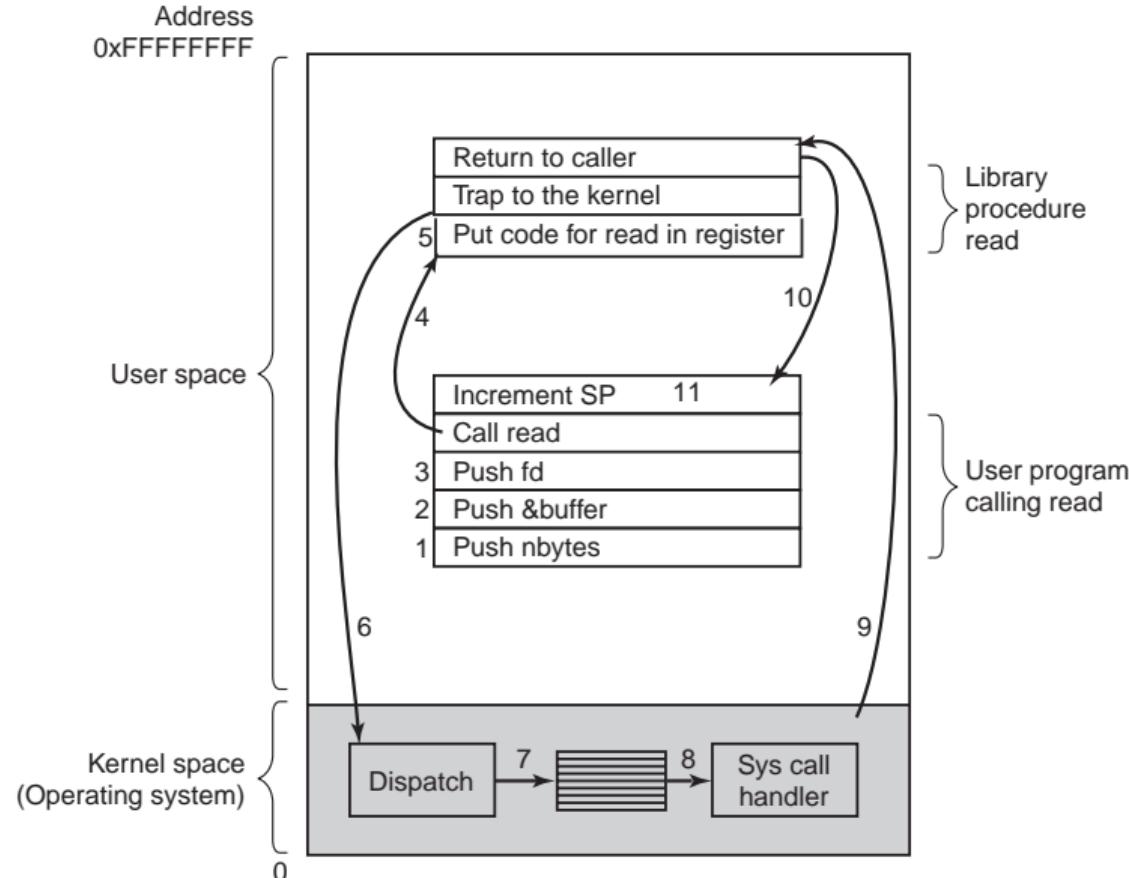
### Miscellaneous

Call	Description
s = chdir(dirname)	Change the working directory
s = chmod(name, mode)	Change a file's protection bits
s = kill(pid, signal)	Send a signal to a process
seconds = time(&seconds)	Get the elapsed time since Jan. 1, 1970





# The 11 steps in making the system call read(fd,buffer,nbytes)



# Example

Linux INT80h

**Interrupt Vector Table:** The very first 1KiB of x86 memory.

- ▶ 256 entries  $\times$  4B = 1KiB
- ▶ Each entry is a complete memory address (segment:offset)
- ▶ It's populated by Linux and BIOS
- ▶ Slot 80h: address of the kernel services dispatcher (☞ sys-call table)

# Example

```
SECTION .DATA
Msg:      db 'Hello, world!',10 ; 10 = ascii for LF
MsgLen:   equ $-Msg

SECTION .TEXT
GLOBAL _start

_start:
    mov eax, 4          ; write(
    mov ebx, 1          ; STDOUT_FILENO,
    mov ecx, Msg        ; "Hello, world!\n",
    mov edx, MsgLen    ; sizeof("Hello, world!\n")
    int 80h             ; );

    mov eax, 1          ; exit(
    mov ebx, 0          ; EXIT_SUCCESS
    int 80h             ; );
```

System call numbers:

```
$ less /usr/include/asm/unistd_32.h
$ less /usr/include/asm/unistd_64.h
```

# System Call Examples

```
int main(void)
{
    write(1, "Hello, world!\n", 14);

    return EXIT_SUCCESS;
}
```

► Actually, `write()` is a wrapper function in glibc.

```
$ man 2 write
$ man 3 write
```

Don't invoke syscall directly whenever possible

```
int main(void) {
    register char* arg2 asm("rsi") = "hello, world!\n";

    /* rax: sys_write; rdi: STDOUT; */
    asm("mov $1, %rax; mov $1, %rdi; mov $14, %rdx; syscall;");

    return 0;
}
```

## System Call Examples

```
$ man 2 fork
```

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

int main ()
{
    puts("Hello World!");
    fork();
    puts("Goodbye Cruel World!");
    return 0;
}
```

```
$ man 3 exec
int main()
{
    printf("Main process (%d) saying hello!\n", getpid());
    if(fork() == 0 ) {                                /* child */
        printf("Child (%d) is listing the source file... \n", getpid());
        execl("/bin/ls", "", NULL);
        /* useless after execl() */
        puts("You can't see this line unless execl() failed.\n");
    }
    else {                                         /* parent */
        int i=60;
        printf("parent (%d) is sleeping for %d seconds... \n", getpid(),i);
        sleep(i);                                     /* for zombie */
    }
    /* only the one who doesn't call execl() can do the following. */
    printf("Hello again from process %d\n", getpid());
    return 0;
}
```

# Hardware INT vs. Software INT

Device:

Send electrical signal to interrupt controller.



Controller:

1. Interrupt CPU.
2. Send digital identification of interrupting device.



Kernel:

1. Save registers.
2. Execute driver software to read I/O device.
3. Send message.
4. Restart a process (not necessarily interrupted process).

(a)

Caller:

1. Put message pointer and destination of message into CPU registers.
2. Execute software interrupt instruction.



Kernel:

1. Save registers.
2. Send and/or receive message.
3. Restart a process (not necessarily calling process).

(b)

## References

- [1] Wikipedia. *Interrupt — Wikipedia, The Free Encyclopedia*. 2015.  
<http://en.wikipedia.org/w/index.php?title=Interrupt&oldid=646521061>.
- [2] Wikipedia. *System call — Wikipedia, The Free Encyclopedia*. 2015.  
[http://en.wikipedia.org/w/index.php?title=System%5C\\_call&oldid=647910319](http://en.wikipedia.org/w/index.php?title=System%5C_call&oldid=647910319).

## Part II

### Process And Thread

## 7 Processes

## 7.1 What's a Process

# Process

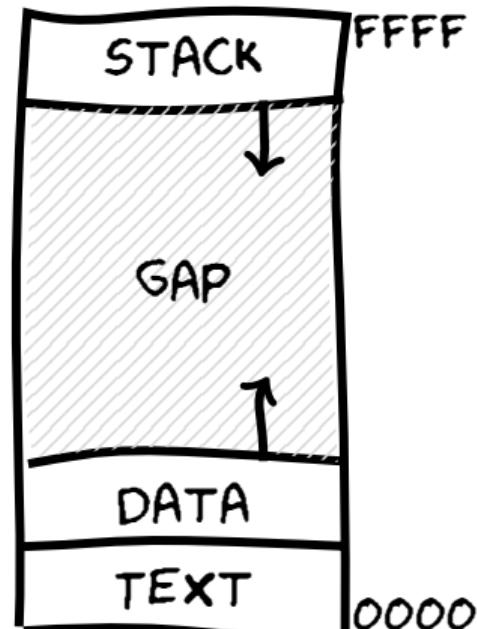
A process is an instance of a program in execution

Processes are like human beings:

- ▶ they are generated
- ▶ they have a life
- ▶ they optionally generate one or more child processes, and
- ▶ eventually they die

A small difference:

- ▶ sex is not really common among processes
- ▶ each process has just one parent



## 7.2 PCB

# Process Control Block (PCB)

## Implementation

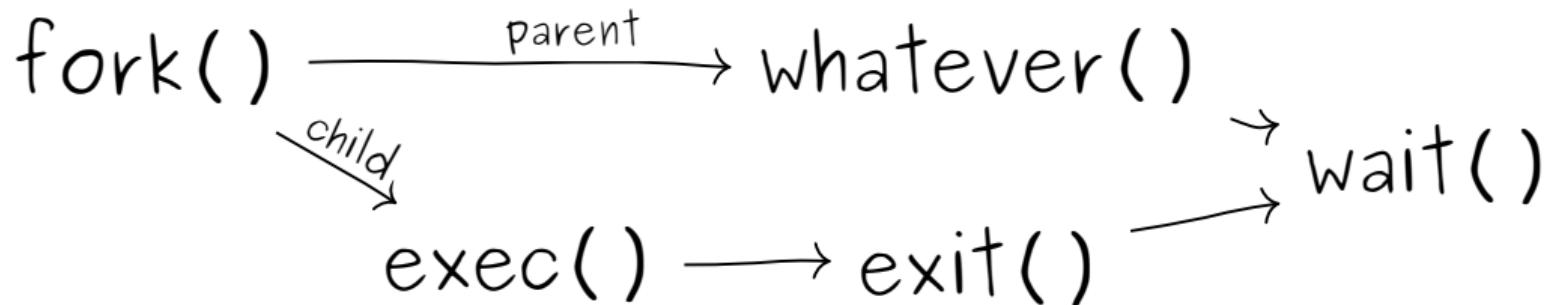
A process is **the collection of data structures** that fully describes how far the execution of the program has progressed.

- ▶ Each process is represented by a **PCB**
- ▶ `task_struct` in 

process state
PID
program counter
registers
memory limits
list of open files
...

## 7.3 Process Creation

## Process Creation



- ▶ When a process is created, it is almost identical to its parent
  - ▶ It receives a (logical) copy of the parent's address space, and
  - ▶ executes the same code as the parent
- ▶ The parent and child have separate copies of the data (stack and heap)

## Forking in C

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

int main ()
{
    puts( "Hello World!" );
    fork();
    puts( "Goodbye Cruel World!" );
    return 0;
}

$ man fork
```

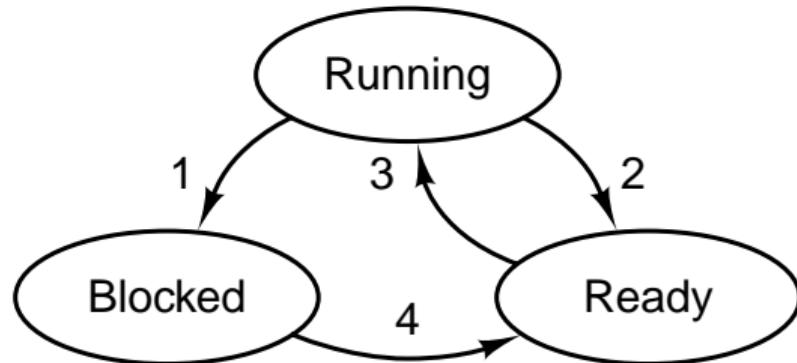
## exec()

```
int main()
{
    pid_t pid;

    pid = fork();
    if(pid < 0) {           /* error */
        fprintf(stderr, "Fork Failed");
        exit(-1);
    }
    else if(pid == 0) {     /* child */
        execlp("/bin/ls", "ls", NULL);
    }
    else {                  /* parent */
        wait(NULL);
        puts("Child Complete");
        exit(EXIT_SUCCESS);
    }
    return 0;
}
```

## 7.4 Process State

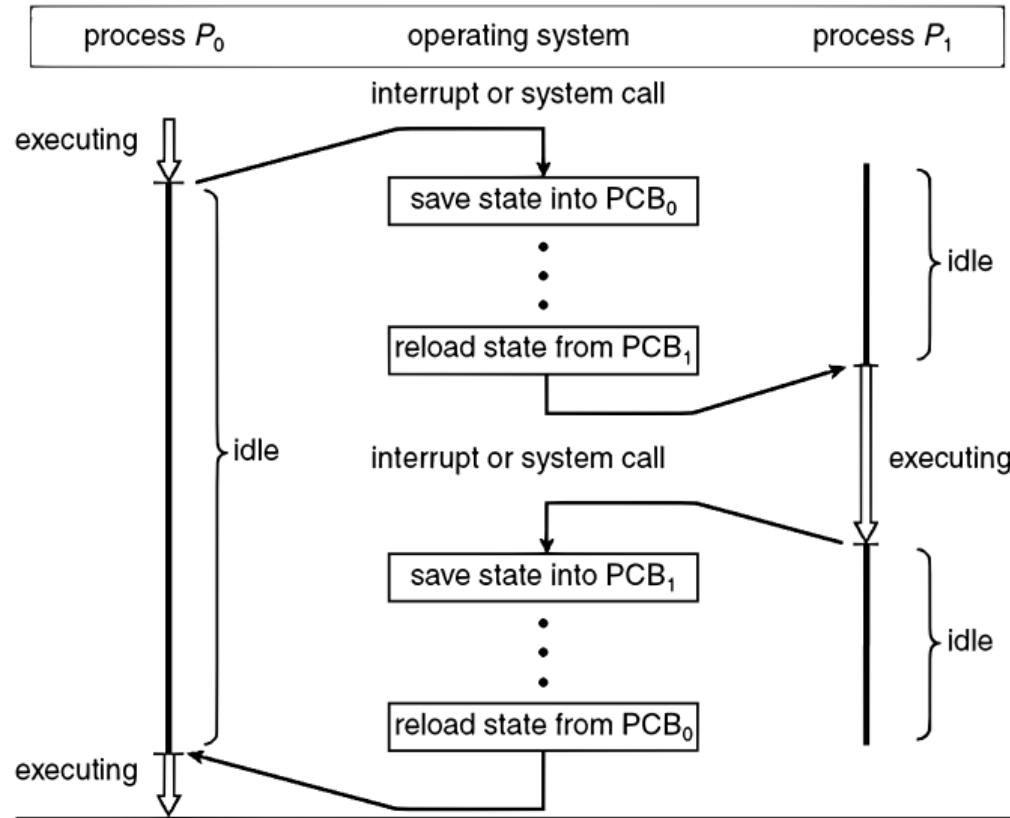
# Process State Transition



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

## 7.5 CPU Switch From Process To Process

# CPU Switch From Process To Process



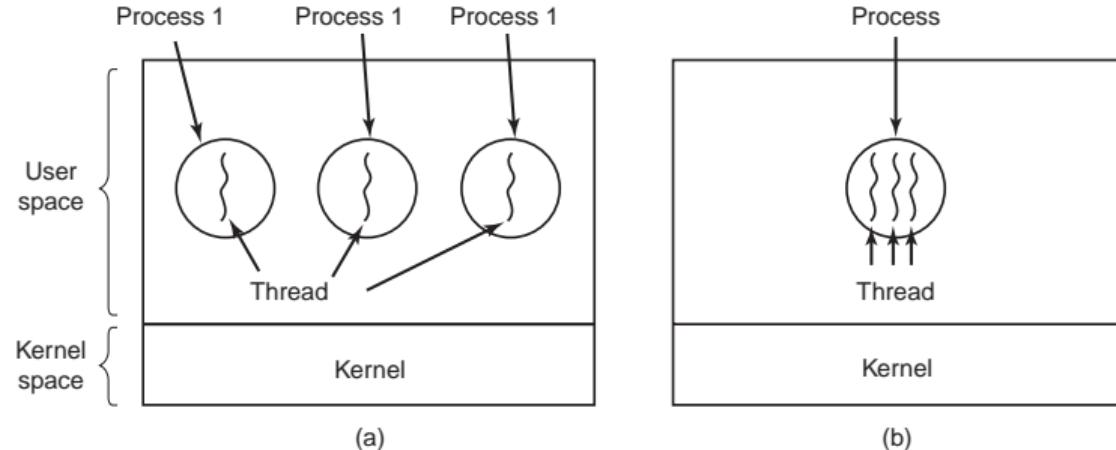
## 8 Threads

## 8.1 Processes vs. Threads

# Process vs. Thread

a single-threaded process = resource + execution

a multi-threaded process = resource + executions



A process = a unit of resource ownership, used to group resources together;

A thread = a unit of scheduling, scheduled for execution on the CPU.

# Process vs. Thread

**multiple threads running in one process:**

share an address space and other resources

**multiple processes running in one computer:**

share physical memory, disk, printers ...

## No protection between threads

impossible — because process is the minimum unit of resource management

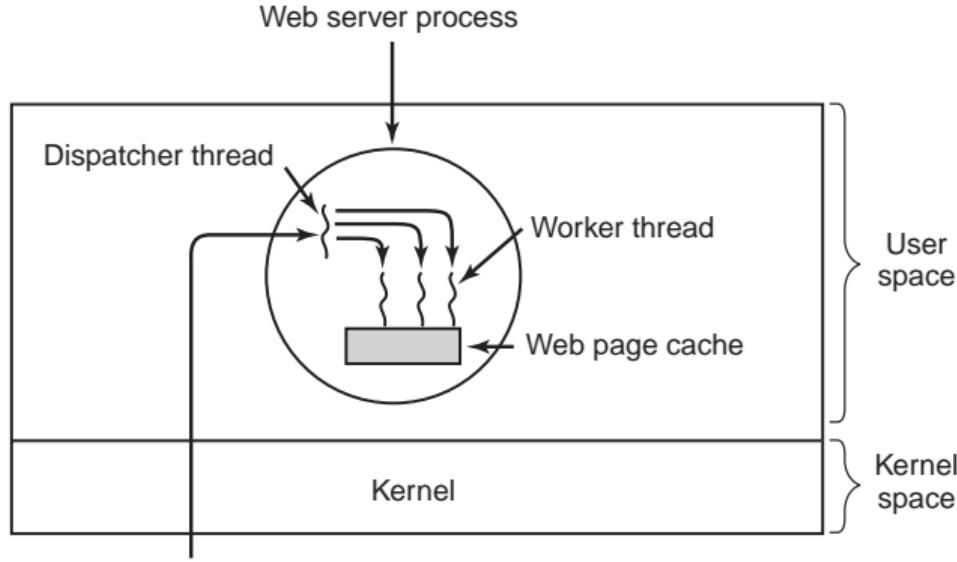
unnecessary — a process is owned by a single user

## Threads

code, data, open files, signals...		
thread ID	thread ID	thread ID
program counter	program counter	program counter
register set	register set	register set
stack	stack	stack

## 8.2 Why Thread?

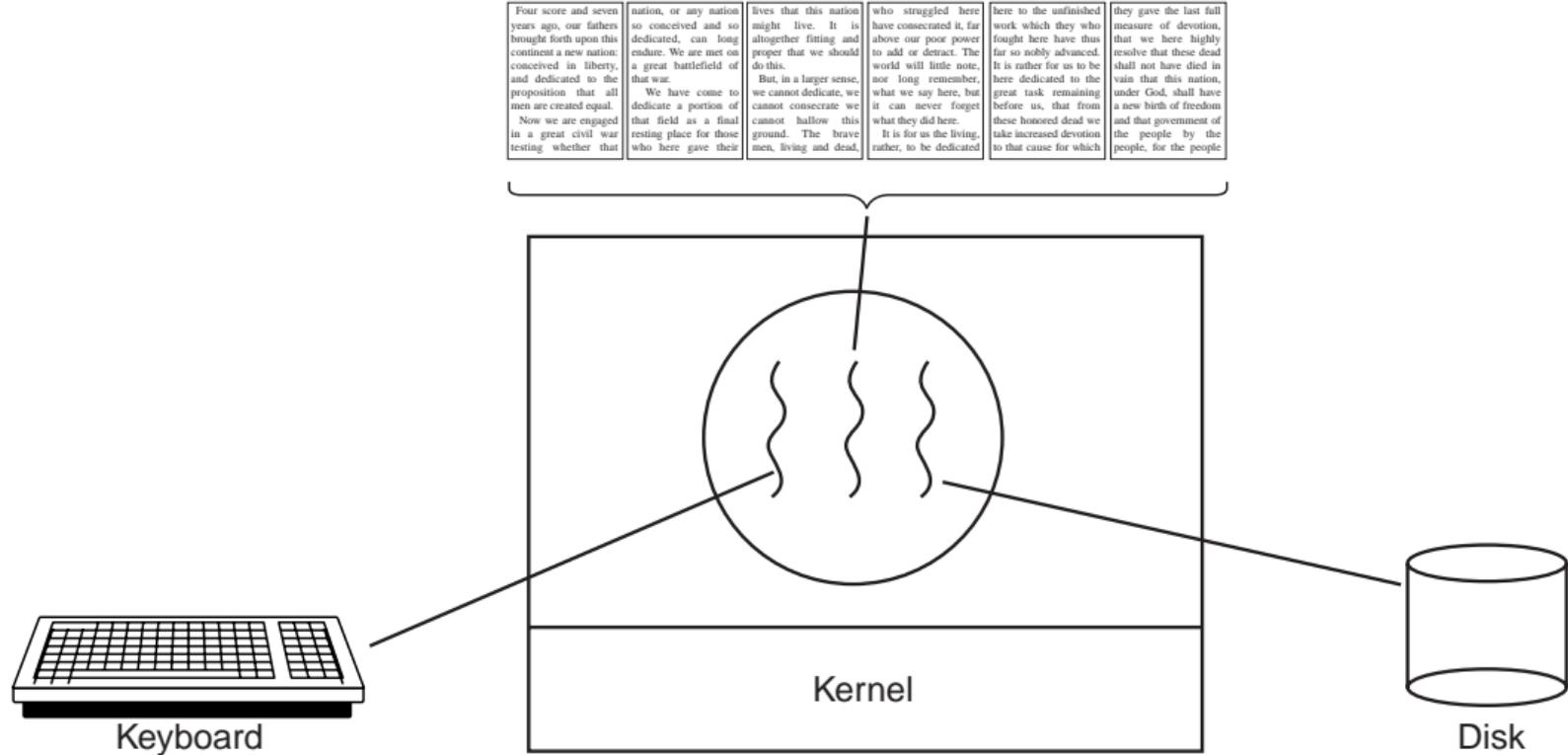
# A Multi-threaded Web Server



```
while (TRUE) {  
    get_next_request(&buf);  
    handoff_work(&buf);  
}
```

```
while (TRUE) {  
    wait_for_work(&buf)  
    look_for_page_in_cache(&buf, &page);  
    if (page_not_in_cache(&page))  
        read_page_from_disk(&buf, &page);  
    return_page(&page);  
}
```

# A Word Processor With 3 Threads



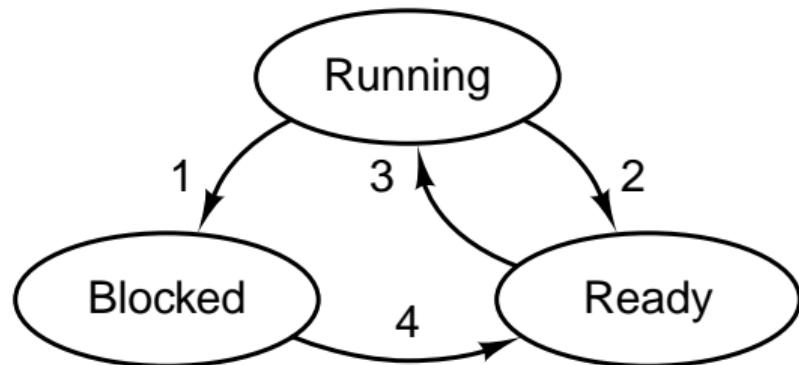
# Why Having a Kind of Process Within a Process?

- ▶ Responsiveness
  - ▶ Good for interactive applications.
  - ▶ A process with multiple threads makes a great server (e.g. a web server):  
Have one server process, many "worker" threads – if one thread blocks (e.g. on a read), others can still continue executing
- ▶ Economy – Threads are cheap!
  - ▶ Cheap to create – only need a stack and storage for registers
  - ▶ Use very little resources – don't need new address space, global data, program code, or OS resources
  - ▶ switches are fast – only have to save/restore PC, SP, and registers
- ▶ Resource sharing – Threads can pass data via shared memory; no need for IPC
- ▶ Can take advantage of multiprocessors

### 8.3 Thread Characteristics

# Thread States Transition

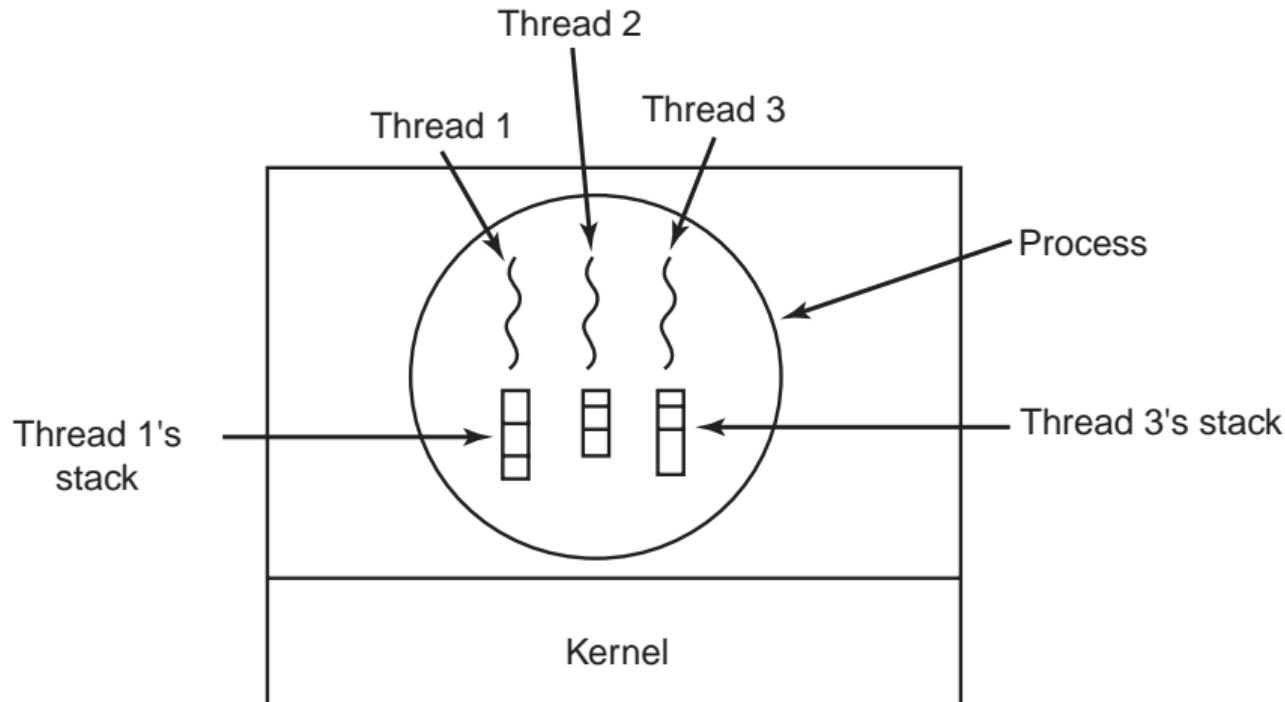
Same as process states transition



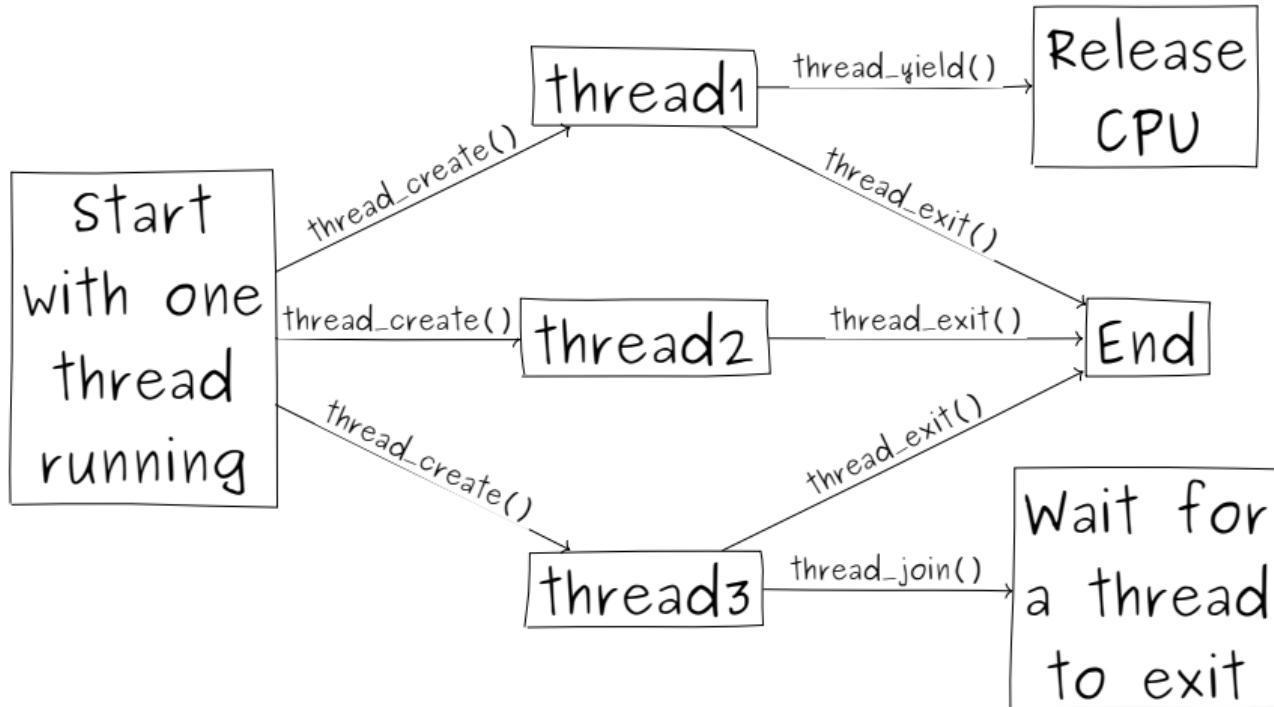
1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

## Each Thread Has Its Own Stack

- ▶ A typical stack stores local data and call information for (usually nested) procedure calls.
- ▶ Each thread generally has a different execution history.



# Thread Operations



## 8.4 POSIX Threads

# POSIX Threads

**IEEE 1003.1c** The standard for writing portable threaded programs. The threads package it defines is called **Pthreads**, including over 60 function calls, supported by most UNIX systems.

## Some of the Pthreads function calls

Thread call	Description
<code>pthread_create</code>	Create a new thread
<code>pthread_exit</code>	Terminate the calling thread
<code>pthread_join</code>	Wait for a specific thread to exit
<code>pthread_yield</code>	Release the CPU to let another thread run
<code>pthread_attr_init</code>	Create and initialize a thread's attribute structure
<code>pthread_attr_destroy</code>	Remove a thread's attribute structure

# Pthreads

## Example 1

```
void *hello(void *arg)
{
    int i;
    for( i=0; i<20; i++ ){
        puts("Thread says hi!");
        sleep(1);
    }
    return NULL;
}

int main(void)
{
    pthread_t t;
    if( pthread_create(&t, NULL, hello, NULL) ) {}

    if( pthread_join(t, NULL) ) {}
    exit(0);
}
```

# Pthreads

`pthread_t` defined in `pthread.h`, is often called a "thread id" (`tid`);  
`pthread_create()` returns zero on success and a non-zero value on failure;  
`pthread_join()` returns zero on success and a non-zero value on failure;

## How to use pthread?

```
#include<pthread.h>
$ gcc thread1.c -o thread1 -pthread
$ ./thread1
```

# Pthreads

## Example 2

```
#define NUMBER_OF_THREADS 5

void *hello(void *tid)
{
    printf ("Hello from thread %d\n", *(int*)tid);
    pthread_exit(NULL);
}

int main(void)
{
    pthread_t t[NUMBER_OF_THREADS];
    int status, i;

    for (i=0; i<NUMBER_OF_THREADS; i++){
        printf("Main: creating thread %d ...", i);

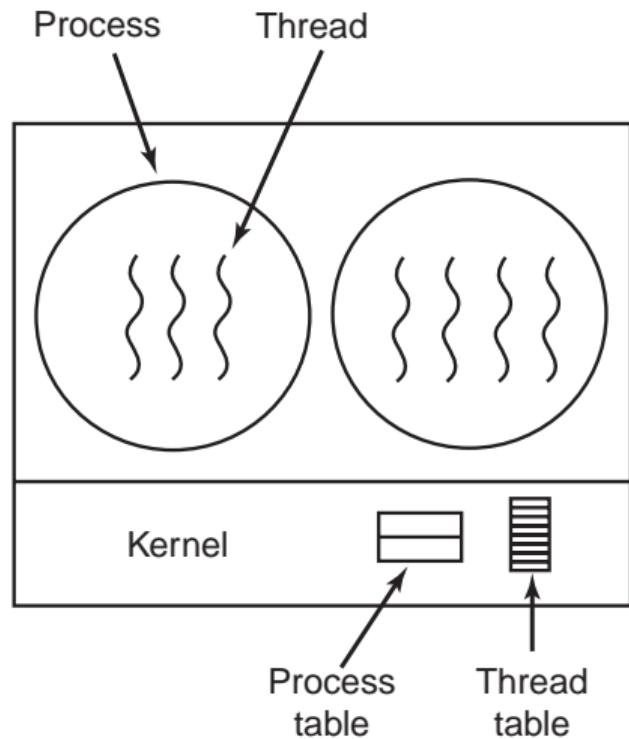
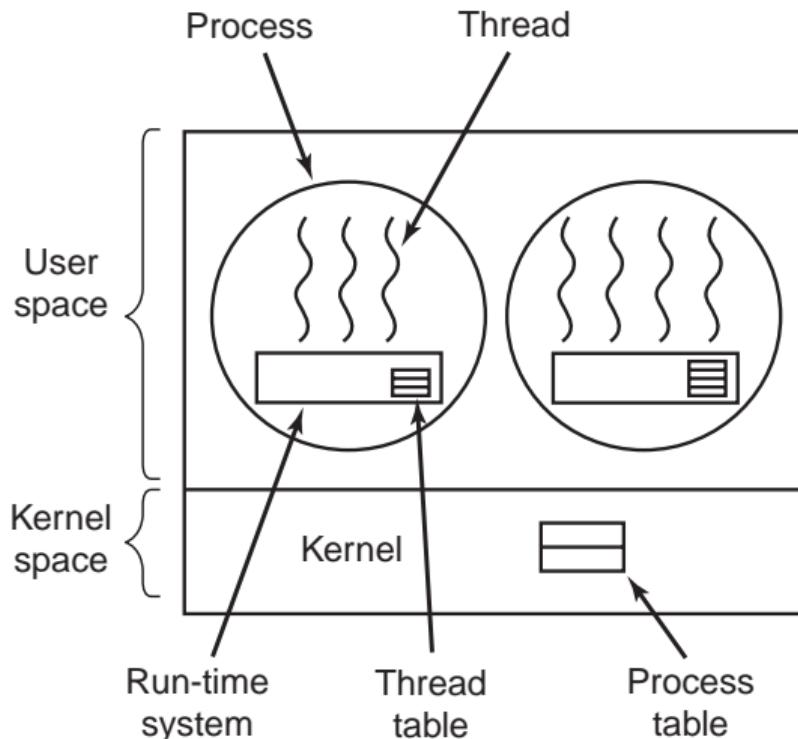
        if( (status = pthread_create(&t[i], NULL, hello, (void *)&i)) ) {}
        puts("done.");
    }

    for (i=0; i<NUMBER_OF_THREADS; i++){
        printf("Joining thread %d ...", i);

        if( (status = pthread_join(t[i], NULL)) ) {}
        puts("done.");
    }
    exit(0);
}
```

## 8.5 User-Level Threads vs. Kernel-level Threads

# User-Level Threads vs. Kernel-Level Threads



# User-Level Threads

User-level threads provide a library of functions to allow user processes to create and manage their own threads.

- 😊 No need to modify the OS
- 😊 Simple representation
  - ▶ each thread is represented simply by a PC, regs, stack, and a small TCB, all stored in the user process' address space
- 😊 Simple Management
  - ▶ creating a new thread, switching between threads, and synchronization between threads can all be done without intervention of the kernel
- 😊 Fast
  - ▶ thread switching is not much more expensive than a procedure call
- 😊 Flexible
  - ▶ CPU scheduling (among threads) can be customized to suit the needs of the algorithm – each process can use a different thread scheduling algorithm

# User-Level Threads

- ⌚ Lack of coordination between threads and OS kernel
  - ▶ Process as a whole gets one time slice
  - ▶ Same time slice, whether process has 1 thread or 1000 threads
  - ▶ Also – up to each thread to relinquish control to other threads in that process
- ⌚ Requires non-blocking system calls (i.e. a multithreaded kernel)
  - ▶ Otherwise, entire process will be blocked in the kernel, even if there are runnable threads left in the process
  - ▶ part of motivation for user-level threads was not to have to modify the OS
- ⌚ If one thread causes a page fault(interrupt!), the entire process blocks

# Kernel-Level Threads

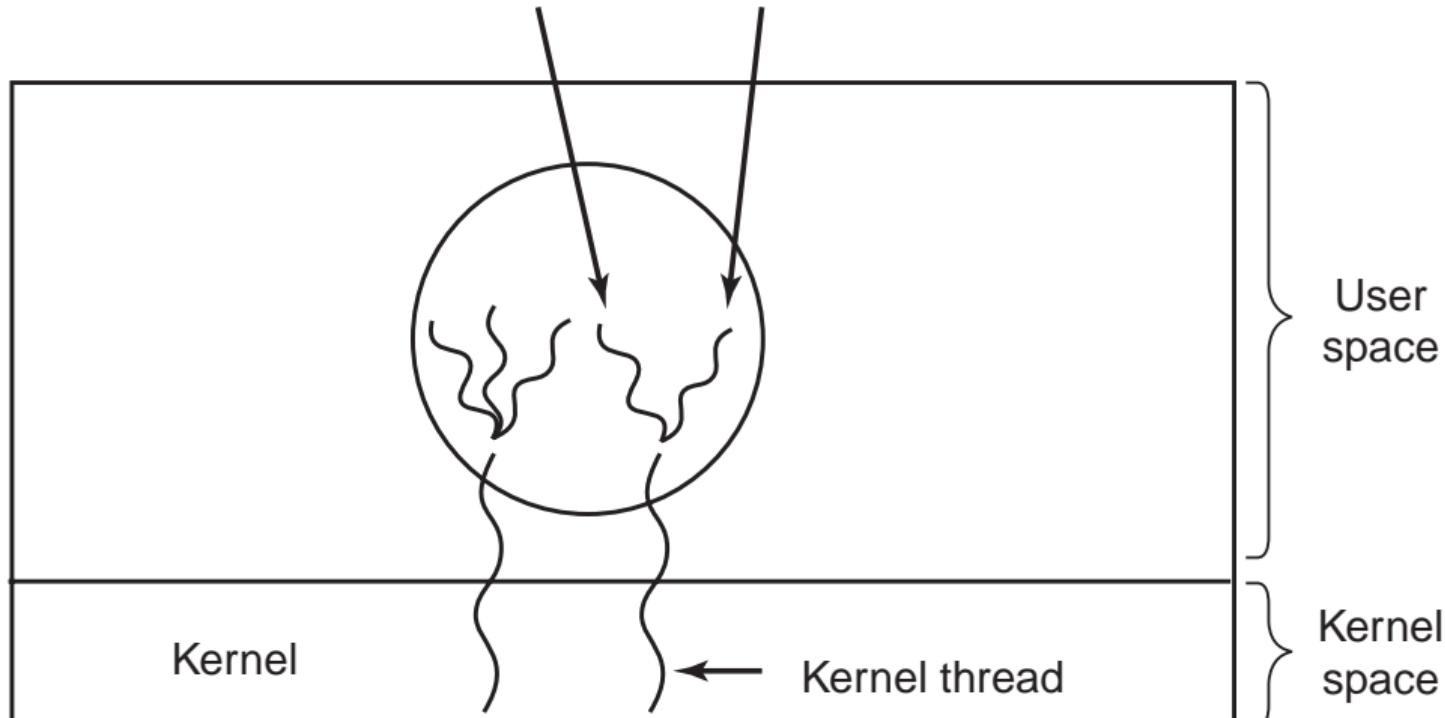
**Kernel-level threads** kernel provides system calls to create and manage threads

- 😊 Kernel has full knowledge of all threads
  - ▶ Scheduler may choose to give a process with 10 threads more time than process with only 1 thread
- 😊 Good for applications that frequently block (e.g. server processes with frequent interprocess communication)
- 😢 Slow – thread operations are 100s of times slower than for user-level threads
- 😢 Significant overhead and increased kernel complexity – kernel must manage and schedule threads as well as processes
  - ▶ Requires a full thread control block (TCB) for each thread

# Hybrid Implementations

Combine the advantages of two

Multiple user threads  
on a kernel thread



## Programming Complications

- ▶ `fork()`: shall the child has the threads that its parent has?
- ▶ What happens if one thread closes a file while another is still reading from it?
- ▶ What happens if several threads notice that there is too little memory?

And sometimes, threads fix the symptom, but not the problem.

## 8.6 Linux Threads

# Linux Threads

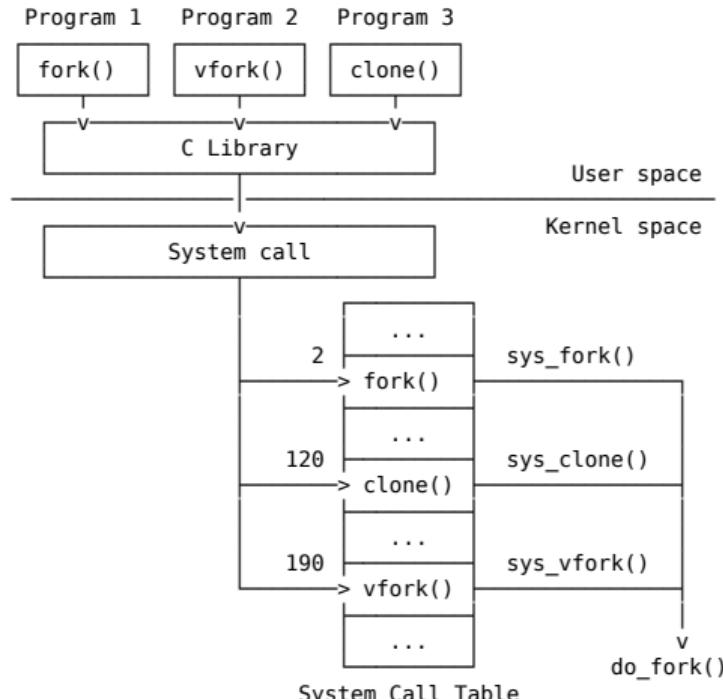
To the Linux kernel, there is no concept of a thread

- ▶ Linux implements all threads as standard processes
- ▶ To Linux, a thread is merely a process that shares certain resources with other processes
- ▶ Some OS (MS Windows, Sun Solaris) have cheap threads and expensive processes.
- ▶ Linux processes are already quite lightweight

On a 75MHz Pentium       $\text{thread: } 1.7\mu\text{s}$   
                                   $\text{fork: } 1.8\mu\text{s}$

# Linux Threads

`clone()` creates a separate process that shares the address space of the calling process. The cloned task behaves *much like* a separate thread.



## The clone() System Call

```
1 #include <sched.h>
2 int clone(int (*fn) (void *), void *child_stack,
3           int flags, void *arg, ...);
```

- arg 1 the function to be executed, i.e. fn(arg), which returns an int;
- arg 2 a pointer to a (usually malloced) memory space to be used as the stack for the new thread;
- arg 3 a set of flags used to indicate how much the calling process is to be shared.  
In fact,

```
clone(0) == fork()
```

- arg 4 the arguments passed to the function.

It returns the PID of the child process or -1 on failure.

```
$ man clone
```

## Some flags:

flag	Shared
CLONE_FS	File-system info
CLONE_VM	Same memory space
CLONE_SIGHAND	Signal handlers
CLONE_FILES	The set of open files

In practice, one should try to avoid calling `clone()` directly

Instead, use a threading library (such as pthreads) which use `clone()` when starting a thread (such as during a call to `pthread_create()`)

## clone() Example

```
1 #include <unistd.h>          16 int main(void)
2 #include <sched.h>           17 {
3 #include <sys/types.h>        18     void *child_stack;
4 #include <stdlib.h>           19     variable = 9;
5 #include <string.h>          20
6 #include <stdio.h>            21     child_stack = (void *) malloc(8192);
7 #include <fcntl.h>            22     printf("The variable was %d\n", variable);
8
9 int variable;                23
10
11 int do_something()           24     clone(do_something, child_stack,
12 {                                CLONE_FS | CLONE_VM | CLONE_FILES, NULL);
13     variable = 42;             25     sleep(1);
14     _exit(0);                 26     printf("The variable is now %d\n", variable);
15 }                                27     return 0;
16 }
```

# clone() Example

```
1 #include <unistd.h>          16 int main(void)
2 #include <sched.h>           17 {
3 #include <sys/types.h>        18     void *child_stack;
4 #include <stdlib.h>           19     variable = 9;
5 #include <string.h>          20
6 #include <stdio.h>            21     child_stack = (void *) malloc(8192);
7 #include <fcntl.h>            22     printf("The variable was %d\n", variable);
8
9 int variable;                23
10
11 int do_something()           24     clone(do_something, child_stack,
12 {                                CLONE_FS | CLONE_VM | CLONE_FILES, NULL);
13     variable = 42;             25     sleep(1);
14     _exit(0);                 26     printf("The variable is now %d\n", variable);
15 }                                27     return 0;
16 }                                28
17 }
```



Stack grows downwards

```
child_stack = (void**)malloc(8192) + 8192/sizeof(*child_stack);
```



## References

- [1] Wikipedia. *Process (computing)* — Wikipedia, The Free Encyclopedia. 2014. [http://en.wikipedia.org/w/index.php?title=Process%5C\\_\(computing\)&oldid=639847817](http://en.wikipedia.org/w/index.php?title=Process%5C_(computing)&oldid=639847817).
- [2] Wikipedia. *Thread (computing)* — Wikipedia, The Free Encyclopedia. 2015. [http://en.wikipedia.org/w/index.php?title=Thread%5C\\_\(computing\)&oldid=648172980](http://en.wikipedia.org/w/index.php?title=Thread%5C_(computing)&oldid=648172980).
- [3] Wikipedia. *Process control block* — Wikipedia, The Free Encyclopedia. 2015. [http://en.wikipedia.org/w/index.php?title=Process%5C\\_control%5C\\_block&oldid=646933587](http://en.wikipedia.org/w/index.php?title=Process%5C_control%5C_block&oldid=646933587).

## 9 Process Synchronization

## 9.1 IPC

# Interprocess Communication

## Example:

```
$ unicode skull | head -1 | cut -f1 -d' '| sm -
```

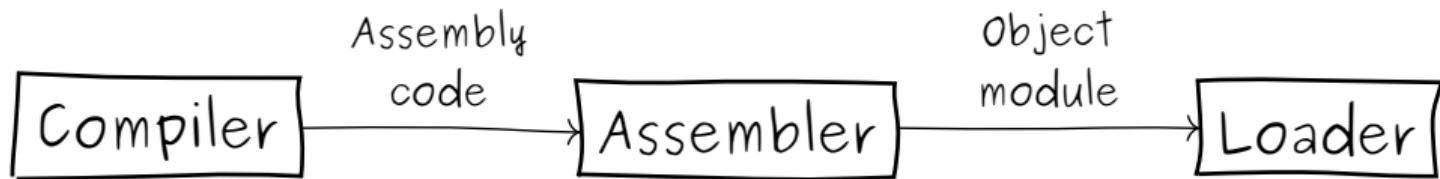
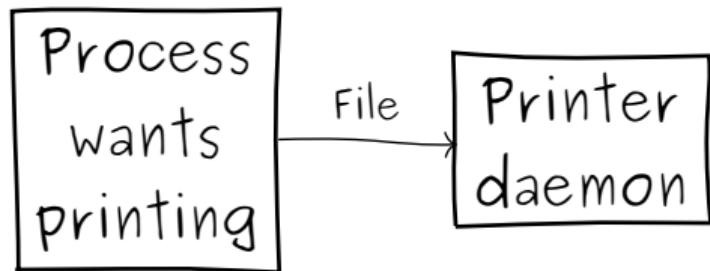
## IPC issues:

1. How one process can pass information to another
2. Be sure processes do not get into each other's way
  - e.g. in an airline reservation system, two processes compete for the last seat
3. Proper sequencing when dependencies are present
  - e.g. if A produces data and B prints them, B has to wait until A has produced some data

## Two models of IPC:

- ▶ Shared memory
- ▶ Message passing (e.g. sockets)

# Producer-Consumer Problem



## 9.2 Shared Memory

# Process Synchronization

## Producer-Consumer Problem

- ▶ Consumers don't try to remove objects from Buffer when it is empty.
- ▶ Producers don't try to add objects to the Buffer when it is full.

```
1 while(TRUE){  
2     while(FULL);  
3     item = produceItem();  
4     insertItem(item);  
5 }
```

```
1 while(TRUE){  
2     while(EMPTY);  
3     item = removeItem();  
4     consumeItem(item);  
5 }
```

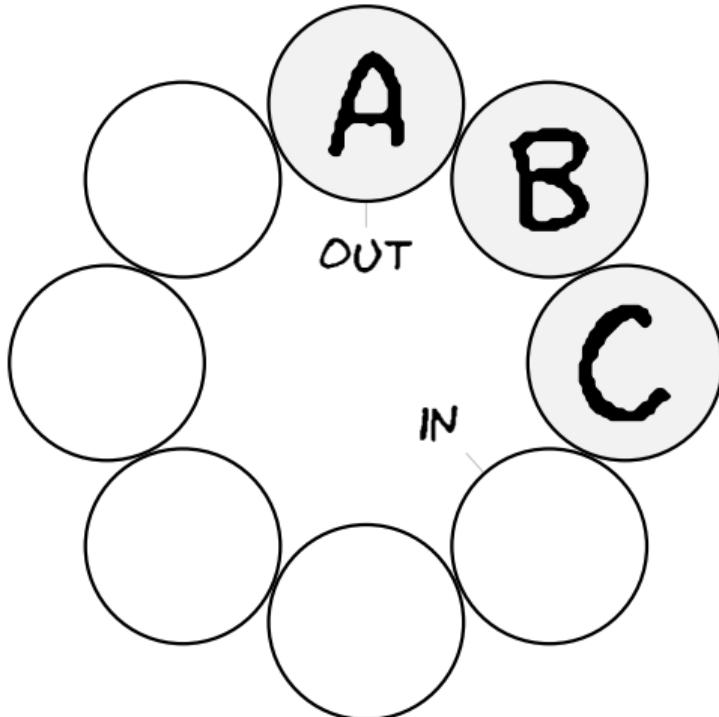
How to define **full/empty**?

# Producer-Consumer Problem

— Bounded-Buffer Problem (Circular Array)

Front(out): the first full position

Rear(in): the next free position



Full or empty when " $front == rear$ "?

# Producer-Consumer Problem

Common solution:

Full: when  $(in + 1) \% \text{BUFFER\_SIZE} == out$

Actually, this is "full - 1"

Empty: when  $in == out$

Can only use " $\text{BUFFER\_SIZE} - 1$ " elements

Shared data:

```
1 #define BUFFER_SIZE 6
2 typedef struct {
3     /* ... */
4 } item;
5 item buffer[BUFFER_SIZE];
6 int in = 0; //the next free position
7 int out = 0; //the first full position
```

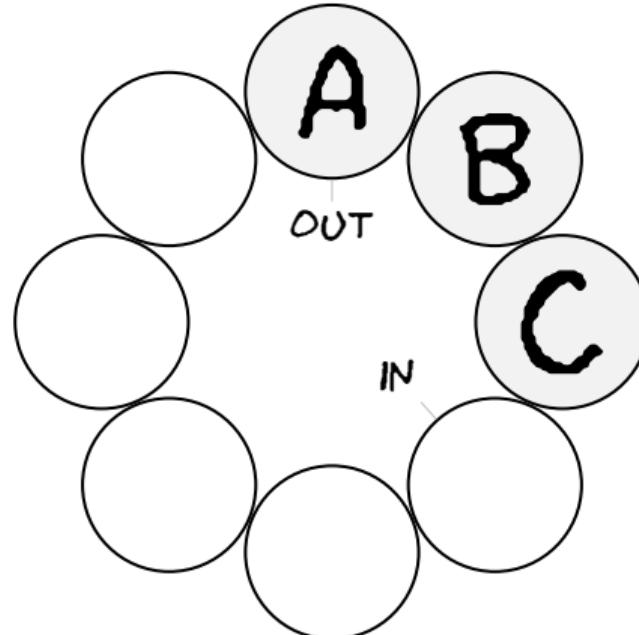
# Bounded-Buffer Problem

## Producer:

```
1 while (true) {  
2     /* do nothing -- no free buffers */  
3     while (((in + 1) % BUFFER_SIZE) == out);  
4  
5     produce(buffer[in]);  
6  
7     in = (in + 1) % BUFFER_SIZE;  
8 }
```

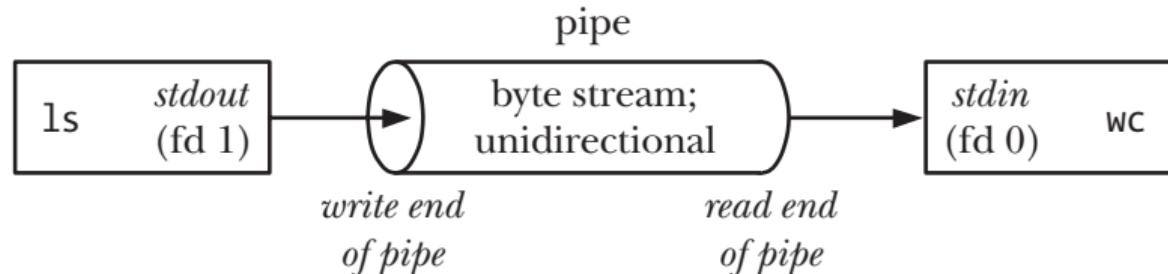
## Consumer:

```
1 while (true) {  
2     while (in == out); // do nothing  
3  
4     consume(buffer[out]);  
5  
6     out = (out + 1) % BUFFER_SIZE;  
7 }
```



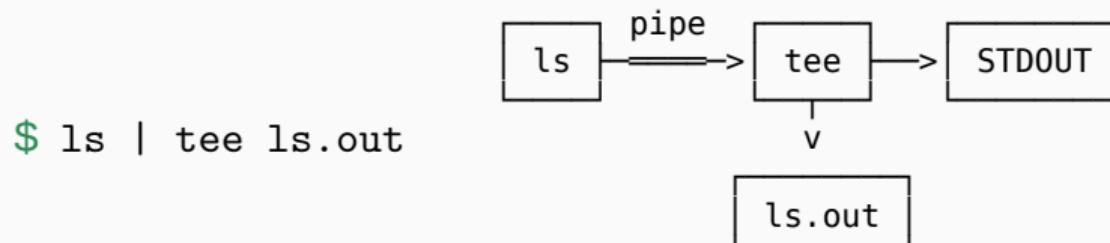
# Pipe

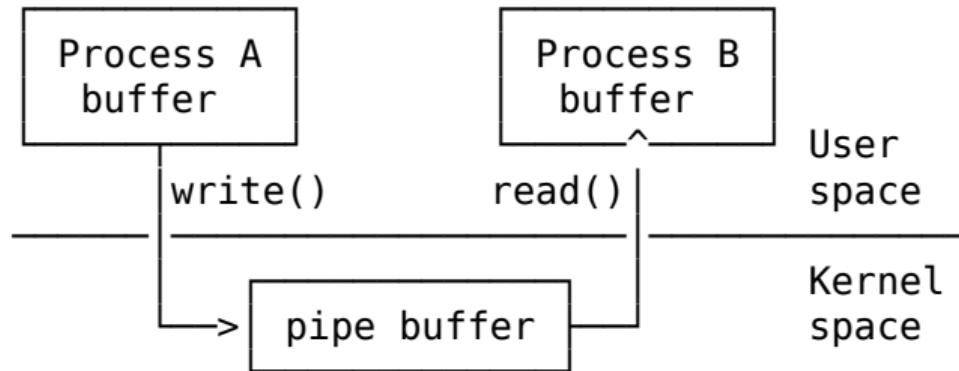
```
$ ls | wc -l
```



- ▶ A pipe is a byte stream
- ▶ Unidirectional
- ▶ `read()` would be blocked if nothing written at the other end

## tee

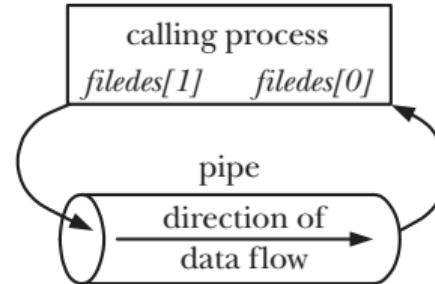




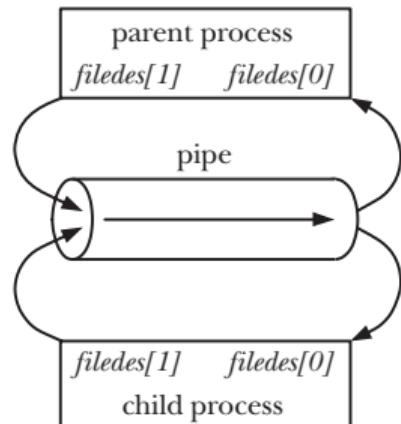
- ▶ No direct link between A and B (need system calls)
  - ▶ A pipe is simply a buffer maintained in kernel memory
- \$ cat /proc/sys/fs/pipe-max-size

# pipe()

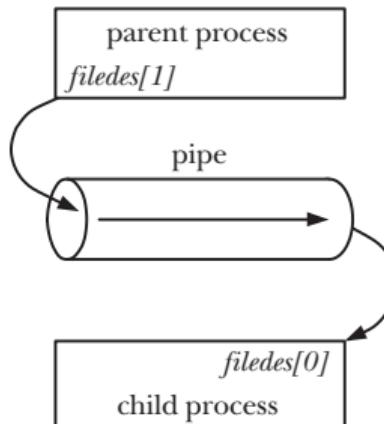
```
1 #include <unistd.h>
2
3 int pipe(int fd[2]);
```



# pipe() + fork()



a) After `fork()`



b) After closing unused descriptors

```

#define BUF_SIZE 10

int main(int argc, char *argv[]) /* Over-simplified! */
{
    int pfd[2]; /* Pipe file descriptors */
    char buf[BUF_SIZE];
    ssize_t numRead;

    pipe(pfd); /* Create the pipe */

    switch (fork()) {
        case 0: /* Child - reads from pipe */
            close(pfd[1]); /* Write end is unused */

            for(;;) { /* Read data from pipe, echo on stdout */
                if( (numRead = read(pfd[0], buf, BUF_SIZE)) == 0 )
                    break; /* End-of-file */
                if( write(1, buf, numRead) != numRead ){}
            }
            puts(""); /* newline */

            close(pfd[0]); _exit(EXIT_SUCCESS);

        default: /* Parent - writes to pipe */
            close(pfd[0]); /* Read end is unused */

            if( (size_t)write(pfd[1], argv[1], strlen(argv[1])) != strlen(argv[1]) ){}

            close(pfd[1]); /* Child will see EOF */

            wait(NULL); /* Wait for child to finish */
            exit(EXIT_SUCCESS);
    }
}

```

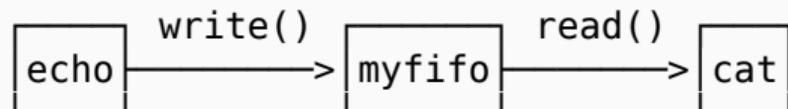
# Named Pipe (FIFO)

PIPs pass data between related processes.

FIFOs pass data between any processes.

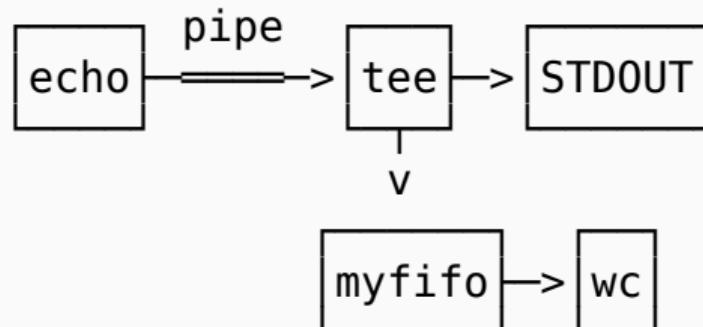
```
$ mkfifo myfifo
```

```
$ echo hello > myfifo  
$ cat myfifo
```



## tee

```
$ echo hello | tee myfifo  
$ wc myfifo
```



# IPC With FIFO

```
#define FIFO_NAME "/tmp/myfifo"

int main(int argc, char *argv[]) /* Oversimplified */
{
    int fd, i, mode = 0;
    char c;

    if (argc < 2) {}

    for(i = 1; i < argc; i++) {
        if (strncmp(++argv, "O_RDONLY", 8) == 0) mode |= O_RDONLY;
        if (strncmp(argv, "O_WRONLY", 8) == 0) mode |= O_WRONLY;
        if (strncmp(argv, "O_NONBLOCK", 10) == 0) mode |= O_NONBLOCK;
    }

    if (access(FIFO_NAME, F_OK) == -1) mkfifo(FIFO_NAME, 0777);

    printf("Process %d: FIFO(fd %d, mode %d) opened.\n",
           getpid(), fd = open(FIFO_NAME, mode), mode);

    if( (mode == 0) | (mode == 2048) )
        while( read(fd,&c,1) == 1 ) putchar(c);

    if( (mode == 1) | (mode == 2049) )
        while( (c = getchar()) != EOF ) write(fd,&c,1);

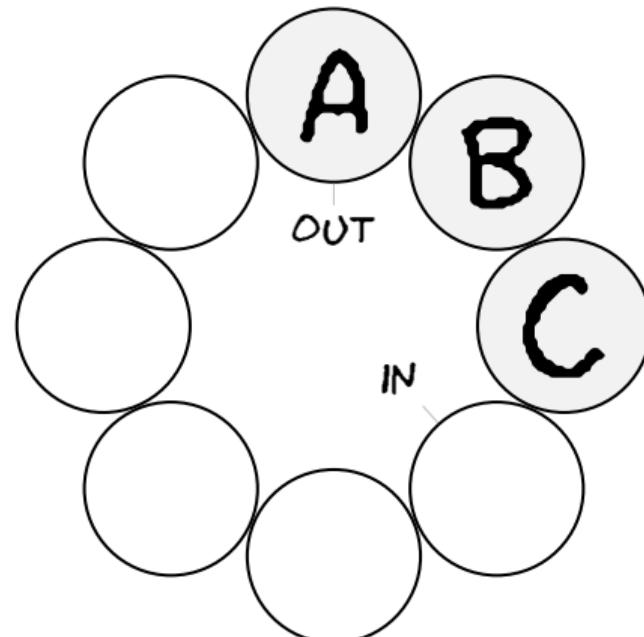
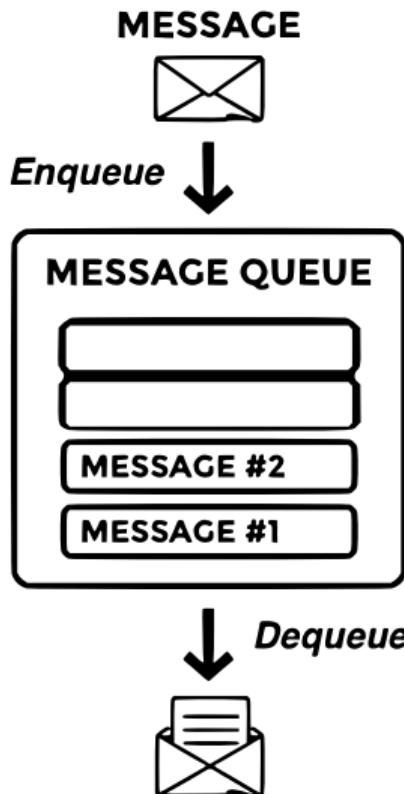
    exit(EXIT_SUCCESS);
}
```

```
$ watch -n.1 'lsof /tmp/myfifo'  
$ ./a.out O_RDONLY  
$ ./a.out O_WRONLY  
$ ./a.out O_RDONLY O_NONBLOCK  
$ ./a.out O_WRONLY O_NONBLOCK
```

## O\_NONBLOCK

- ▶ A `read()`/`write()` will wait on an empty blocking FIFO
- ▶ A `read()` on an empty nonblocking FIFO will return 0 bytes
- ▶ `open(const char *path, O_WRONLY | O_NONBLOCK);`
  - ▶ Returns an error (-1) if FIFO not open
  - ▶ Okay if someone's reading the FIFO
- ▶ If opened with `O_RDWR`, the result is undefined.

# Message Queues



# Message Queues

## Send

```
int main(int argc, char **argv)
{
    mqd_t queue;
    struct mq_attr attrs;
    size_t msg_len;

    if (argc < 3) {}

    queue = mq_open(argv[1], O_WRONLY | O_CREAT, S_IRUSR | S_IWUSR, NULL);
    if (queue == (mqd_t)-1) {}

    if (mq_getattr(queue, &attrs) == -1) {}

    msg_len = strlen(argv[2]);
    if (msg_len > LONG_MAX || (long)msg_len > attrs.mq_msgsize) {}

    if (mq_send(queue, argv[2], strlen(argv[2]), 0) == -1) {}

    return 0;
}
```

# Message Queues

## Receive

```
int main(int argc, char **argv)
{
    mqd_t queue;
    struct mq_attr attrs;
    char *msg_ptr;
    ssize_t recvd;
    size_t i;

    if (argc < 2) {}

    queue = mq_open(argv[1], O_RDONLY | O_CREAT, S_IRUSR | S_IWUSR, NULL);
    if (queue == (mqd_t)-1) {}

    if (mq_getattr(queue, &attrs) == -1) {}

    msg_ptr = calloc(1, attrs.mq_msgsize);
    if (msg_ptr == NULL) {}

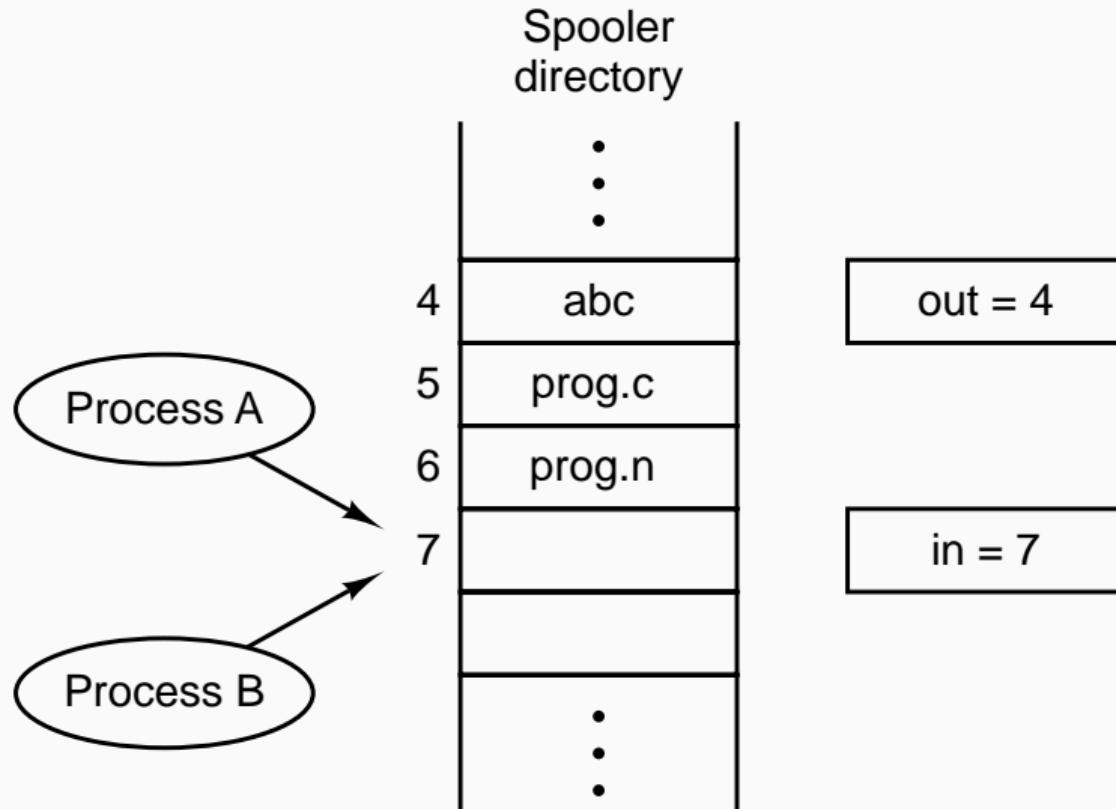
    recvd = mq_receive(queue, msg_ptr, attrs.mq_msgsize, NULL);
    if (recvд == -1) {}

    printf("Message: ");
    for (i = 0; i < (size_t)recvд; i++)
        putchar(msg_ptr[i]);
    puts("");
}
```

### 9.3 Race Condition and Mutual Exclusion

# Race Conditions

Now, let's have two producers



# Race Conditions

Two producers

```
1 #define BUFFER_SIZE 100
2 typedef struct {
3     /* ... */
4 } item;
5 item buffer[BUFFER_SIZE];
6 int in = 0;
7 int out = 0;
```

Process A and B do the same thing:

```
1 while (true) {
2     while (((in + 1) % BUFFER_SIZE) == out);
3     buffer[in] = item;
4     in = (in + 1) % BUFFER_SIZE;
5 }
```

## Race Conditions

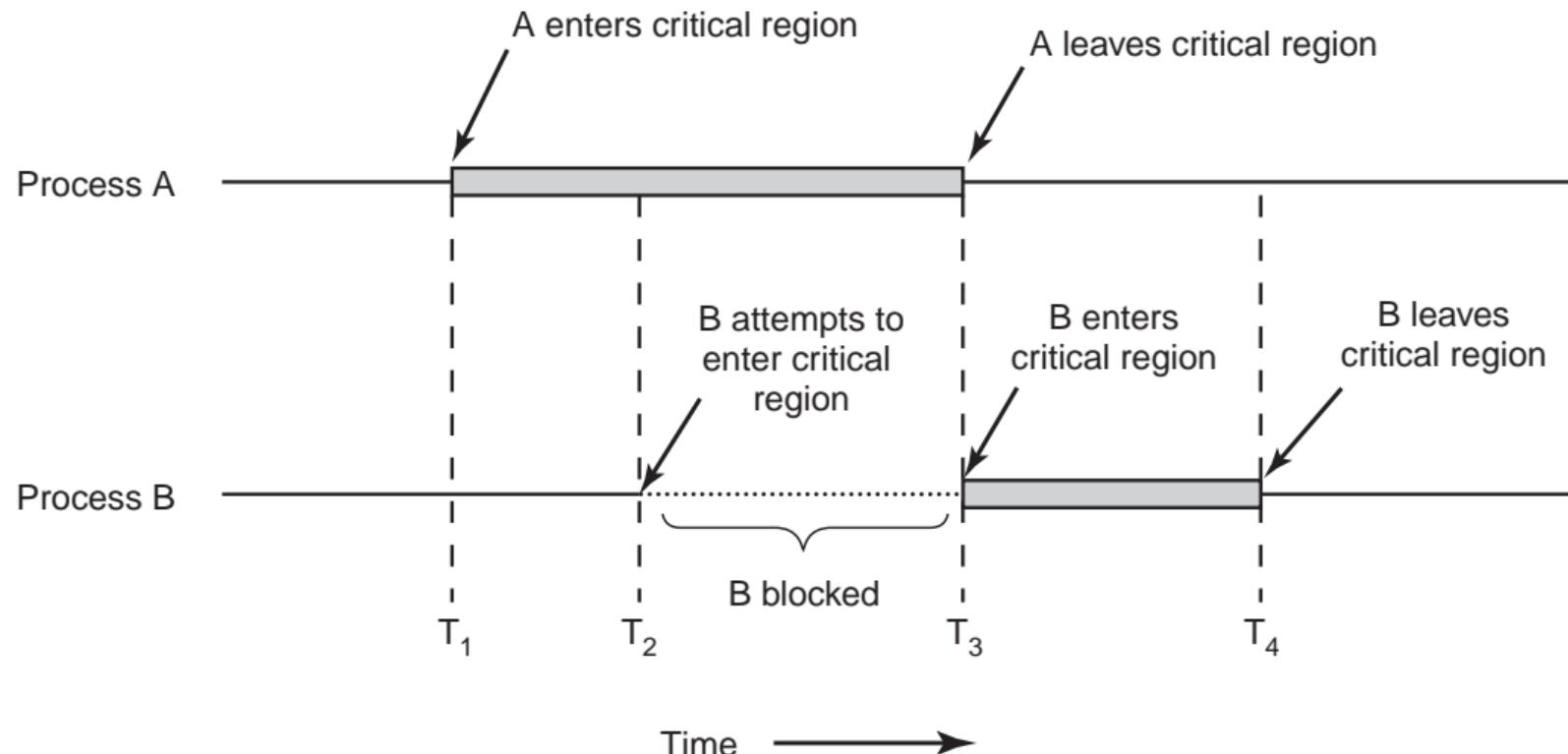
Problem: Process B started using one of the *shared variables* before Process A was finished with it.

Solution: **Mutual exclusion**. If one process is using a shared variable or file, the other processes will be excluded from doing the same thing.

# Critical Regions

## Mutual Exclusion

**Critical Region:** is a piece of code accessing a common resource.



## Critical Region

A solution to the critical region problem must satisfy three conditions:

**Mutual Exclusion:** No two process may be simultaneously inside their critical regions.

**Progress:** No process running outside its critical region may block other processes.

**Bounded Waiting:** No process should have to wait forever to enter its critical region.

# Mutual Exclusion With Busy Waiting

## Disabling Interrupts

```
1  {
2    ...
3    disableINT();
4    critical_code();
5    enableINT();
6    ...
7 }
```

### Problems:

- ▶ It's not wise to give user process the power of turning off INTs.
  - ▶ Suppose one did it, and never turned them on again
- ▶ useless for multiprocessor system

Disabling INTs is often a useful technique within the kernel itself but is not a general mutual exclusion mechanism for user processes.

# Mutual Exclusion With Busy Waiting

## Lock Variables

```
1 int lock=0; //shared variable
2 {
3     ...
4     while(lock); //busy waiting
5     lock=1;
6     critical_code();
7     lock=0;
8     ...
9 }
```

### Problem:

- ▶ What if an interrupt occurs right at line 5?
- ▶ Checking the lock again while backing from an interrupt?

# Mutual Exclusion With Busy Waiting

Strict Alternation

```
1 while(TRUE){  
2     while(turn != 0);  
3     critical_region();  
4     turn = 1;  
5     noncritical_region();  
6 }
```

```
1 while(TRUE){  
2     while(turn != 1);  
3     critical_region();  
4     turn = 0;  
5     noncritical_region();  
6 }
```

Problem: violates condition-2

- ▶ One process can be blocked by another not in its critical region.
- ▶ Requires the two processes strictly alternate in entering their critical region.

# Mutual Exclusion With Busy Waiting

Peterson's Solution

```
1 int interest[0] = 0;  
2 int interest[1] = 0;  
3 int turn;
```

**P0**

```
1 interest[0] = 1;  
2 turn = 1;  
3 while(interest[1] == 1  
       && turn == 1);  
4 critical_section();  
5 interest[0] = 0;
```

**P1**

```
1 interest[1] = 1;  
2 turn = 0;  
3 while(interest[0] == 1  
       && turn == 0);  
4 critical_section();  
5 interest[1] = 0;
```

- [1] Wikipedia. *Peterson's algorithm* — Wikipedia, The Free Encyclopedia. 2015.  
[http://en.wikipedia.org/w/index.php?title=Peterson%27s%5C\\_algorithm&oldid=646078826](http://en.wikipedia.org/w/index.php?title=Peterson%27s%5C_algorithm&oldid=646078826).

# Mutual Exclusion With Busy Waiting

Lock file

```
const char *mylock = "/tmp/LCK.test2";

int main() {
    int fd;

    for(;;) {
        while( (fd = open(mylock, O_RDWR | O_CREAT | O_EXCL, 0444)) != -1 ) {
            printf("Process(%d) - Working in critical region...\n", getpid());
            sleep(2); /* working */
            close(fd);
            if ( unlink(mylock) == 0 ) puts("Done.\nResource unlocked.");
            sleep(3); /* non-critical region */
        }
        printf("Process(%d) - Waiting for lock...\n", getpid());
    }
    exit(EXIT_SUCCESS);
}
```

- ⌚ Lock file could be left in system after **Ctrl**+**c**

```

const char *mylock = "/tmp/LCK.test2";

void sigint(int signo) {
    if ( unlink(mylock) == 0 ) puts("Quit. Lock released.");
    exit(EXIT_SUCCESS);
}

int main() {
    int fd;

    signal(SIGINT,sigint);

    for(;;){
        while( (fd = open(mylock, O_RDWR | O_CREAT | O_EXCL, 0444)) != -1 ) {
            printf("Process(%d) - Working in critical region...\\n", getpid());
            sleep(2); /* working */
            close(fd);
            if ( unlink(mylock) == 0 ) puts("Done.\\nResource unlocked.");
            sleep(3); /* non-critical region */
        }
        printf("Process(%d) - Waiting for lock...\\n", getpid());
    }
    exit(EXIT_SUCCESS);
}

```

⌚ sigint() is too crude to be reliable. Need a more sophisticated design.

# Mutual Exclusion With Busy Waiting

Hardware Solution: The TSL Instruction

## Lock the memory bus

enter\_region:

```
TSL REGISTER,LOCK  
CMP REGISTER,#0  
JNE enter_region  
RET
```

| copy lock to register and set lock to 1  
| was lock zero?  
| if it was non zero, lock was set, so loop  
| return to caller; critical region entered

leave\_region:

```
MOVE LOCK,#0  
RET
```

| store a 0 in lock  
| return to caller

# Mutual Exclusion Without Busy Waiting

Sleep & Wakeup

```
1 #define N 100 /* number of slots in the buffer */  
2 int count = 0; /* number of items in the buffer */  
  
1 void producer(){  
2     int item;  
3     while(TRUE){  
4         item = produce_item();  
5         if(count == N)  
6             sleep();  
7         insert_item(item);  
8         count++;  
9         if(count == 1)  
10            wakeup(consumer);  
11    }  
12}  
13  
14 void consumer(){  
15     int item;  
16     while(TRUE){  
17         if(count == 0)  
18             sleep();  
19         item = rm_item();  
20         count--;  
21         if(count == N - 1)  
22             wakeup(producer);  
23         consume_item(item);  
24     }  
25}
```

# Mutual Exclusion Without Busy Waiting

## Sleep & Wakeup

```
1 #define N 100 /* number of slots in the buffer */  
2 int count = 0; /* number of items in the buffer */  
  
1 void producer(){  
2     int item;  
3     while(TRUE){  
4         item = produce_item();  
5         if(count == N)  
6             sleep();  
7         insert_item(item);  
8         count++;  
9         if(count == 1)  
10            wakeup(consumer);  
11    }  
12 }  
13  
14 void consumer(){  
15     int item;  
16     while(TRUE){  
17         if(count == 0)  
18             sleep();  
19         item = rm_item();  
20         count--;  
21         if(count == N - 1)  
22             wakeup(producer);  
23         consume_item(item);  
24     }  
25 }
```

Deadlock!

# Producer-Consumer Problem

## Race Condition

### Problem

1. Consumer is going to sleep upon seeing an empty buffer, but INT occurs;
2. Producer inserts an item, increasing count to 1, then call `wakeup(consumer)`;
3. But the consumer is not asleep, though `count` was 0. So *the wakeup() signal is lost*;
4. Consumer is back from INT remembering `count` is 0, and goes to sleep;
5. Producer sooner or later will fill up the buffer and also goes to sleep;
6. Both will sleep forever, and waiting to be waken up by the other process.  
Deadlock!

# Producer-Consumer Problem

## Race Condition

Solution: Add a *wakeup waiting bit*

1. The bit is set, when a wakeup is sent to an awaken process;
2. Later, when the process wants to sleep, it checks the bit first. Turns it off if it's set, and stays awake.

What if many processes try going to sleep?

## 9.4 Semaphores

# What is a Semaphore?

- ▶ A locking mechanism
- ▶ An integer or ADT

Atomic Operations	
P()	V()
Wait()	Signal()
Down()	Up()
Decrement()	Increment()
...	...

```
1 | down(S){  
2 |   while(S<=0);  
3 |   S--;  
4 | }
```

```
1 | up(S){  
2 |   S++;  
3 | }
```

More meaningful names:

- ▶ increment\_and\_wake\_a\_waiting\_process\_if\_any()
- ▶ decrement\_and\_block\_if\_the\_result\_is\_negative()

## How to ensure atomic?

1. For single CPU, implement `up()` and `down()` as system calls, with the OS disabling all interrupts while accessing the semaphore;
2. For multiple CPUs, to make sure only one CPU at a time examines the semaphore, a lock variable should be used with the TSL instructions.

# Semaphore is a Special Integer



A semaphore is like an integer, with three differences:

1. You can initialize its value to any integer, but after that the only operations you are allowed to perform are *increment* ( $s++$ ) and *decrement* ( $s--$ ).
2. When a thread decrements the semaphore, if the result is negative ( $s \leq 0$ ), the thread blocks itself and cannot continue until another thread increments the semaphore.
3. When a thread increments the semaphore, if there are other threads waiting, one of the waiting threads gets unblocked.

## Why Semaphores?

We don't need semaphores to solve synchronization problems, but there are some advantages to using them:

- ▶ Semaphores impose deliberate constraints that help programmers avoid errors.
- ▶ Solutions using semaphores are often clean and organized, making it easy to demonstrate their correctness.
- ▶ Semaphores can be implemented efficiently on many systems, so solutions that use semaphores are portable and usually efficient.

# The Simplest Use of Semaphore

## Signaling

- ▶ One thread sends a signal to another thread to indicate that something has happened
- ▶ it solves the serialization problem

Signaling makes it possible to guarantee that a section of code in one thread will run before a section of code in another thread

1	statement a1
2	sem.signal()

1	sem.wait()
2	statement b1

What's the initial value of sem?

# Semaphore

## Rendezvous Puzzle

1 | statement a1  
2 | statement a2

1 | statement b1  
2 | statement b2

Q: How to guarantee that

1. a1 happens before b2, and
2. b1 happens before a2

$a1 \rightarrow b2; b1 \rightarrow a2$

Hint: Use two semaphores initialized to 0.

---

	<b>Thread A:</b>	<b>Thread B:</b>
Solution 1:	1 statement a1 2 sem1.wait() 3 sem2.signal() 4 statement a2	1 statement b1 2 sem1.signal() 3 sem2.wait() 4 statement b2
Solution 2:	1 statement a1 2 sem2.signal() 3 sem1.wait() 4 statement a2	1 statement b1 2 sem1.signal() 3 sem2.wait() 4 statement b2
Solution 3:	1 statement a1 2 sem2.wait() 3 sem1.signal() 4 statement a2	1 statement b1 2 sem1.wait() 3 sem2.signal() 4 statement b2

---

	<b>Thread A:</b>	<b>Thread B:</b>
Solution 1:	1 statement a1 2 sem1.wait() 3 sem2.signal() 4 statement a2	1 statement b1 2 sem1.signal() 3 sem2.wait() 4 statement b2
Solution 2:	1 statement a1 2 sem2.signal() 3 sem1.wait() 4 statement a2	1 statement b1 2 sem1.signal() 3 sem2.wait() 4 statement b2
Solution 3:	1 statement a1 2 sem2.wait() 3 sem1.signal() 4 statement a2	1 statement b1 2 sem1.wait() 3 sem2.signal() 4 statement b2

Deadlock!

# Example: Signaling With Semaphore

```
void *func(void *arg);
sem_t sem;
#define BUFSIZE 1024
char buf[BUFSIZE];

int main() {
    pthread_t t;

    if( sem_init(&sem, 0, 0) != 0 ) {}

    if( pthread_create(&t, NULL, func, NULL) != 0 ) {}

    puts("Please input some text. Ctrl-d to quit.");

    while( fgets(buf, BUFSIZE, stdin) )
        sem_post(&sem);

    sem_post(&sem);          /* in case of Ctrl-d */

    if( pthread_join(t, NULL) != 0 ) {}

    sem_destroy(&sem);  exit(EXIT_SUCCESS);
}

void *func(void *arg) {
    sem_wait(&sem);
    while( buf[0] != '\0' ) {
        printf("You input %ld characters\n", strlen(buf)-1);
        buf[0] = '\0';      /* in case of Ctrl-d */
        sem_wait(&sem);
    }
    pthread_exit(NULL);
}
```

## Mutex

- ▶ A second common use for semaphores is to enforce mutual exclusion
- ▶ It guarantees that only one thread accesses the shared variable at a time
- ▶ A `mutex` is like a token that passes from one thread to another, allowing one thread at a time to proceed

Q: Add semaphores to the following example to enforce mutual exclusion to the shared variable `i`.

Thread A: `i++`

Thread B: `i++`

Why? Because `i++` is not atomic.

## j++ can go wrong!

```
static int glob = 0;

static void *threadFunc(void *arg) /* loop 'arg' times */
{
    int j;
    for (j = 0; j < *((int *) arg); j++) glob++; /* not atomic! */
    return NULL;
}

int main(int argc, char *argv[])
{
    pthread_t t1, t2;
    int loops;

    loops = (argc > 1) ? atoi(argv[1]) : 10000000;

    if( pthread_create(&t1, NULL, threadFunc, &loops) != 0 ) {}

    if( pthread_create(&t2, NULL, threadFunc, &loops) != 0 ) {}

    if( pthread_join(t1, NULL) != 0 ) {}

    if( pthread_join(t2, NULL) != 0 ) {}

    printf("glob = %d\n", glob);
    exit(EXIT_SUCCESS);
}
```

## i++ is not atomic in assembly language

```
1 LOAD    [i], r0      ;load the value of 'i' into  
2                      ;a register from memory  
3 ADD     r0, 1       ;increment the value  
4                      ;in the register  
5 STORE   r0, [i]     ;write the updated  
6                      ;value back to memory
```

Interrupts might occur in between. So, `i++` needs to be protected with a `mutex`.

## Mutex Solution

Create a semaphore named `mutex` that is initialized to 1

- 1: a thread may proceed and access the shared variable
- 0: it has to wait for another thread to release the mutex

```
1 | mutex.wait()  
2 |     i++  
3 | mutex.signal()
```

```
1 | mutex.wait()  
2 |     i++  
3 | mutex.signal()
```

```
static int glob = 0;
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;

static void *threadFunc(void *arg)
{
    int j;
    for (j = 0; j < *((int *) arg); j++) {
        if (pthread_mutex_lock(&mtx) != 0) {}
        glob++;
        if (pthread_mutex_unlock(&mtx) != 0) {}
    }
    return NULL;
}

int main(int argc, char *argv[])
{
    pthread_t t1, t2;
    int loops;

    loops = (argc > 1) ? atoi(argv[1]) : 10000000;

    if( pthread_create(&t1, NULL, threadFunc, &loops) != 0 ){}
    if( pthread_create(&t2, NULL, threadFunc, &loops) != 0 ){}

    if( pthread_join(t1, NULL) != 0 ){}
    if( pthread_join(t2, NULL) != 0 ){}

    printf("glob = %d\n", glob);
    exit(EXIT_SUCCESS);
}
```

```
static int glob = 0;
static sem_t sem;

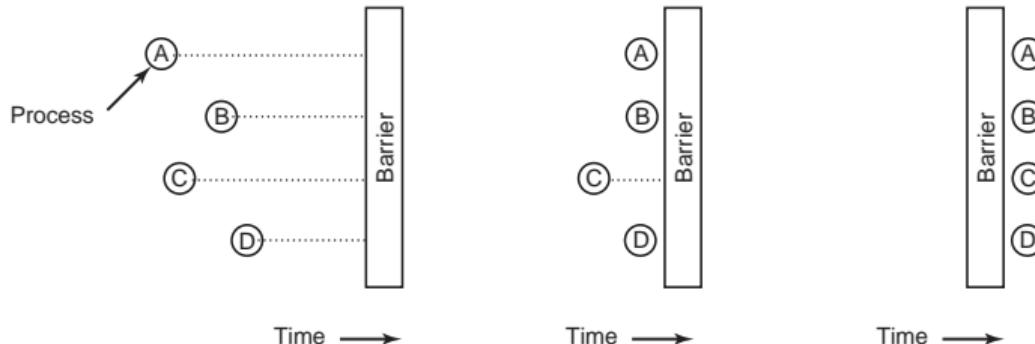
static void *threadFunc(void *arg)
{
    int j;
    for (j = 0; j < *((int *) arg); j++) {
        if (sem_wait(&sem) == -1) {}
        glob++;
        if (sem_post(&sem) == -1) {}
    }
    return NULL;
}
```

## Multiplex — Without Busy Waiting

```
1 typedef struct{  
2     int space;           //number of free resources  
3     struct process *P; //a list of queueing producers  
4     struct process *C; //a list of queueing consumers  
5 } semaphore;  
6 semaphore S;  
7 S.space = 5;
```

<pre>1 void down(S){ 2     S.space--; 3     if(S.space == 4){ 4         rmFromQueue(S.C); 5         wakeup(S.C); 6     } 7     if(S.space &lt; 0){ 8         addToQueue(S.P); 9         sleep(); 10    } 11 }</pre>	<pre>1 void up(S){ 2     S.space++; 3     if(S.space &gt; 5){ 4         addToQueue(S.C); 5         sleep(); 6     } 7     if(S.space &gt;= 0){ 8         rmFromQueue(S.P); 9         wakeup(S.P); 10    } 11 }</pre>
---	--

# Barrier



1. Processes approaching a barrier
2. All processes but one blocked at the barrier
3. When the last process arrives at the barrier, all of them are let through

Synchronization requirement:

```
specific_task()  
critical_point()
```

No thread executes `critical_point()` until after all threads have executed `specific_task()`.

# Barrier Solution

```
1 n = the number of threads  
2 count = 0  
3 mutex = Semaphore(1)  
4 barrier = Semaphore(0)
```

count: keeps track of how many threads have arrived

mutex: provides exclusive access to count

barrier: is locked ( $\leq 0$ ) until all threads arrive

When `barrier.value < 0`,

`barrier.value == Number of queueing processes`

```
1 specific_task();  
2 mutex.wait();  
3     count++;  
4 mutex.signal();  
5 if (count < n)  
6     barrier.wait();  
7 barrier.signal();  
8 critical_point();
```

```
1 specific_task();  
2 mutex.wait();  
3     count++;  
4 mutex.signal();  
5 if (count == n)  
6     barrier.signal();  
7 barrier.wait();  
8 critical_point();
```

# Barrier Solution

```
1 n = the number of threads  
2 count = 0  
3 mutex = Semaphore(1)  
4 barrier = Semaphore(0)
```

count: keeps track of how many threads have arrived

mutex: provides exclusive access to count

barrier: is locked ( $\leq 0$ ) until all threads arrive

When `barrier.value < 0`,

`barrier.value == Number of queueing processes`

```
1 specific_task();  
2 mutex.wait();  
3     count++;  
4 mutex.signal();  
5 if (count < n)  
6     barrier.wait();  
7 barrier.signal();  
8 critical_point();
```

```
1 specific_task();  
2 mutex.wait();  
3     count++;  
4 mutex.signal();  
5 if (count == n)  
6     barrier.signal();  
7 barrier.wait();  
8 critical_point();
```

Only one thread can pass the barrier!

## Barrier Solution

```
1 specific_task();  
2  
3 mutex.wait();  
4     count++;  
5 mutex.signal();  
6  
7 if (count == n)  
8     barrier.signal();  
9  
10 barrier.wait();  
11 barrier.signal();  
12  
13 critical_point();
```

```
1 specific_task();  
2  
3 mutex.wait();  
4     count++;  
5  
6 if (count == n)  
7     barrier.signal();  
8  
9 barrier.wait();  
10 barrier.signal();  
11 mutex.signal();  
12  
13 critical_point();
```

## Barrier Solution

```
1 specific_task();  
2  
3 mutex.wait();  
4     count++;  
5 mutex.signal();  
6  
7 if (count == n)  
8     barrier.signal();  
9  
10 barrier.wait();  
11 barrier.signal();  
12  
13 critical_point();
```

```
1 specific_task();  
2  
3 mutex.wait();  
4     count++;  
5  
6 if (count == n)  
7     barrier.signal();  
8  
9 barrier.wait();  
10 barrier.signal();  
11 mutex.signal();  
12  
13 critical_point();
```

```
barrier.wait();  
barrier.signal();
```

## Turnstile

This pattern, a `wait` and a `signal` in rapid succession, occurs often enough that it has a name called a *turnstile*, because

- ▶ it allows one thread to pass at a time, and
- ▶ it can be locked to bar all threads

# Producer-Consumer Problem With Bounded-Buffer

Given:

```
semaphore items = 0;  
semaphore spaces = BUFFER_SIZE;
```

Can we?

```
if (items >= BUFFER_SIZE)  
    producer.block();
```

if: the buffer is full

then: the producer blocks until a consumer removes an item

# Producer-Consumer Problem With Bounded-Buffer

Given:

```
semaphore items = 0;  
semaphore spaces = BUFFER_SIZE;
```

Can we?

```
if (items >= BUFFER_SIZE)  
    producer.block();
```

if: the buffer is full

then: the producer blocks until a consumer removes an item

No! We can't check the current value of a semaphore, because

! the only operations are `wait` and `signal`.

? But...

## 9.5 Monitors

# Monitors

Monitor a high-level synchronization object for achieving mutual exclusion.

- ▶ It's a language concept, and C does not have it.
- ▶ Only one process can be active in a monitor at any instant.
- ▶ It is up to the compiler to implement mutual exclusion on monitor entries.
  - ▶ The programmer just needs to know that by turning all the critical regions into monitor procedures, no two processes will ever execute their critical regions at the same time.

```
1  monitor example
2      integer i;
3      condition c;
4
5      procedure producer();
6      ...
7      end;
8
9      procedure consumer();
10     ...
11     end;
12 end monitor;
```

# Monitor

## The producer-consumer problem

```
1 monitor ProducerConsumer
2     condition full, empty;
3     integer count;
4
5     procedure insert(item: integer);
6     begin
7         if count = N then wait(full);
8         insert_item(item);
9         count := count + 1;
10        if count = 1 then signal(empty)
11    end;
12
13    function remove: integer;
14    begin
15        if count = 0 then wait(empty);
16        remove = remove_item;
17        count := count - 1;
18        if count = N - 1 then signal(full)
19    end;
20    count := 0;
21 end monitor;
```

```
1 procedure producer;
2 begin
3     while true do
4     begin
5         item = produce_item;
6         ProducerConsumer.insert(item)
7     end
8 end;
9
10 procedure consumer;
11 begin
12     while true do
13     begin
14         item = ProducerConsumer.remove;
15         consume_item(item)
16     end
17 end;
```

## 9.6 Message Passing

## Message Passing

- ▶ Semaphores are too low level
- ▶ Monitors are not usable except in a few programming languages
- ▶ Neither monitor nor semaphore is suitable for distributed systems
- ▶ No conflicts, easier to implement

Message passing uses two primitives, send and receive system calls:

- `send(destination, &message);`
- `receive(source, &message);`

# Message Passing

## Design issues

- ▶ Message can be lost by network; — ACK
- ▶ What if the ACK is lost? — SEQ
- ▶ What if two processes have the same name? — socket
- ▶ Am I talking with the right guy? Or maybe a MIM? — authentication
- ▶ What if the sender and the receiver on the same machine? — Copying messages is always slower than doing a semaphore operation or entering a monitor.

# Message Passing

## TCP Header Format

0	1	2	3
Source Port		Destination Port	
Sequence Number			
Acknowledgment Number			
Data Offset	0 0 0	N C E U A P R S F W C R C S S Y I S R E G K H T N N	Window
Checksum		Urgent Pointer	
Options		Padding	

# Message Passing

## The producer-consumer problem

```
1 #define N 100 /* number of slots in the buffer */
2 void producer(void)
3 {
4     int item;
5     message m;                      /* message buffer */
6     while (TRUE) {
7         item = produce_item();      /* generate something to put in buffer */
8         receive(consumer, &m);    /* wait for an empty to arrive */
9         build_message(&m, item); /* construct a message to send */
10        send(consumer, &m);      /* send item to consumer */
11    }
12 }
13
14 void consumer(void)
15 {
16     int item, i;
17     message m;
18     for (i=0; i<N; i++) send(producer, &m); /* send N empties */
19     while (TRUE) {
20         receive(producer, &m);    /* get message containing item */
21         item = extract_item(&m); /* extract item from message */
22         send(producer, &m);      /* send back empty reply */
23         consume_item(item);    /* do something with the item */
24     }
25 }
```

# Sockets

To create a socket:

```
fd = socket(domain, type, protocol)
```

**Domain** Determines address format and the range of communication (local or remote). The most commonly used domains are:

<b>Domain</b>	<b>Addr structure</b>	<b>Addr format</b>
AF_UNIX	sockaddr_un	/path/name
AF_INET	sockaddr_in	ip:port
AF_INET6	sockaddr_in6	ip6:port

Type SOCK\_STREAM (TCP), SOCK\_DGRAM (UDP)

Protocol always 0

# Socket System Calls

`socket()` creates a new socket

`bind()` binds a socket to an address (usually a well-known address on server side)

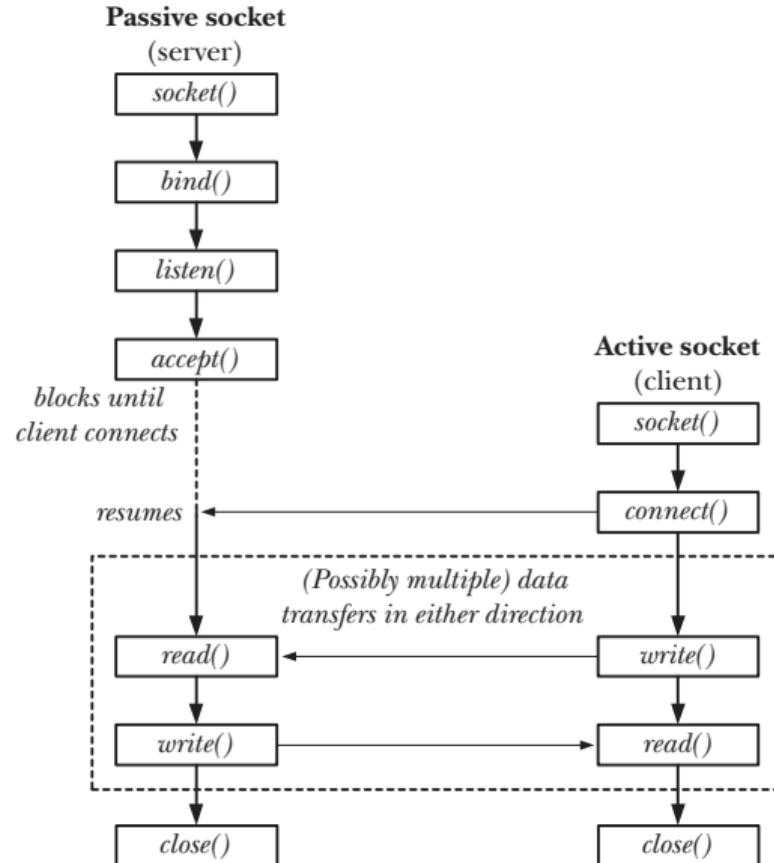
`listen()` waits for incoming connection requests

`connect()` sends a connection request to peer

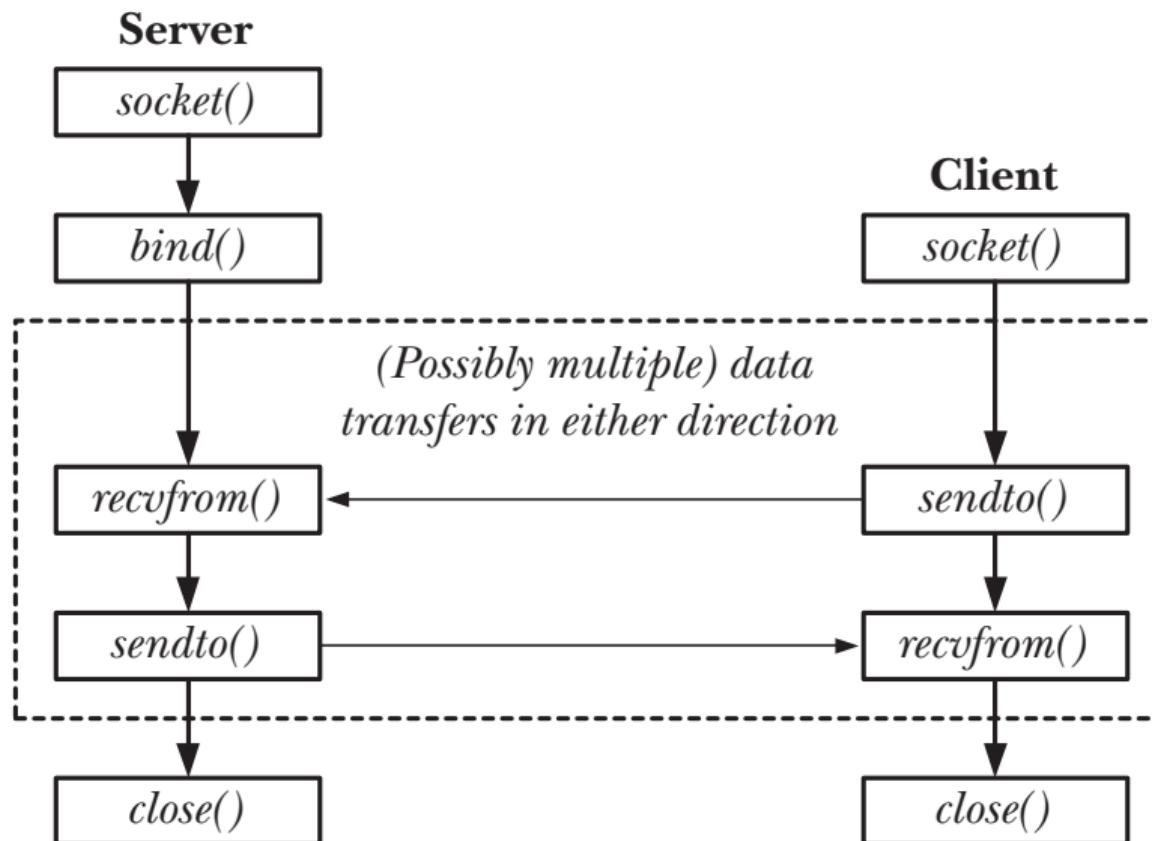
`accept()` accepts a connection request

`send()/recv()` data transfer

# Stream Sockets



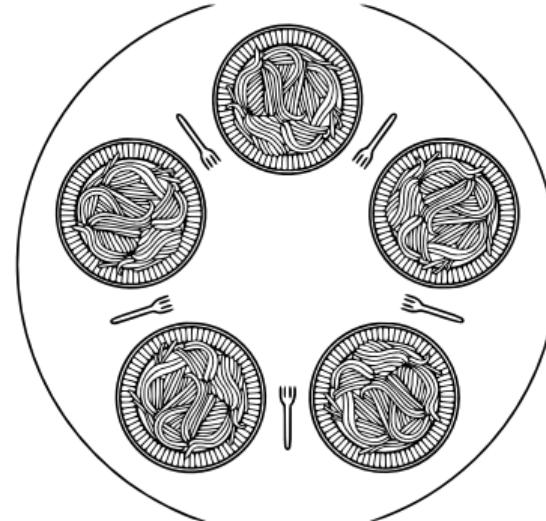
# Datagram Sockets



## 9.7 Classical IPC Problems

# The Dining Philosophers Problem

```
1 while True:  
2     think()  
3     get_forks()  
4     eat()  
5     put_forks()
```



How to implement `get_forks()` and `put_forks()` to ensure

1. No deadlock
2. No starvation
3. Allow more than one philosopher to eat at the same time

# The Dining Philosophers Problem

```
1 #define N 5                      /* number of philosophers */
2
3 void philosopher(int i)    /* i: philosopher number, from 0 to 4 */
4 {
5     while (TRUE) {
6         think();                  /* philosopher is thinking */
7         take_fork(i);           /* take left fork */
8         take_fork((i+1) % N);  /* take right fork; % is modulo operator */
9         eat();                   /* yum-yum, spaghetti */
10        put_fork(i);            /* put left fork back on the table */
11        put_fork((i+1) % N);   /* put right fork back on the table */
12    }
13 }
```

# The Dining Philosophers Problem

```
1 #define N 5                      /* number of philosophers */
2
3 void philosopher(int i)    /* i: philosopher number, from 0 to 4 */
4 {
5     while (TRUE) {
6         think();                  /* philosopher is thinking */
7         take_fork(i);           /* take left fork */
8         take_fork((i+1) % N);  /* take right fork; % is modulo operator */
9         eat();                   /* yum-yum, spaghetti */
10        put_fork(i);            /* put left fork back on the table */
11        put_fork((i+1) % N);   /* put right fork back on the table */
12    }
13 }
```

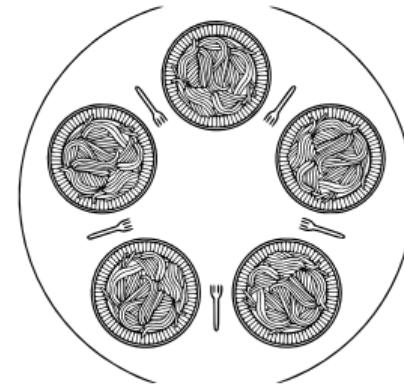
Deadlock!

- ? Put down the left fork and wait for a while if the right one is not available?  
Similar to CSMA/CD — Starvation

# The Dining Philosophers Problem

With One Mutex

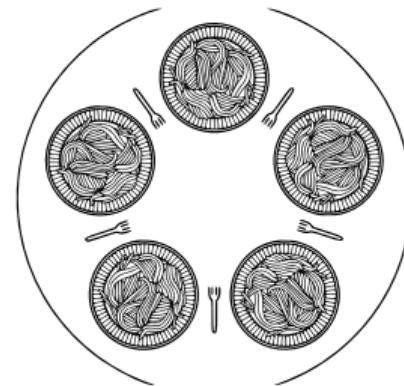
```
1 #define N 5
2 semaphore mutex=1;
3
4 void philosopher(int i)
{
    while (TRUE) {
        think();
        wait(&mutex);
        take_fork(i);
        take_fork((i+1) % N);
        eat();
        put_fork(i);
        put_fork((i+1) % N);
        signal(&mutex);
    }
}
```



# The Dining Philosophers Problem

With One Mutex

```
1 #define N 5
2 semaphore mutex=1;
3
4 void philosopher(int i)
{
    while (TRUE) {
        think();
        wait(&mutex);
        take_fork(i);
        take_fork((i+1) % N);
        eat();
        put_fork(i);
        put_fork((i+1) % N);
        signal(&mutex);
    }
}
```



- ⌚ Only one philosopher can eat at a time.
- ⌚ How about 2 mutexes? 5 mutexes?

# The Dining Philosophers Problem

## AST Solution (Part 1)

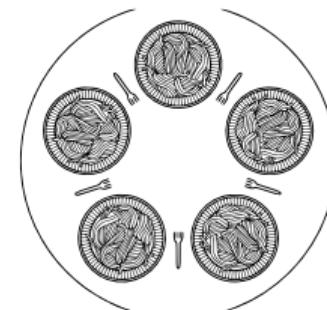
A philosopher may only move into eating state if neither neighbor is eating

```
1 #define N 5          /* number of philosophers */
2 #define LEFT (i+N-1)%N /* number of i's left neighbor */
3 #define RIGHT (i+1)%N /* number of i's right neighbor */
4 #define THINKING 0    /* philosopher is thinking */
5 #define HUNGRY 1      /* philosopher is trying to get forks */
6 #define EATING 2      /* philosopher is eating */
7 typedef int semaphore;
8 int state[N];          /* state of everyone */
9 semaphore mutex = 1;   /* for critical regions */
10 semaphore s[N];       /* one semaphore per philosopher */
11
12 void philosopher(int i) /* i: philosopher number, from 0 to N-1 */
13 {
14     while(TRUE) {
15         think();
16         take_forks(i); /* acquire two forks or block */
17         eat();
18         put_forks(i); /* put both forks back on table */
19     }
20 }
```

# The Dining Philosophers Problem

## AST Solution (Part 2)

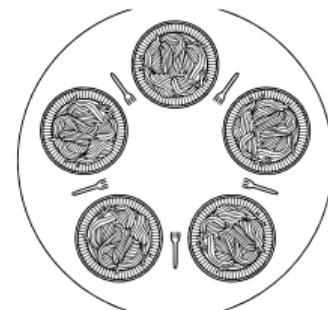
```
1 void take_forks(int i)          /* i: philosopher number */
2 {
3     down(&mutex);
4     state[i] = HUNGRY;
5     test(i);                  /* try to acquire 2 forks */
6     up(&mutex);
7     down(&s[i]);              /* block if forks were not acquired */
8 }
9 void put_forks(i)             /* i: philosopher number */
10 {
11     down(&mutex);
12     state[i] = THINKING;
13     test(LEFT);             /* see if left neighbor can now eat */
14     test(RIGHT);            /* see if right neighbor can now eat */
15     up(&mutex);
16 }
17 void test(i)                 /* i: philosopher number */
18 {
19     if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING)
20     {
21         state[i] = EATING;
22         up(&s[i]);
23     }
24 }
```



# The Dining Philosophers Problem

## AST Solution (Part 2)

```
1 void take_forks(int i)           /* i: philosopher number */
2 {
3     down(&mutex);
4     state[i] = HUNGRY;
5     test(i);
6     up(&mutex);
7     down(&s[i]);
8 }
9 void put_forks(i)
10 {
11     down(&mutex);
12     state[i] = THINKING;
13     test(LEFT);
14     test(RIGHT);
15     up(&mutex);
16 }
17 void test(i)                   /* i: philosopher number */
18 {
19     if(state[i] == HUNGRY && state[LEFT] != EATING && state[RIGHT] != EATING)
20     {
21         state[i] = EATING;
22         up(&s[i]);
23     }
24 }
```



# The Dining Philosophers Problem

More Solutions

- ▶ If there is at least one leftie and at least one rightie, then deadlock is not possible
- ▶ [Wikipedia: Dining philosophers problem](#)

# The Readers-Writers Problem

Constraint: no process may access the shared data for reading or writing while another process is writing to it.

```
1 void reader(void)
2 {
3     semaphore mutex = 1;
4     semaphore noOther = 1;
5     int readers = 0;
6
7     void writer(void)
8     {
9         while (TRUE) {
10             wait(&noOther);
11             writing();
12             signal(&noOther);
13         }
14     }
15
16     while (TRUE) {
17         wait(&mutex);
18         readers++;
19         if (readers == 1)
20             wait(&noOther);
21         signal(&mutex);
22         reading();
23         wait(&mutex);
24         readers--;
25         if (readers == 0)
26             signal(&noOther);
27         signal(&mutex);
28         anything();
29     }
30 }
```

# The Readers-Writers Problem

Constraint: no process may access the shared data for reading or writing while another process is writing to it.

```
1 void reader(void)
2 {
3     semaphore mutex = 1;
4     semaphore noOther = 1;
5     int readers = 0;
6
7     void writer(void)
8     {
9         while (TRUE) {
10             wait(&noOther);
11             writing();
12             signal(&noOther);
13         }
14     }
15
16     while (TRUE) {
17         wait(&mutex);
18         readers++;
19         if (readers == 1)
20             wait(&noOther);
21         signal(&mutex);
22         reading();
23         wait(&mutex);
24         readers--;
25         if (readers == 0)
26             signal(&noOther);
27         signal(&mutex);
28         anything();
29     }
30 }
```

Starvation!

# The Readers-Writers Problem

No starvation

```
1  semaphore mutex = 1;
2  semaphore noOther = 1;
3  semaphore turnstile = 1;
4  int readers = 0;
5
6  void writer(void)
7  {
8      while (TRUE) {
9          turnstile.wait();
10         wait(&noOther);
11         writing();
12         signal(&noOther);
13         turnstile.signal();
14     }
15 }
```

```
1  void reader(void)
2  {
3      while (TRUE) {
4          turnstile.wait();
5          turnstile.signal();
6
7          wait(&mutex);
8          readers++;
9          if (readers == 1)
10              wait(&noOther);
11          signal(&mutex);
12          reading();
13          wait(&mutex);
14          readers--;
15          if (readers == 0)
16              signal(&noOther);
17          signal(&mutex);
18          anything();
19      }
20 }
```

# The Sleeping Barber Problem



Where's the problem?

- ▶ the barber saw an empty room right before a customer arrives the waiting room;
- ▶ Several customer could race for a single chair;

# Solution

```
1 #define CHAIRS 5
2 semaphore customers = 0; // any customers or not?
3 semaphore bber = 0;      // barber is busy
4 semaphore mutex = 1;
5 int waiting = 0;         // queueing customers
```

<pre>1 void barber(void) 2 { 3     while (TRUE) { 4         wait(&amp;customers); 5         wait(&amp;mutex); 6         waiting--; 7         signal(&amp;mutex); 8         cutHair(); 9         signal(&amp;bber); 10    } 11 }</pre>	<pre>1 void customer(void) 2 { 3     if(waiting == CHAIRS) 4         goHome(); 5     else { 6         wait(&amp;mutex); 7         waiting++; 8         signal(&amp;mutex); 9         signal(&amp;customers); 10        wait(&amp;bber); 11        getHairCut(); 12    } 13 }</pre>
---	--

## Solution2

```
1 #define CHAIRS 5
2 semaphore customers = 0;
3 semaphore bber = ?;
4 semaphore mutex = 1;
5 int waiting = 0;
6
7 void barber(void)
8 {
9     while (TRUE) {
10         wait(&customers);
11         cutHair();
12     }
13 }
```

```
1 void customer(void)
2 {
3     if (waiting == CHAIRS)
4         goHome();
5     else {
6         wait(&mutex);
7         waiting++;
8         signal(&mutex);
9         signal(&customers);
10        wait(&bber);
11        getHairCut();
12        signal(&bber);
13        wait(&mutex);
14        waiting--;
15        signal(&mutex);
16    }
17 }
```

## References

- [1] Wikipedia. *Inter-process communication* — Wikipedia, The Free Encyclopedia. 2015. [http://en.wikipedia.org/w/index.php?title=Inter-process%5C\\_communication&oldid=645037874](http://en.wikipedia.org/w/index.php?title=Inter-process%5C_communication&oldid=645037874).
- [2] Wikipedia. *Semaphore (programming)* — Wikipedia, The Free Encyclopedia. 2015. [http://en.wikipedia.org/w/index.php?titleSemaphore%5C\\_\(programming\)&oldid=647556304](http://en.wikipedia.org/w/index.php?titleSemaphore%5C_(programming)&oldid=647556304).

## 10 CPU Scheduling

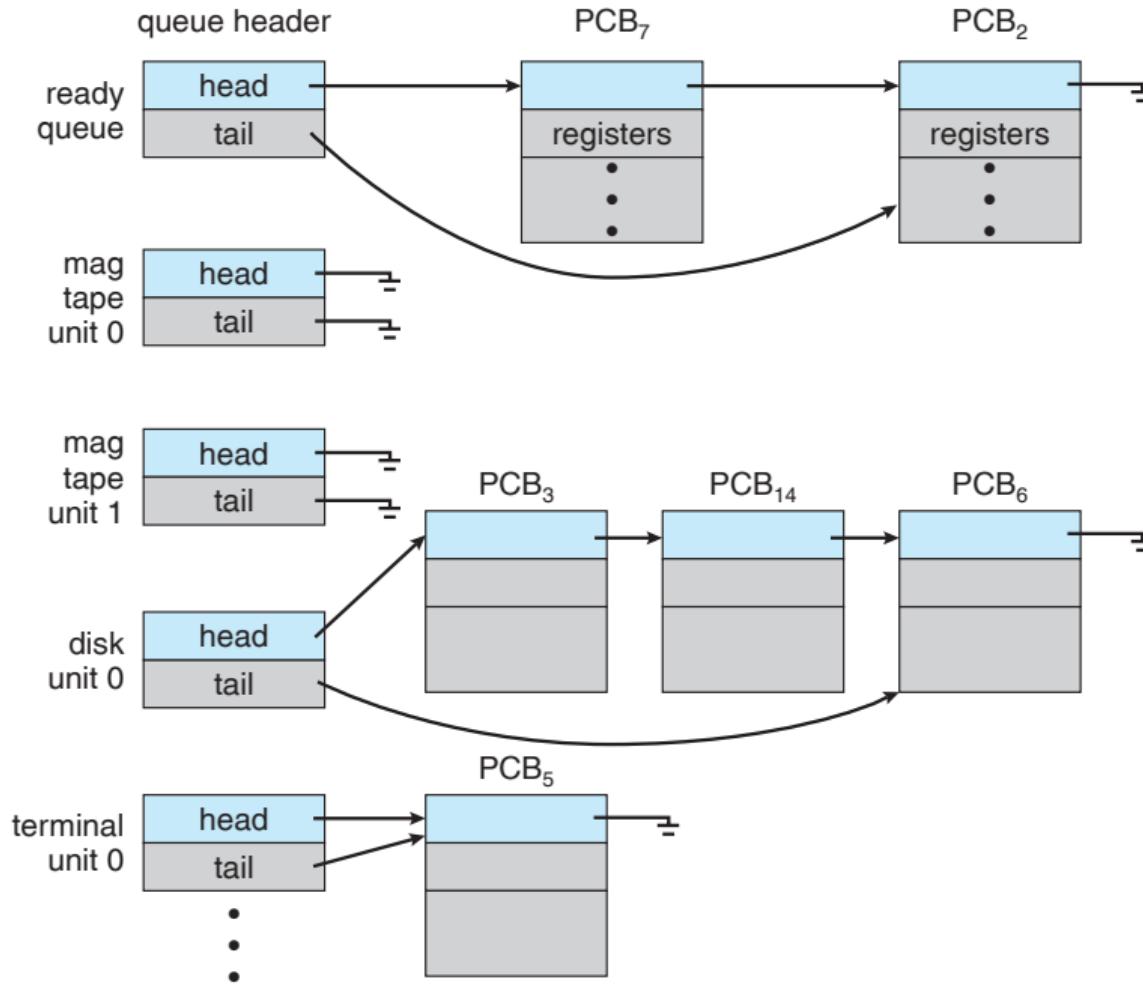
## 10.1 Process Scheduling Queues

## Scheduling Queues

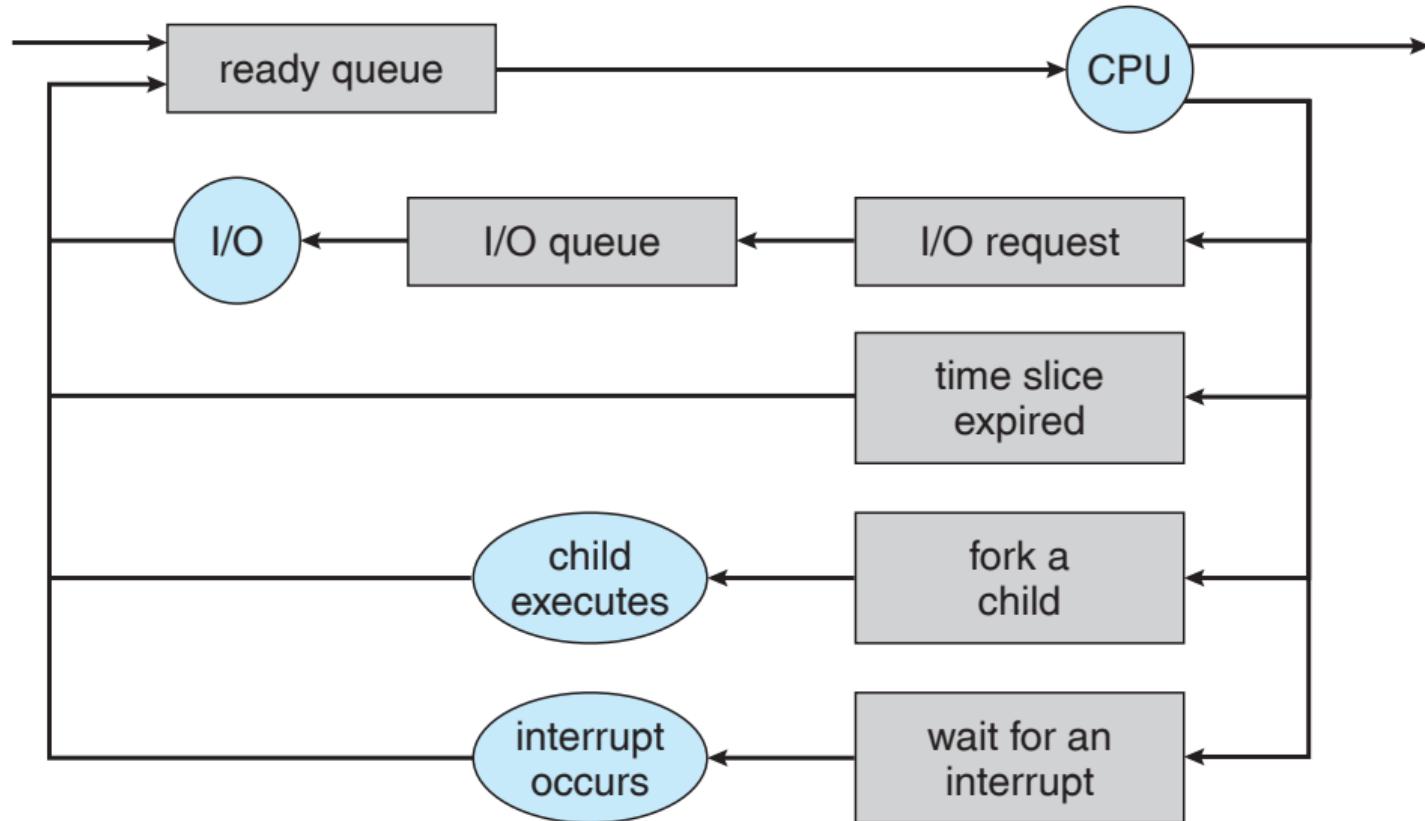
**Job queue** consists all the processes in the system

**Ready queue** A linked list consists processes in the main memory ready for execute

**Device queue** Each device has its own device queue



# Queueing Diagram



## 10.2 Scheduling

# Scheduling

- ▶ Scheduler uses scheduling algorithm to choose a process from the ready queue
- ▶ Scheduling doesn't matter much on simple PCs, because
  1. Most of the time there is only one active process
  2. The CPU is too fast to be a scarce resource any more
- ▶ Scheduler has to make efficient use of the CPU because process switching is expensive
  1. User mode → kernel mode
  2. Save process state, registers, memory map...
  3. Selecting a new process to run by running the scheduling algorithm
  4. Load the memory map of the new process
  5. The process switch usually invalidates the entire memory cache

# Scheduling Algorithm Goals

## All systems

Fairness giving each process a fair share of the CPU

Policy enforcement seeing that stated policy is carried out

Balance keeping all parts of the system busy

## Batch systems

Throughput maximize jobs per hour

Turnaround time minimize time between submission and termination

CPU utilization keep the CPU busy all the time

## Interactive systems

Response time respond to requests quickly

Proportionality meet users' expectations

## Real-time systems

Meeting deadlines avoid losing data

Predictability avoid quality degradation in multimedia systems

# Process Classification

## Traditionally

CPU-bound processes vs. I/O-bound processes

## Alternatively

Interactive processes responsiveness

- ▶ command shells, editors, graphical apps

Batch processes no user interaction, run in background, often penalized by the scheduler

- ▶ programming language compilers, database search engines, scientific computations

Real-time processes video and sound apps, robot controllers, programs that collect data from physical sensors

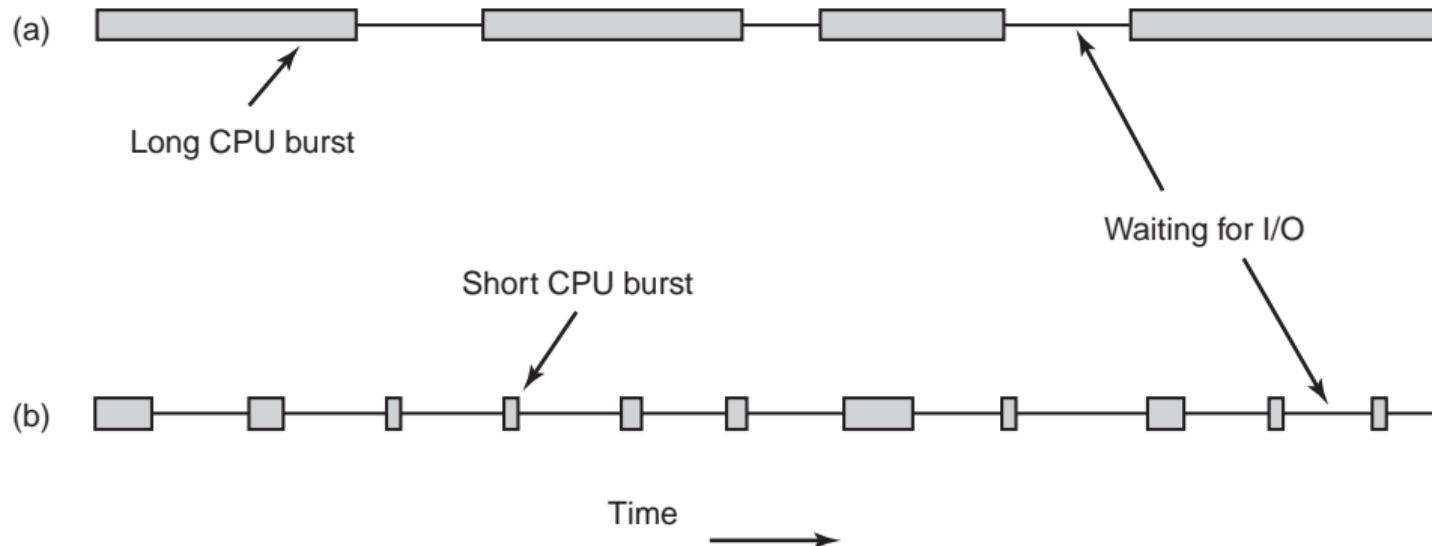
- ▶ should never be blocked by lower-priority processes
- ▶ should have a short guaranteed response time with a minimum variance

# Process Behavior

## CPU-bound vs. I/O-bound

Types of CPU bursts:

- ▶ long bursts – CPU bound (i.e. batch work)
- ▶ short bursts – I/O bound (i.e. emacs)



As CPUs get faster, processes tend to get more I/O-bound.

# Schedulers

Long-term scheduler (or job scheduler) - selects which processes should be brought into the ready queue.

Short-term scheduler (or CPU scheduler) - selects which process should be executed next and allocates CPU.

Medium-term scheduler swapping.

- ▶ LTS is responsible for a good *process mix* of I/O-bound and CPU-bound process leading to best performance.
- ▶ Time-sharing systems, e.g. UNIX, often have no long-term scheduler.

## Nonpreemptive vs. preemptive

A **nonpreemptive scheduling algorithm** lets a process run as long as it wants until it blocks (I/O or waiting for another process) or until it voluntarily releases the CPU.

A **preemptive scheduling algorithm** will forcibly suspend a process after it runs for sometime. — clock interruptable

### 10.3 Scheduling In Batch Systems

# Scheduling In Batch Systems

## First-Come First-Served

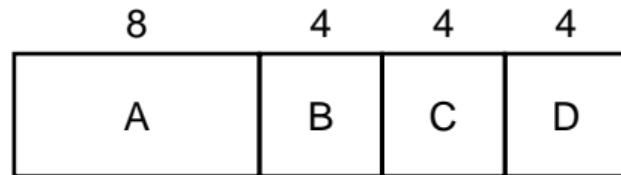
- ▶ nonpreemptive
- ▶ simple
- ▶ also has a disadvantage

What if a CPU-bound process (e.g. runs 1s at a time) followed by many I/O-bound processes (e.g. 1000 disk reads to complete)?

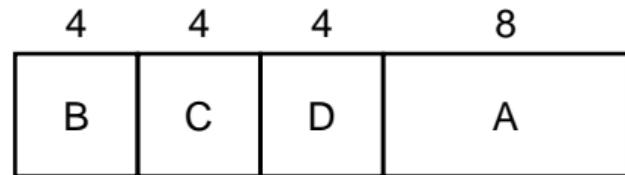
- ▶ In this case, a preemptive scheduling is preferred.

# Scheduling In Batch Systems

## Shortest Job First



(a)



(b)

## Average turnaround time

(a)  $(8 + 12 + 16 + 20) \div 4 = 14$

(b)  $(4 + 8 + 12 + 20) \div 4 = 11$

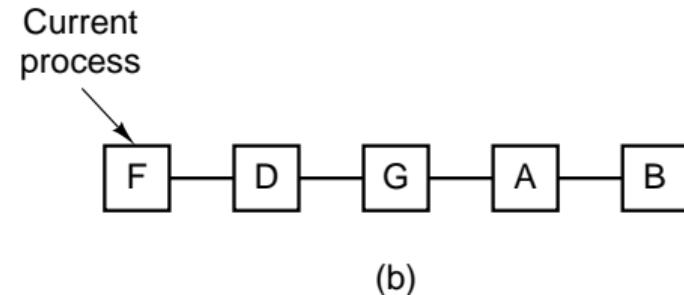
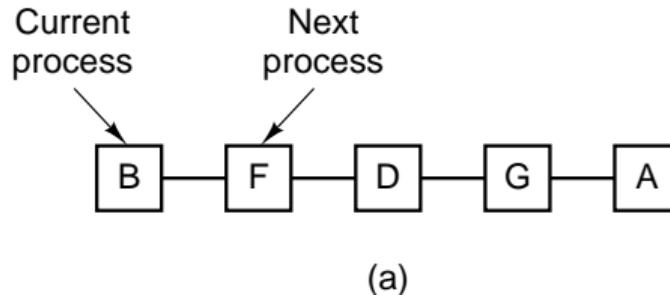
How to know the length of the next CPU burst?

- ▶ For long-term (job) scheduling, user provides
- ▶ For short-term scheduling, no way

## 10.4 Scheduling In Interactive Systems

# Scheduling In Interactive Systems

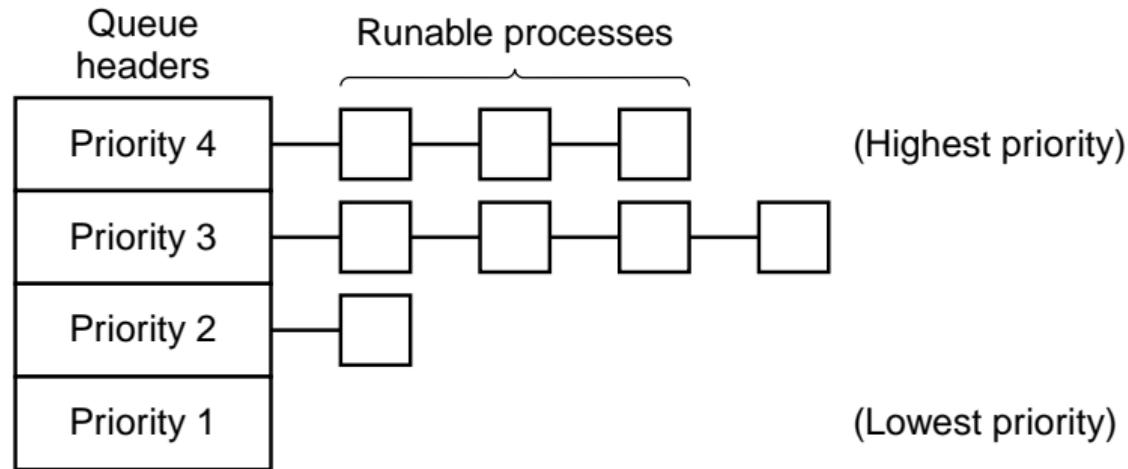
## Round-Robin Scheduling



- ▶ Simple, and most widely used;
- ▶ Each process is assigned a time interval, called its *quantum*;
- ▶ How long should the quantum be?
  - ▶ too short — too many process switches, lower CPU efficiency;
  - ▶ too long — poor response to short interactive requests;
  - ▶ usually around 20 ~ 50ms.

# Scheduling In Interactive Systems

## Priority Scheduling

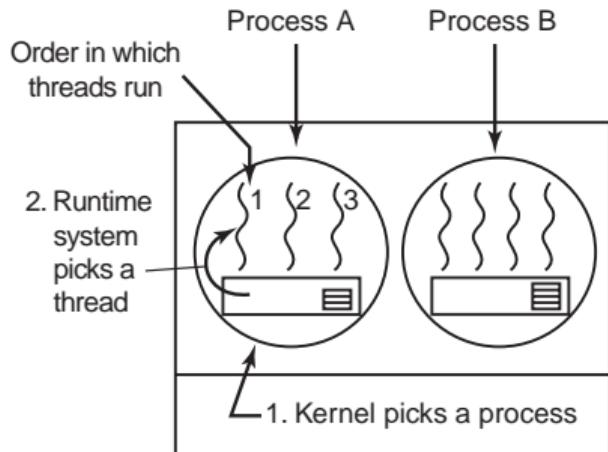


- ▶ SJF is a priority scheduling;
- ▶ Starvation — low priority processes may never execute;
  - ▶ Aging — as time progresses increase the priority of the process;

\$ man nice

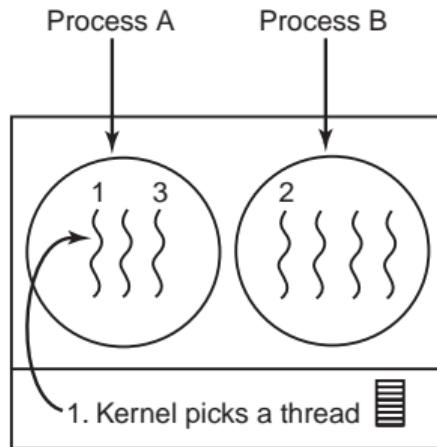
## 10.5 Thread Scheduling

# Thread Scheduling



Possible: A1, A2, A3, A1, A2, A3  
Not possible: A1, B1, A2, B2, A3, B3

(a)



Possible: A1, A2, A3, A1, A2, A3  
Also possible: A1, B1, A2, B2, A3, B3

(b)

- ▶ With kernel-level threads, sometimes a full context switch is required
- ▶ Each process can have its own application-specific thread scheduler, which usually works better than kernel can

## 10.6 Linux Scheduling

# Process Scheduling In Linux

A preemptive, priority-based algorithm with two separate priority ranges:

1. **real-time** range (0 ~ 99), for tasks where absolute priorities are more important than fairness
2. **nice value** range (100 ~ 139), for fair preemptive scheduling among multiple processes

numeric priority	relative priority	time quantum
0	highest	200 ms
•		
•		
•		
99		
100		
•		
•		
•		
139	lowest	10 ms

## In Linux, Process Priority is Dynamic

The scheduler keeps track of what processes are doing and adjusts their priorities periodically

- ▶ Processes that have been denied the use of a CPU for a long time interval are boosted by dynamically increasing their priority (usually I/O-bound)
- ▶ Processes running for a long time are penalized by decreasing their priority (usually CPU-bound)
- ▶ Priority adjustments are performed only on user tasks, not on real-time tasks

Tasks are determined to be I/O-bound or CPU-bound based on an interactivity heuristic

A task's interactivity metric is calculated based on how much time the task executes compared to how much time it sleeps

## Problems With The Pre-2.6 Scheduler

- (:) an algorithm with  $O(n)$  complexity
- ▶ a single runqueue for all processors
  - (:) good for load balancing
  - (:) bad for CPU caches, when a task is rescheduled from one CPU to another
- (:) a single runqueue lock — only one CPU working at a time

# Scheduling In Linux 2.6 Kernel

- 😊  $O(1)$  — Time for finding a task to execute depends not on *the number of active tasks* but instead on *the number of priorities*
- 😊 Each CPU has its own *runqueue*, and schedules itself independently; better cache efficiency
- ▶ The job of the scheduler is simple — Choose the task on the highest priority list to execute

## How to know there are processes waiting in a priority list?

A priority bitmap (5 32-bit words for 140 priorities) is used to define when tasks are on a given priority list.

- ▶ `find-first-bit-set` instruction is used to find the highest priority bit.

Each runqueue has two priority arrays

**active  
array**

priority	task lists
[0]	
[1]	
•	•
•	•
•	•
[139]	○

**expired  
array**

priority	task lists
[0]	
[1]	○
•	•
•	•
•	•
[139]	

# Completely Fair Scheduling (CFS)

## Linux's Process Scheduler

up to 2.4: simple, scaled poorly

- ▶  $O(n)$
- ▶ non-preemptive in kernel mode
- ▶ single run queue (cache? SMP?)

from 2.5 on:  $O(1)$  scheduler

- 😊 140 priority lists — scaled well
- 😊 one run queue per CPU — true SMP support
- 😊 preemptive
- 😊 ideal for large server workloads
- 😢 showed latency on desktop systems

from 2.6.23 on: Completely Fair Scheduler (CFS)

- 😊 improved interactive performance

# Completely Fair Scheduler (CFS)

For a perfect (unreal) multitasking CPU

- ▶  $n$  runnable processes can run at the same time
- ▶ each process should receive  $\frac{1}{n}$  of CPU power

For a real world CPU

- ▶ can run only a single task at once — unfair
  - 😊 while one task is running
  - 😢 the others have to wait
- ▶ `p->wait_runtime` is the amount of time the task should now run on the CPU for it becomes completely fair and balanced.
  - 😊 on ideal CPU, the `p->wait_runtime` value would always be zero
- ▶ CFS always tries to run the task with the largest `p->wait_runtime` value

In practice it works like this:

- ▶ While a task is using the CPU, its `wait_runtime` decreases

```
    wait_runtime = wait_runtime - time_running
```

**if:** its `wait_runtime`  $\neq \text{MAX}_{\text{wait\_runtime}}$  (among all processes)

**then:** it gets preempted

- ▶ Newly woken tasks (`wait_runtime = 0`) are put into the tree more and more to the right
- ▶ slowly but surely giving a chance for every task to become the “leftmost task” and thus get on the CPU within a deterministic amount of time

## References

- [1] Wikipedia. *Scheduling (computing)* — Wikipedia, The Free Encyclopedia. 2015.  
[http://en.wikipedia.org/w/index.php?title=Scheduling%5C\\_\(computing\)&oldid=647892123](http://en.wikipedia.org/w/index.php?title=Scheduling%5C_(computing)&oldid=647892123).

## 11 Deadlock

## 11.1 Resources

# A Major Class of Deadlocks Involve Resources

Processes need access to resources in reasonable order

Suppose...

- ▶ a process holds resource A and requests resource B. At same time,
- ▶ another process holds B and requests A

Both are blocked and remain so

Examples of computer resources

- ▶ printers
- ▶ memory space
- ▶ data (e.g. a locked record in a DB)
- ▶ semaphores

# Resources

```
typedef int semaphore;  
semaphore resource_1;  
semaphore resource_2;  
  
void process_A(void) {  
    down(&resource_1);  
    down(&resource_2);  
    use_both_resources( );  
    up(&resource_2);  
    up(&resource_1);  
}  
  
void process_B(void) {  
    down(&resource_1);  
    down(&resource_2);  
    use_both_resources( );  
    up(&resource_2);  
    up(&resource_1);  
}  
  
(a)
```

```
semaphore resource_1;  
semaphore resource_2;  
  
void process_A(void) {  
    down(&resource_1);  
    down(&resource_2);  
    use_both_resources( );  
    up(&resource_2);  
    up(&resource_1);  
}  
  
void process_B(void) {  
    down(&resource_2);  
    down(&resource_1);  
    use_both_resources( );  
    up(&resource_1);  
    up(&resource_2);  
}  
  
(b)
```

# Resources

Deadlocks occur when ...

processes are granted exclusive access to *resources*

e.g. devices, data records, files, ...

Preemptable resources can be taken away from a process with no ill effects

e.g. memory

Nonpreemptable resources will cause the process to fail if taken away

e.g. CD recorder

In general, deadlocks involve nonpreemptable resources.

# Resources

Sequence of events required to use a resource



What if request is denied?

Requesting process

- ▶ may be blocked
- ▶ may fail with error code

## 11.2 Introduction to Deadlocks

## The Best Illustration of a Deadlock

A law passed by the Kansas legislature early in the 20th century

“When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone.”

## Deadlock

A set of processes is deadlocked if each process in the set is waiting for an event that only another process in the set can cause.

- ▶ Usually the event is release of a currently held resource
- ▶ None of the processes can ...
  - ▶ run
  - ▶ release resources
  - ▶ be awakened

## Four Conditions For Deadlocks

**Mutual exclusion condition** each resource can only be assigned to one process or is available

**Hold and wait condition** process holding resources can request additional

**No preemption condition** previously granted resources cannot forcibly taken away

**Circular wait condition**

- ▶ must be a circular chain of 2 or more processes
- ▶ each is waiting for resource held by next member of the chain

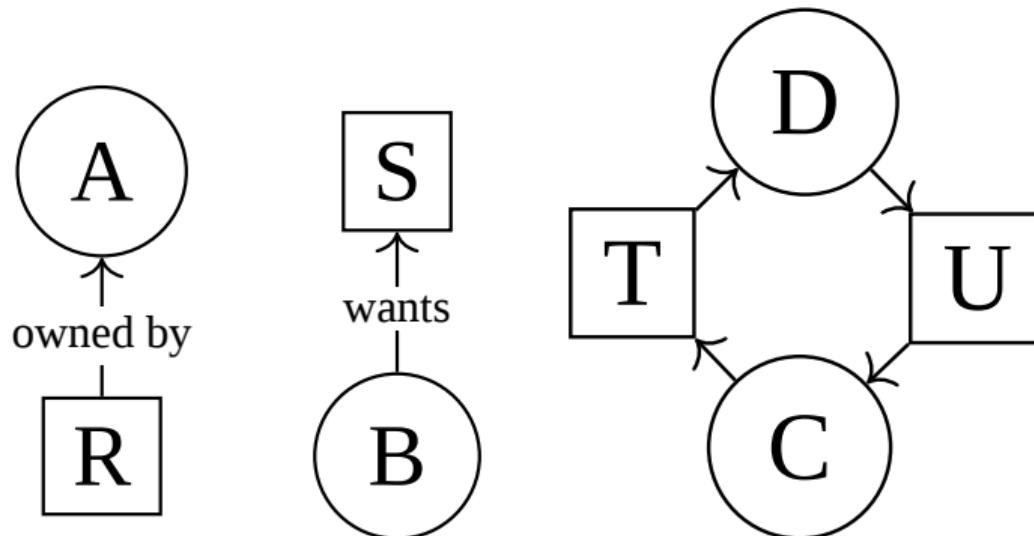
## Four Conditions For Deadlocks

Unlocking a deadlock is to answer 4 questions:

1. Can a resource be assigned to more than one process at once?
2. Can a process hold a resource and ask for another?
3. can resources be preempted?
4. Can circular waits exits?

### 11.3 Deadlock Modeling

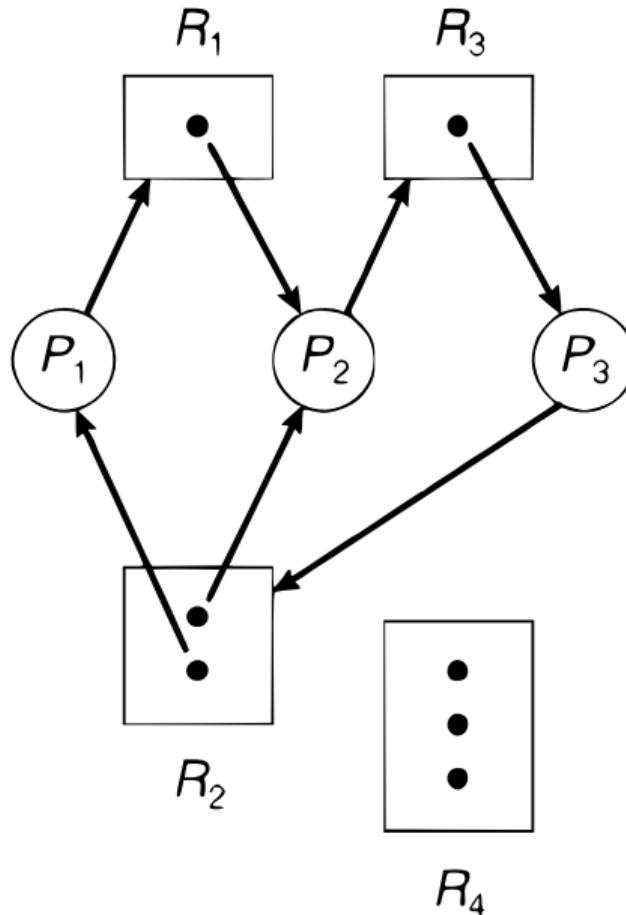
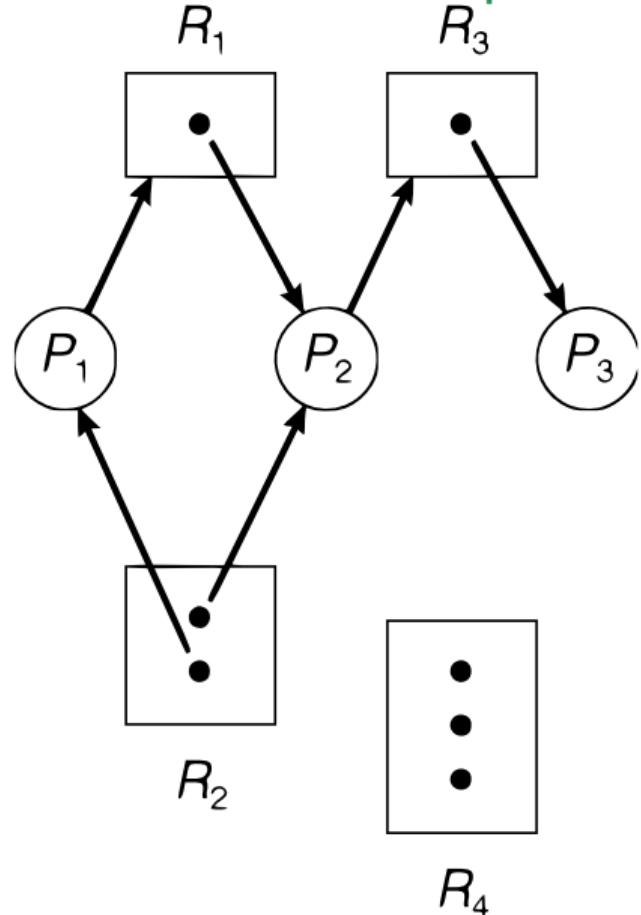
# Resource-Allocation Graph



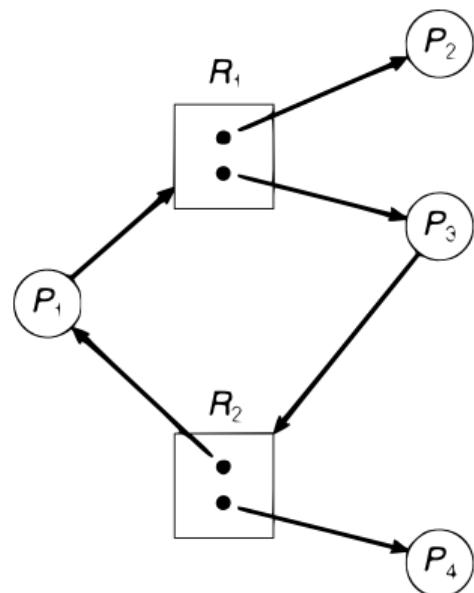
## Strategies for dealing with Deadlocks

1. detection and recovery
2. dynamic avoidance — careful resource allocation
3. prevention — negating one of the four necessary conditions
4. just ignore the problem altogether

## Resource-Allocation Graph



# Resource-Allocation Graph



## Basic facts:

- ▶ No cycles  $\Rightarrow$  no deadlock
- ▶ If graph contains a cycle  $\Rightarrow$ 
  - ▶ if only one instance per resource type, then deadlock
  - ▶ if several instances per resource type, possibility of deadlock

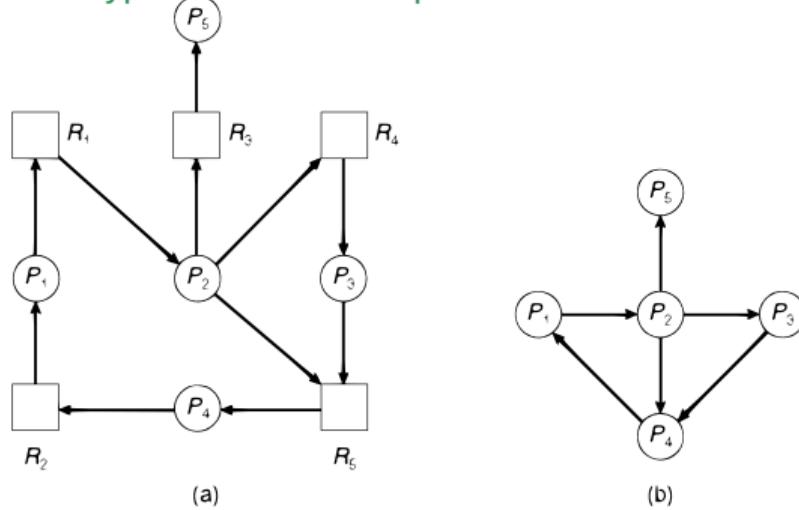
## 11.4 Deadlock Detection and Recovery

## Deadlock Detection

- ▶ Allow system to enter deadlock state
- ▶ Detection algorithm
- ▶ Recovery scheme

# Deadlock Detection

Single Instance of Each Resource Type — Wait-for Graph



- ▶  $P_i \rightarrow P_j$  if  $P_i$  is waiting for  $P_j$ ;
- ▶ Periodically invoke an algorithm that searches for a cycle in the graph. If there is a cycle, there exists a deadlock.
- ▶ An algorithm to detect a cycle in a graph requires an order of  $n^2$  operations, where  $n$  is the number of vertices in the graph.

# Deadlock Detection

## Several Instances of a Resource Type

$$E = \begin{pmatrix} 4 & 2 & 3 & 1 \end{pmatrix}$$

Tape drives  
Plotters  
Scanners  
CD Roms

$$A = \begin{pmatrix} 2 & 1 & 0 & 0 \end{pmatrix}$$

Tape drives  
Plotters  
Scanners  
CD Roms

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

Row n:

C: current allocation to process n

R: current requirement of process n

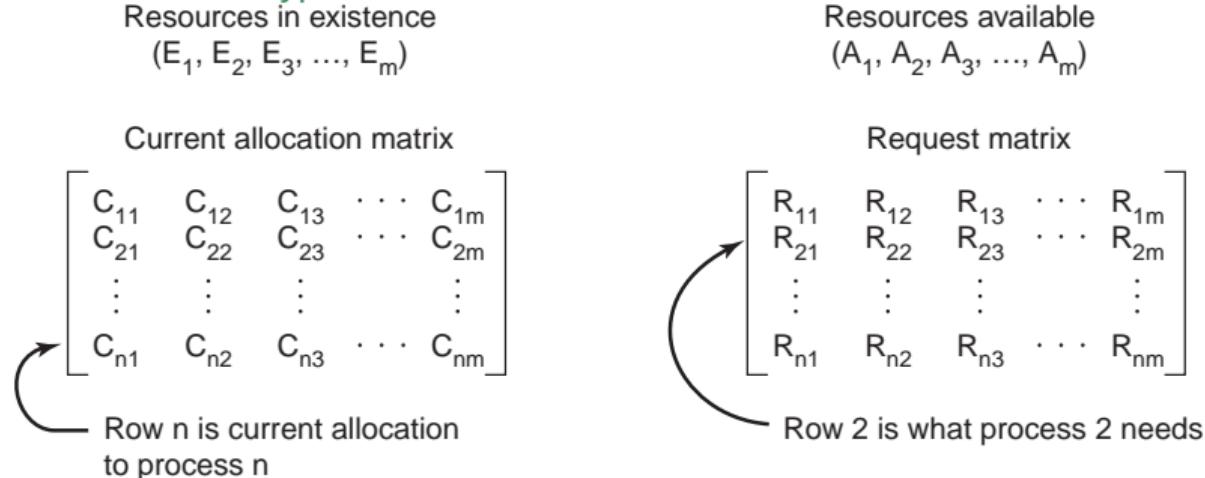
Column m:

C: current allocation of resource class m

R: current requirement of resource class m

# Deadlock Detection

## Several Instances of a Resource Type



$$\sum_{i=1}^n C_{ij} + A_j = E_j$$

e.g.

$$(C_{13} + C_{23} + \dots + C_{n3}) + A_3 = E_3$$

## Maths recall: vectors comparison

For two vectors,  $X$  and  $Y$

$$X \leq Y \quad \text{iff} \quad X_i \leq Y_i \quad \text{for } 0 \leq i \leq m$$

e.g.

$$\begin{bmatrix} 1 & 2 & 3 & 4 \end{bmatrix} \leq \begin{bmatrix} 2 & 3 & 4 & 4 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 2 & \mathbf{3} & 4 \end{bmatrix} \not\leq \begin{bmatrix} 2 & 3 & \mathbf{2} & 4 \end{bmatrix}$$

# Deadlock Detection

Several Instances of a Resource Type

Tape drives  
Plotters  
Scanners  
CD Roms

$$E = ( 4 \quad 2 \quad 3 \quad 1 )$$

Tape drives  
Plotters  
Scanners  
CD Roms

$$A = ( 2 \quad 1 \quad 0 \quad 0 )$$

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

# Deadlock Detection

Several Instances of a Resource Type

Tape drives  
Plotters  
Scanners  
CD Roms

$$E = (4 \quad 2 \quad 3 \quad 1)$$

Tape drives  
Plotters  
Scanners  
CD Roms

$$A = (2 \quad 1 \quad 0 \quad 0)$$

$$(2 \overset{A}{1} 0 0) \geq R_3, (2 \overset{R}{1} 0 0)$$

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

# Deadlock Detection

Several Instances of a Resource Type

Tape drives  
Plotters  
Scanners  
CD Roms

$$E = (4 \quad 2 \quad 3 \quad 1)$$

Tape drives  
Plotters  
Scanners  
CD Roms

$$A = (2 \quad 1 \quad 0 \quad 0)$$

$$\begin{matrix} A \\ (2 \ 1 \ 0 \ 0) \end{matrix} \geq R_3, \begin{matrix} R \\ (2 \ 1 \ 0 \ 0) \end{matrix}$$
$$\begin{matrix} (2 \ 2 \ 2 \ 0) \end{matrix} \geq R_2, \begin{matrix} (1 \ 0 \ 1 \ 0) \end{matrix}$$

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

# Deadlock Detection

Several Instances of a Resource Type

Tape drives  
Plotters  
Scanners  
CD Roms

$$E = (4 \quad 2 \quad 3 \quad 1)$$

Tape drives  
Plotters  
Scanners  
CD Roms

$$A = (2 \quad 1 \quad 0 \quad 0)$$

$$\begin{array}{l} A \\ (2 \ 1 \ 0 \ 0) \geq R_3, (2 \ 1 \ 0 \ 0) \\ (2 \ 2 \ 2 \ 0) \geq R_2, (1 \ 0 \ 1 \ 0) \\ (4 \ 2 \ 2 \ 1) \geq R_1, (2 \ 0 \ 0 \ 1) \end{array}$$

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

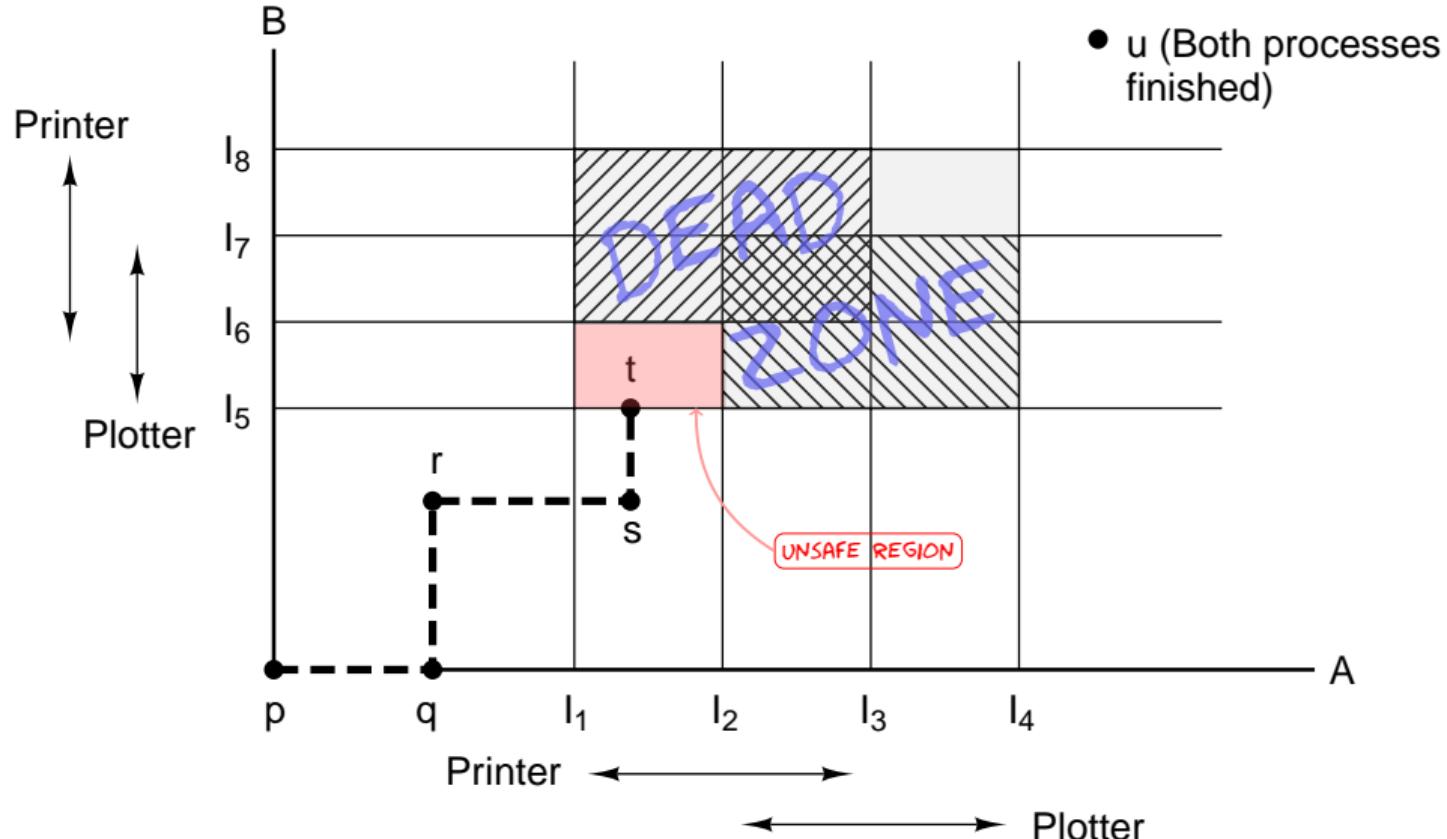
## Recovery From Deadlock

- ▶ Recovery through preemption
  - ▶ take a resource from some other process
  - ▶ depends on nature of the resource
- ▶ Recovery through rollback
  - ▶ checkpoint a process periodically
  - ▶ use this saved state
  - ▶ restart the process if it is found deadlocked
- ▶ Recovery through killing processes

## 11.5 Deadlock Avoidance

# Deadlock Avoidance

## Resource Trajectories



# Deadlock Avoidance

Safe and Unsafe States

Assuming  $E = 10$

## Unsafe

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3  
(a)

	Has	Max
A	4	9
B	2	4
C	2	7

Free: 2  
(b)

	Has	Max
A	4	9
B	4	4
C	2	7

Free: 0  
(c)

	Has	Max
A	4	9
B	—	—
C	2	7

Free: 4  
(d)

## Safe

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3  
(a)

	Has	Max
A	3	9
B	4	4
C	2	7

Free: 1  
(b)

	Has	Max
A	3	9
B	0	—
C	2	7

Free: 5  
(c)

	Has	Max
A	3	9
B	0	—
C	7	7

Free: 0  
(d)

	Has	Max
A	3	9
B	0	—
C	0	—

Free: 7  
(e)

# Deadlock Avoidance

## The Banker's Algorithm for a Single Resource

The banker's algorithm considers each request as it occurs, and sees if granting it leads to a safe state.

	Has	Max
A	0	6
B	0	5
C	0	4
D	0	7

Free: 10

(a)

	Has	Max
A	1	6
B	1	5
C	2	4
D	4	7

Free: 2

(b)

	Has	Max
A	1	6
B	2	5
C	2	4
D	4	7

Free: 1

(c)

*unsafe  $\neq$  deadlock*

# Deadlock Avoidance

The Banker's Algorithm for Multiple Resources

	Process	Tape drives	Plotters	Scanners	CD ROMs
A	3	0	1	1	
B	0	1	0	0	
C	1	1	1	0	
D	1	1	0	1	
E	0	0	0	0	

Resources assigned

$$D \rightarrow A \rightarrow B, C, E$$

$$D \rightarrow E \rightarrow A \rightarrow B, C$$

	Process	Tape drives	Plotters	Scanners	CD ROMs
A	1	1	0	0	
B	0	1	1	2	
C	3	1	0	0	
D	0	0	1	0	
E	2	1	1	0	

Resources still needed

$$\begin{aligned}E &= (6342) \\P &= (5322) \\A &= (1020)\end{aligned}$$

# Deadlock Avoidance

Mission Impossible

## In practice

- ▶ processes rarely know in advance their max future resource needs;
- ▶ the number of processes is not fixed;
- ▶ the number of available resources is not fixed.

Conclusion: Deadlock avoidance is essentially a mission impossible.

## 11.6 Deadlock Prevention

# Deadlock Prevention

## Break The Four Conditions

### Attacking the Mutual Exclusion Condition

- ▶ For example, using a *printing daemon* to avoid exclusive access to a printer.
- ▶ Not always possible
  - ▶ Not required for sharable resources;
  - ▶ must hold for nonsharable resources.
- ▶ The best we can do is to avoid mutual exclusion as much as possible
  - ▶ Avoid assigning a resource when not really necessary
  - ▶ Try to make sure as few processes as possible may actually claim the resource

## Attacking the Hold and Wait Condition

Must guarantee that whenever a process requests a resource, it does not hold any other resources.

Try: the processes must request all their resources before starting execution

if everything is available  
then can run  
    if one or more resources are busy  
    then nothing will be allocated (just wait)

### Problem:

- ▶ many processes don't know what they will need before running
- ▶ Low resource utilization; starvation possible

## Attacking the No Preemption Condition

if a process that is holding some resources requests another resource that cannot be immediately allocated to it

then

1. All resources currently being held are released
2. Preempted resources are added to the list of resources for which the process is waiting
3. Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting

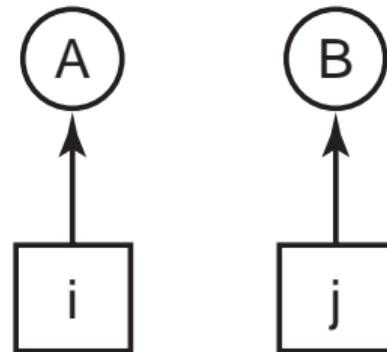
Low resource utilization; starvation possible

## Attacking Circular Wait Condition

Impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration

1. Imagesetter
2. Scanner
3. Plotter
4. Tape drive
5. CD Rom drive

(a)



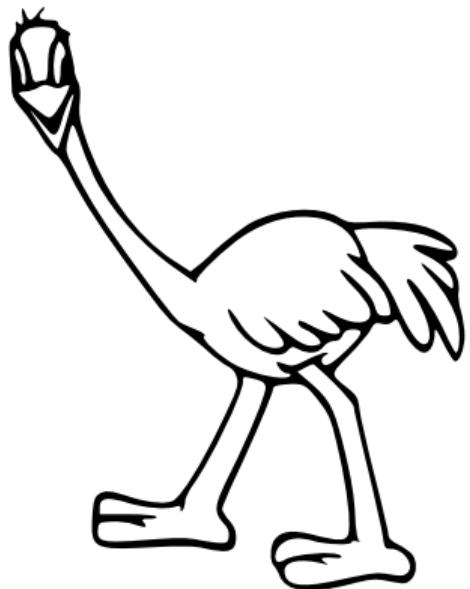
(b)

It's hard to find an ordering that satisfies everyone.

## 11.7 The Ostrich Algorithm

# The Ostrich Algorithm

- ▶ Pretend there is no problem
- ▶ Reasonable if
  - ▶ deadlocks occur very rarely
  - ▶ cost of prevention is high
- ▶ UNIX and Windows takes this approach
- ▶ It is a trade off between
  - ▶ convenience
  - ▶ correctness



## References

- [1] Wikipedia. *Deadlock — Wikipedia, The Free Encyclopedia*. 2015.  
<http://en.wikipedia.org/w/index.php?title=Deadlock&oldid=645602687>.

## Part III

### Memory Management

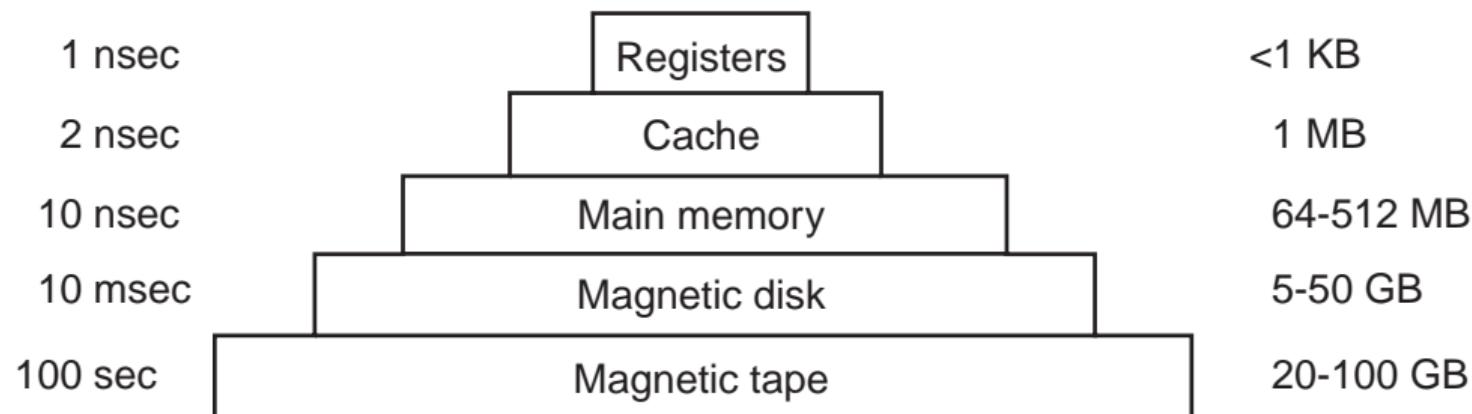
## 12 Background

# Memory Management

In a perfect world Memory is *large, fast, non-volatile*

In real world ...

Typical access time	Typical capacity
---------------------	------------------



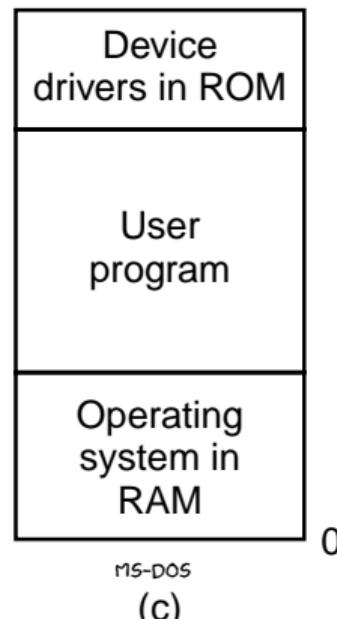
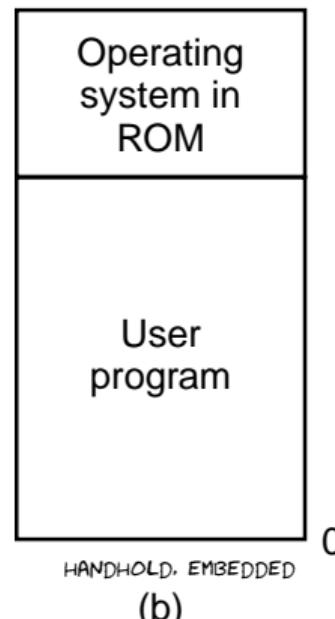
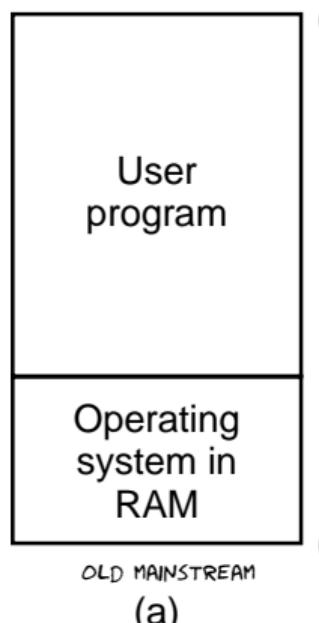
Memory manager handles the memory hierarchy.

# Basic Memory Management

## Real Mode

In the old days ...

- ▶ Every program simply saw the physical memory
- ▶ mono-programming without swapping or paging



# Basic Memory Management

## Relocation Problem

EXPOSING  
PHYSICAL MEMORY  
TO  
PROCESSES  
IS NOT  
A GOOD IDEA

0 16380

⋮

ADD	28
MOV	24
	20
	16
	12
	8
	4
JMP 24	0

0 16380

⋮

CMP	28
	24
	20
	16
	12
	8
	4
JMP 28	0

0 32764

⋮

CMP	16412
	16408
	16404
	16400
	16396
	16392
	16388
JMP 28	16384
	0
	16380

ADD	28
MOV	24
	20
	16
	12
	8
	4
JMP 24	0

(a)

(b)

(c)

# Memory Protection

## Protected mode

We need

- ▶ Protect the OS from access by user programs
- ▶ Protect user programs from one another

**Protected mode** is an operational mode of x86-compatible CPU.

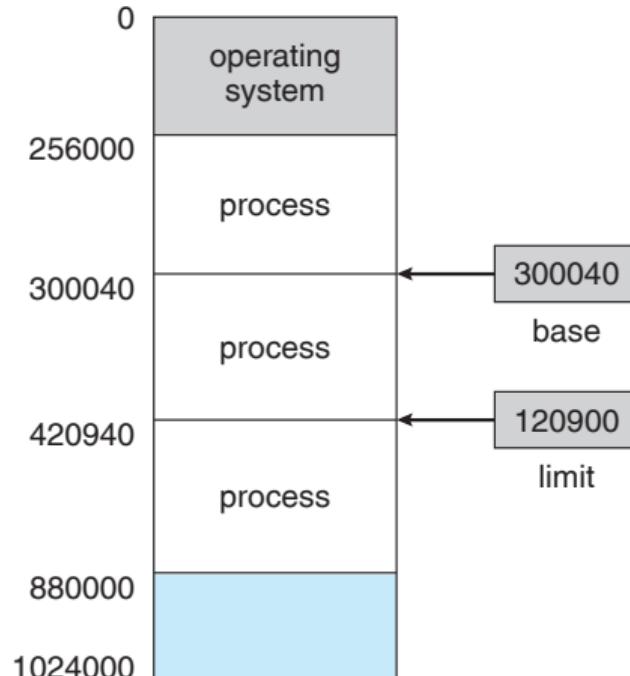
- ▶ The purpose is to protect everyone else (including the OS) from your program.

# Memory Protection

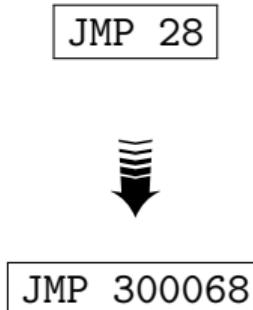
## Logical Address Space

Base register holds the smallest legal physical memory address

Limit register contains the size of the range

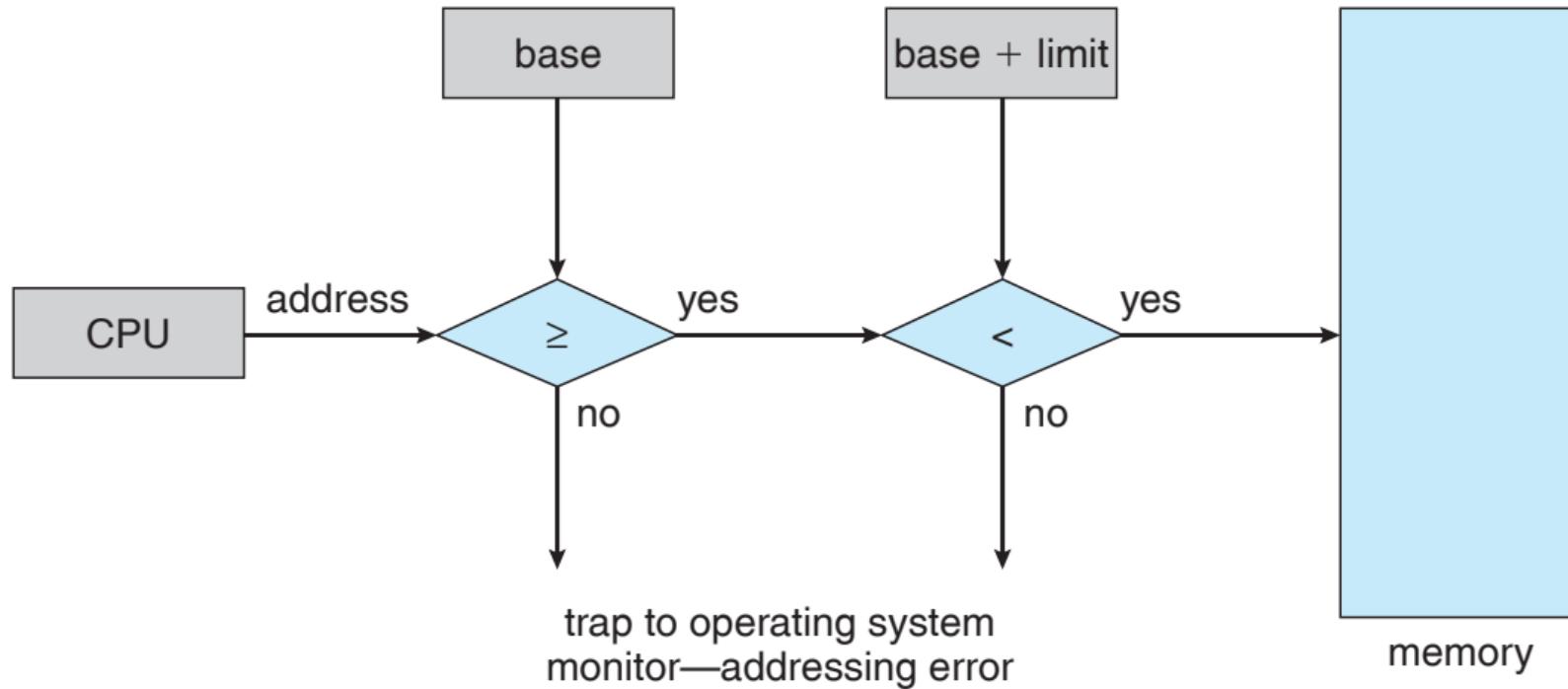


A pair of base and limit registers define the logical address space

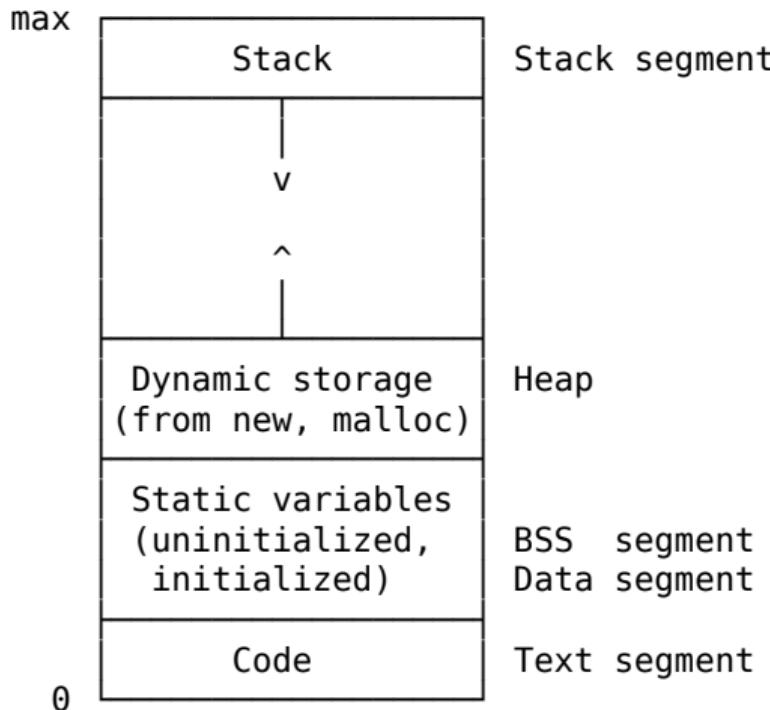


# Memory Protection

Base and limit registers



# UNIX View of a Process' Memory



Stack segment

text: program code

data: initialized global and static data

bss: uninitialized global and static data

heap: dynamically allocated with  
malloc, new

stack: local variables

THE SIZE OF A PROCESS  
(TEXT + DATA + BSS) IS  
ESTABLISHED AT COMPILE TIME

# Stack vs. Heap

Stack	Heap
compile-time allocation	run-time allocation
auto clean-up	you clean-up
inflexible	flexible
smaller	bigger
quicker	slower

How large is the ...

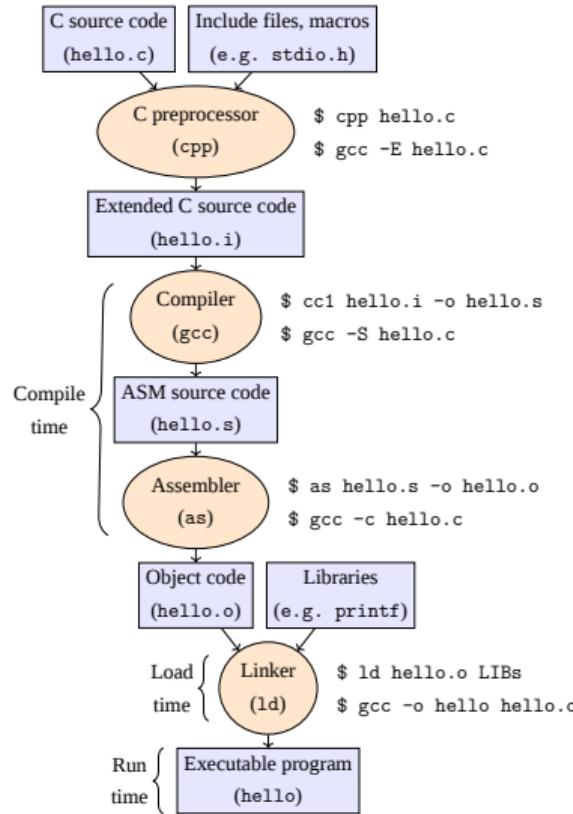
stack: ulimit -s

heap: could be as large as your virtual memory

text|data|bss: size a.out

# Multi-step Processing of a User Program

When is space allocated?



**Static:** before program start running

- ▶ Compile time
- ▶ Load time

**Dynamic:** as program runs

- ▶ Execution time

# Address Binding

Who assigns memory to segments?

## Static-binding: before a program starts running

Compile time: Compiler and assembler generate an object file for each source file

Load time:

- ▶ Linker combines all the object files into a single executable object file
- ▶ Loader (part of OS) loads an executable object file into memory at location(s) determined by the OS
  - invoked via the execve system call

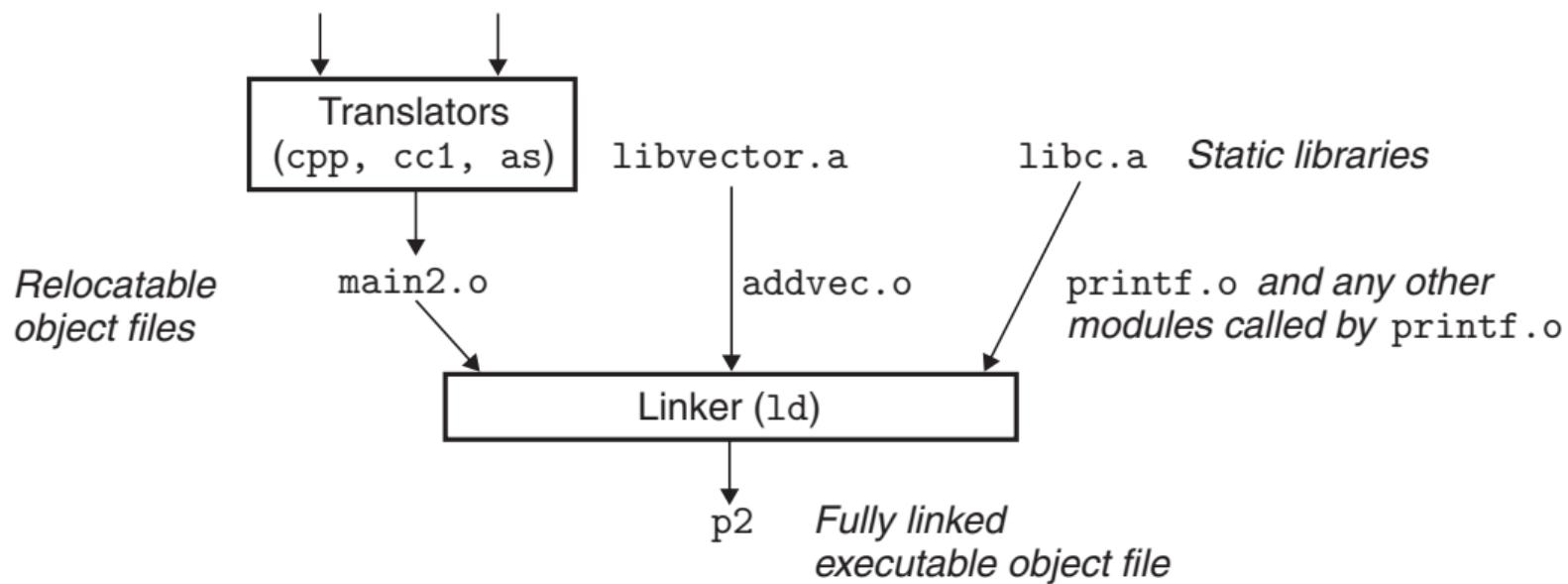
## Dynamic-binding: as program runs

- ▶ Execution time:
  - ▶ uses new and malloc to dynamically allocate memory
  - ▶ gets space on stack during function calls

## Static loading

- ▶ The entire program and all data of a process must be in physical memory for the process to execute
- ▶ The size of a process is thus limited to the size of physical memory

*Source files main2.c vector.h*



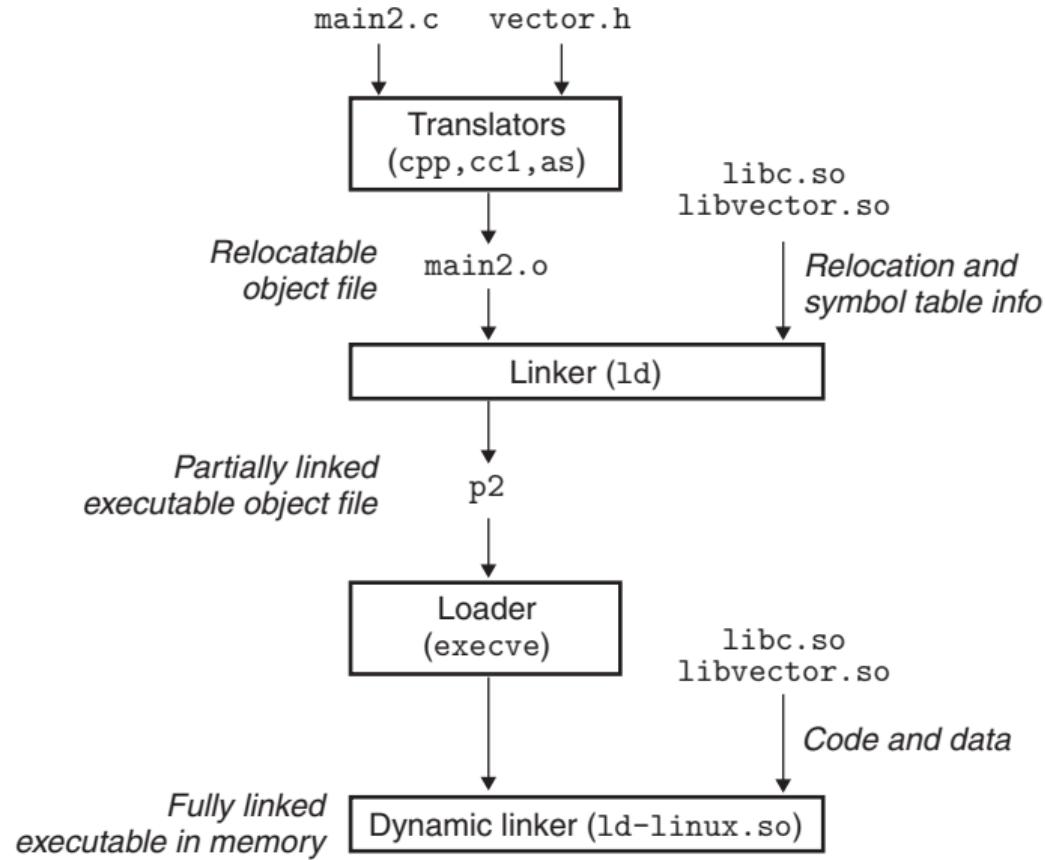
## Dynamic Linking

A **dynamic linker** is actually a special loader that loads external shared libraries into a running process

- ▶ Small piece of code, `stub`, used to locate the appropriate memory-resident library routine
- ▶ Only one copy in memory
- ▶ Don't have to re-link after a library update

```
1 if ( stub_is_executed ){  
2     if ( !routine_in_memory )  
3         load_routine_into_memory();  
4     stub_replaces_itself_with_routine();  
5     execute_routine();  
6 }
```

# Dynamic Linking



# Library Files

Static libraries `.a` files. Very old ones, but still alive.

```
$ find /usr/lib -name "*.a"
```

Shared libraries `.so` files. The preferred ones.

```
$ find /usr/lib -name "*.so.*"
```

Examples:

```
$ gcc -o hello hello.c /usr/lib/libm.a
```

```
$ gcc -o hello hello.c -lm
```

# Build A Static Library

Source codes

main.c

```
1 #include "lib.h"
2
3 int main(int argc, char* argv[])
4 {
5     int i=1;
6
7     for (; i<argc; i++)
8     {
9         hello(argv[i]);
10        hi(argv[i]);
11    }
12
13    return 0;
}
```

lib.h

```
1 #include <stdio.h>
2
3 void hello(char *);
4 void hi(char *);
```

hello.c

```
1 #include <stdio.h>
2
3 void hello(char *arg)
4 {
5     printf("Hello, %s!\n", arg);
6 }
```

hi.c

```
1 #include <stdio.h>
2
3 void hi(char *arg)
4 {
5     printf("Hi, %s!\n", arg);
6 }
```

# Build A Static Library

## Step by step

1. Get `hi.o`, `hello.o`  
\$ gcc -c hi.c hello.c
2. Put `*.o` into `libhi.a`  
\$ ar crv libhi.a hi.o  
    hello.o
3. Use `libhi.a`  
\$ gcc main.c libhi.a

## Makefile

```
1  main: main.c lib.h libhi.a
2          gcc -Wall -o main main.c libhi.a
3
4  libhi.a: hello.o hi.o
5          ar crv libhi.a hello.o hi.o
6
7  hello.o: hello.c
8          gcc -Wall -c hello.c
9
10 hi.o: hi.c
11         gcc -Wall -c hi.c
12
13 clean:
14         rm -f *.o *.a main
```

# Build A Shared Library

Step by step

1. Get `hi.o`, `hello.o`

```
$ gcc -fPIC -c hi.c hello.c
```

2. Get `libhi.so`

```
$ gcc -shared -o libhi.so hi.o hello.o
```

3. Use `libhi.so`

```
$ gcc -L. -Wl,-rpath=. main.c -lhi
```

4. Check it

```
$ ldd a.out
```

# Build A Shared Library

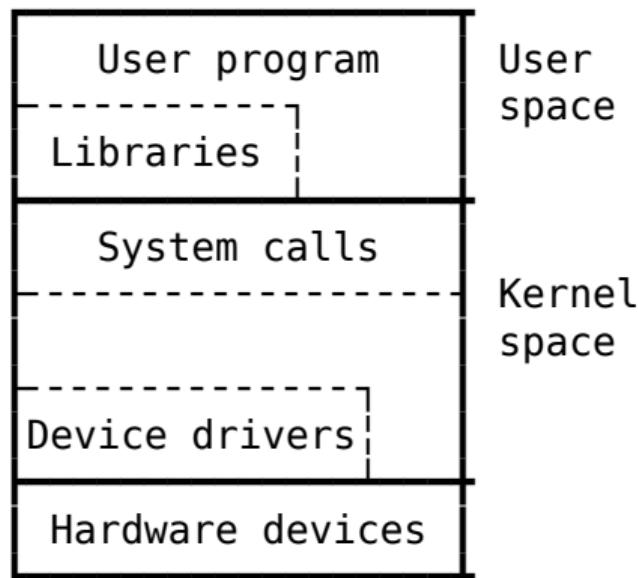
## Makefile

```
1 main: main.c lib.h libhi.so
2         gcc -L. -Wl,-rpath=. -Wall -o main main.c -lhi
3             # -L           - tells ld where to search libraries
4             # -Wl,option - pass option as an option to the linker (ld)
5             # -rpath=dir - Add a directory to the runtime library search path
6 libhi.so: hi.o hello.o
7         gcc -shared -o libhi.so hi.o hello.o
8 hi.o: hi.c
9         gcc -fPIC -c hi.c
10 hello.o: hello.c
11         gcc -fPIC -c hello.c
12 clean:
13         rm -f *.o *.so main
```

# GNU C Library

Linux API > POSIX API

```
$ man 7 libc  
$ man 3 intro  
$ man gcc  
$ info gcc  
① sudo apt install gcc-doc
```



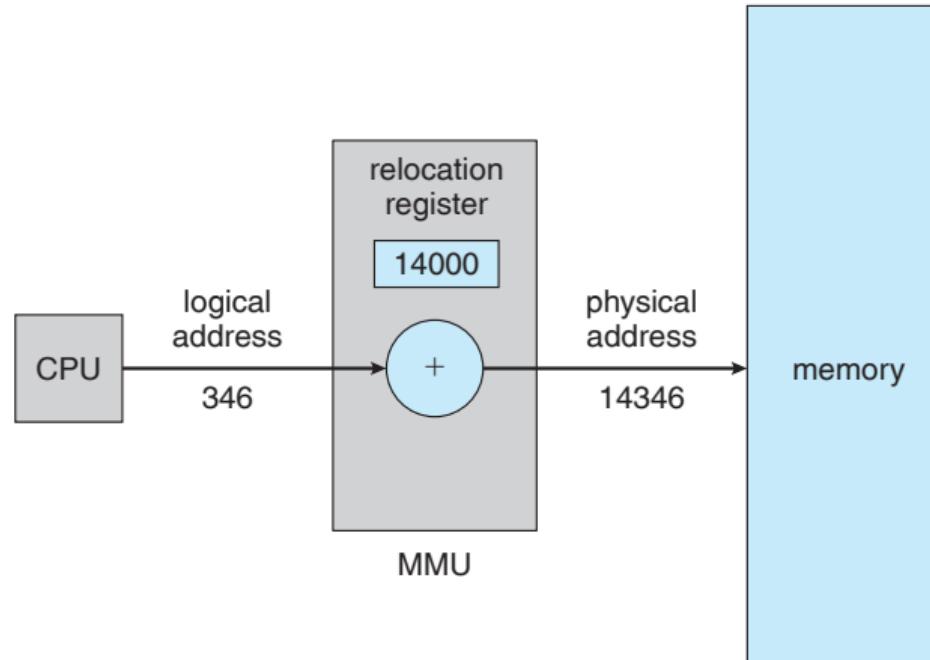
## Logical vs. Physical Address Space

- ▶ Mapping logical address space to physical address space is central to MM
  - Logical address** generated by the CPU; also referred to as **virtual address**
  - Physical address** address seen by the memory unit
- ▶ In compile-time and load-time address binding schemes, LAS and PAS are identical in size
- ▶ In execution-time address binding scheme, they differ.

# Logical vs. Physical Address Space

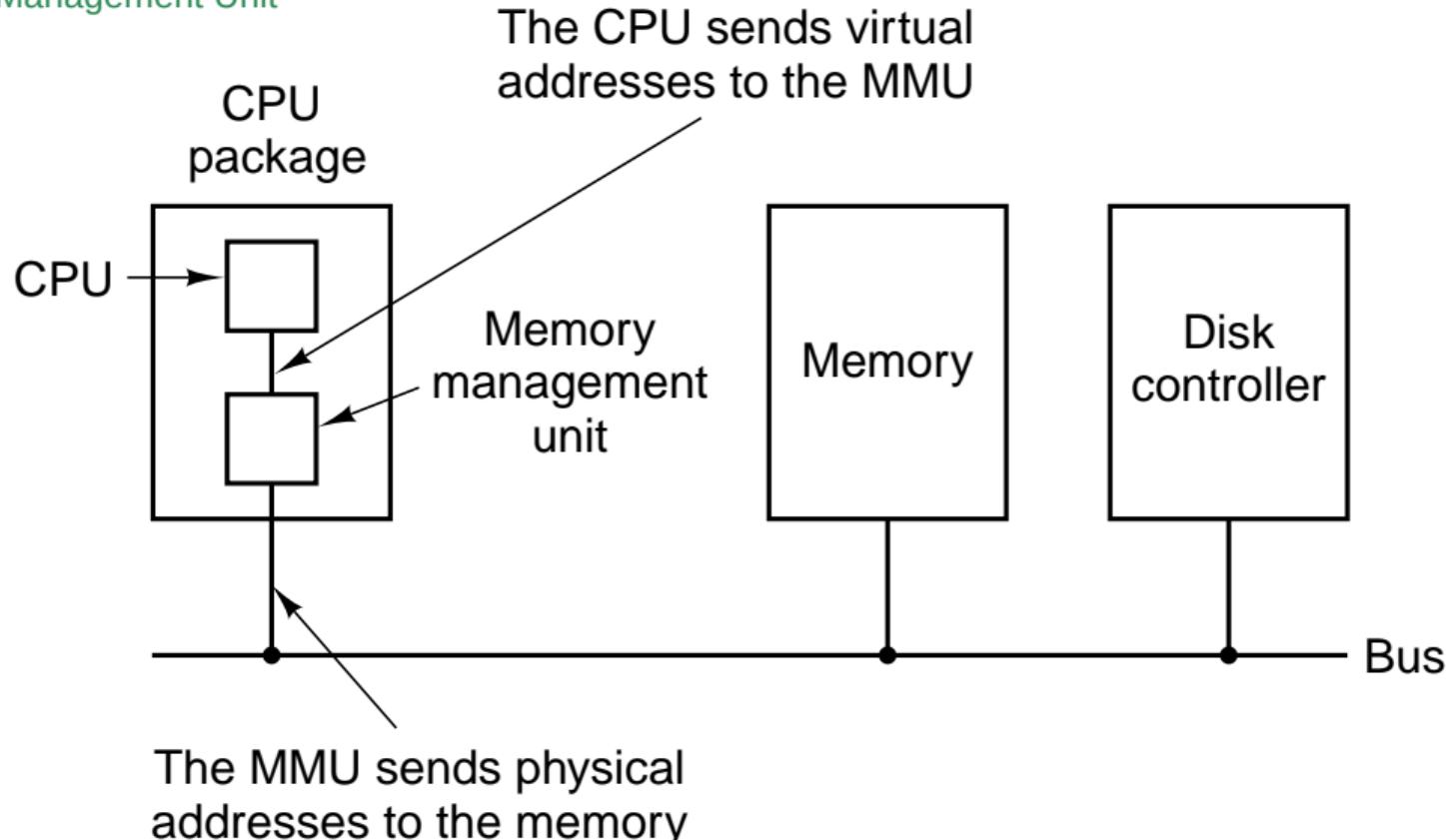
The user program

- ▶ deals with logical addresses
- ▶ never sees the real physical addresses

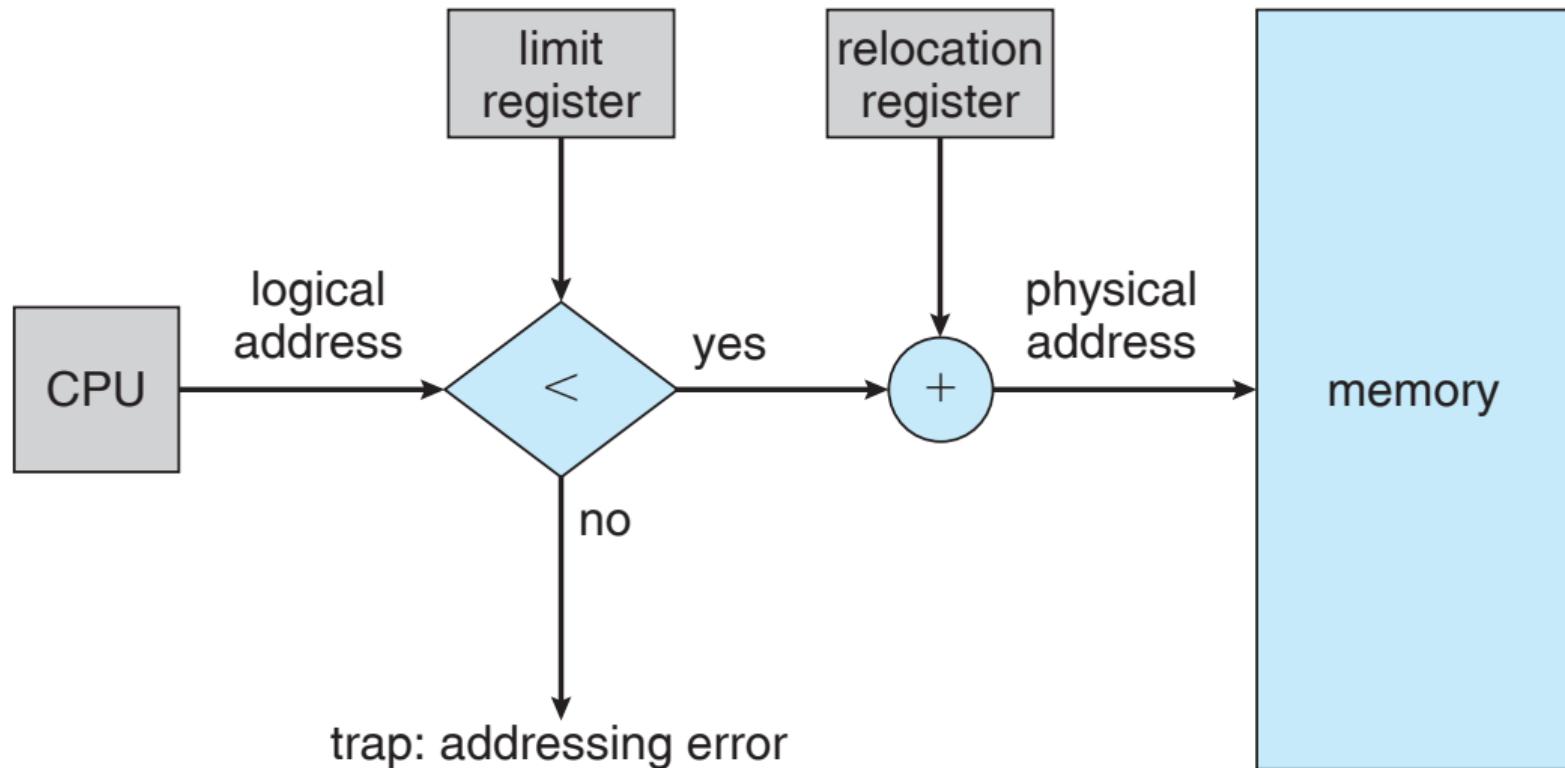


# MMU

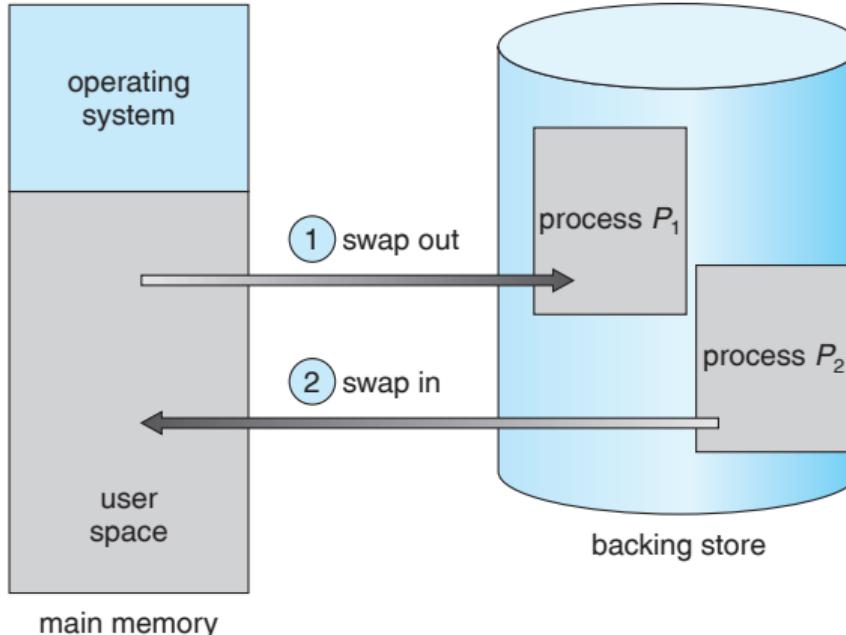
Memory Management Unit



# Memory Protection



# Swapping



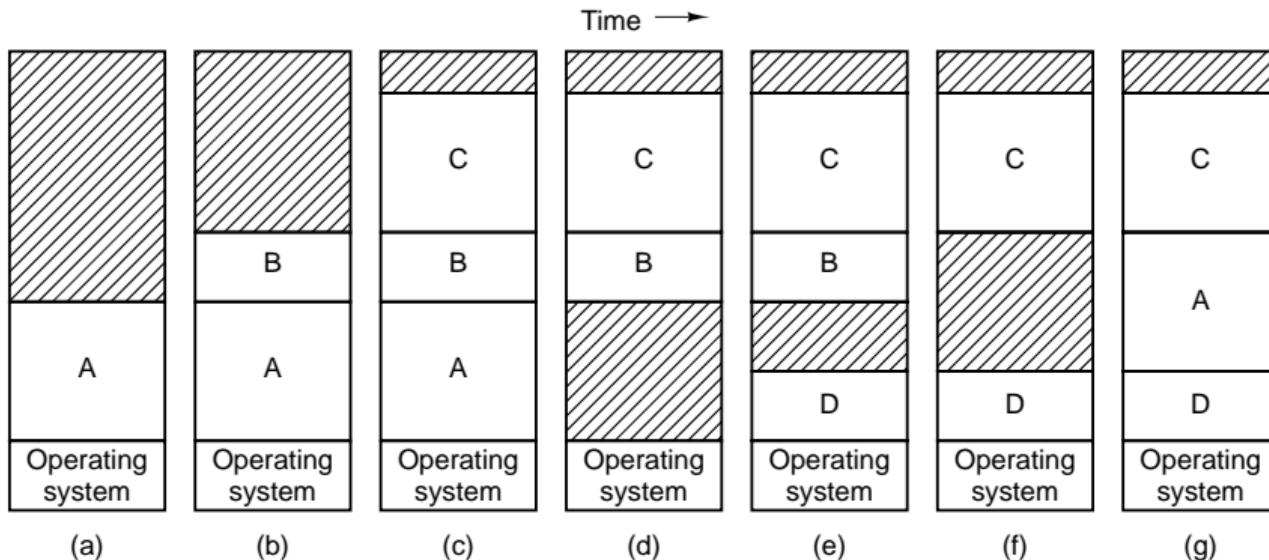
Major part of swap time is transfer time

Total transfer time is directly proportional to the amount of memory swapped

## 13 Contiguous Memory Allocation

# Contiguous Memory Allocation

Multiple-partition allocation

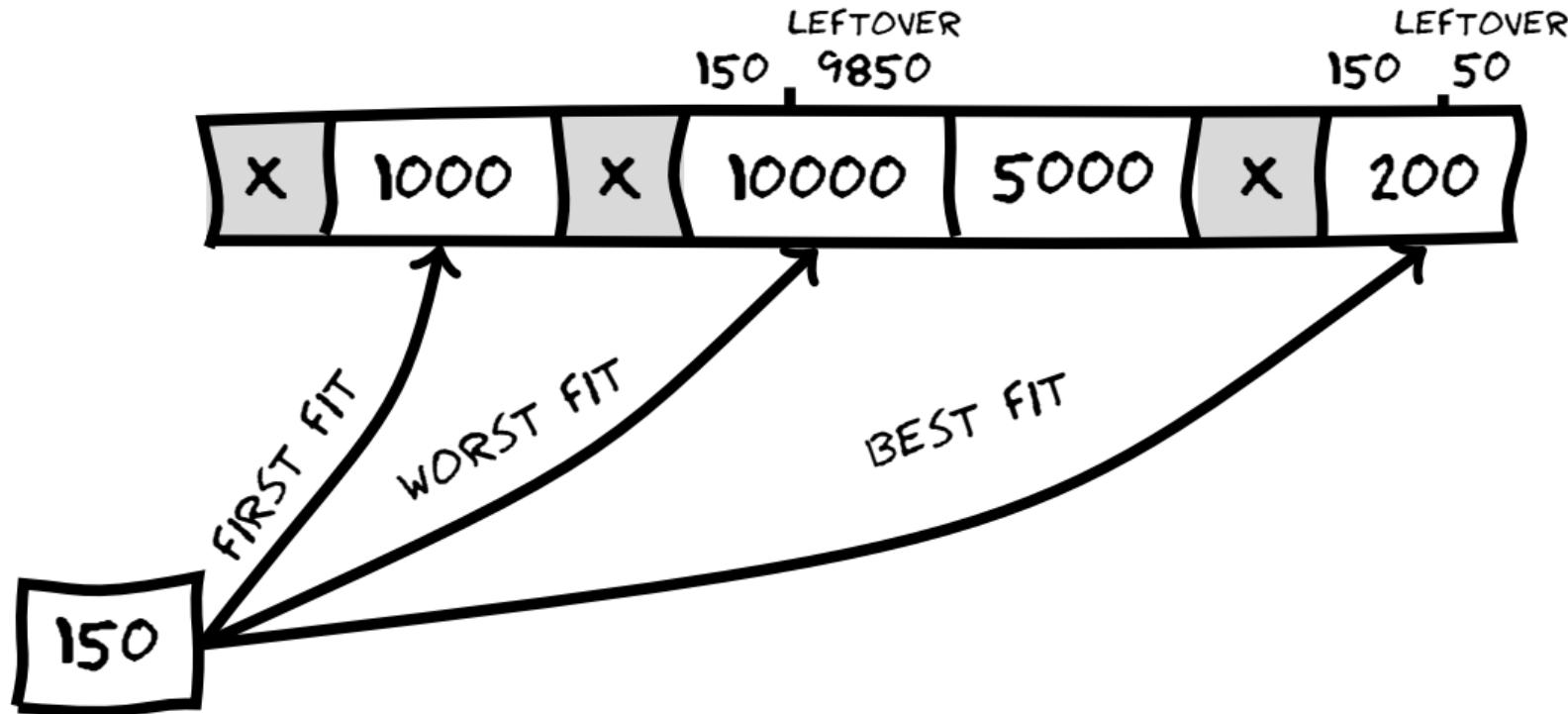


Operating system maintains information about:

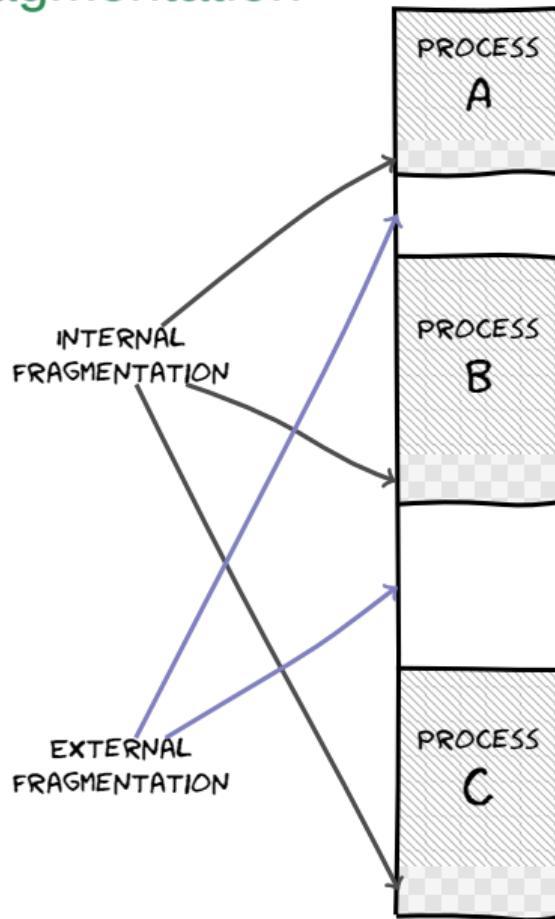
- a allocated partitions
- b free partitions (hole)

# Dynamic Storage-Allocation Problem

First Fit, Best Fit, Worst Fit



# Fragmentation



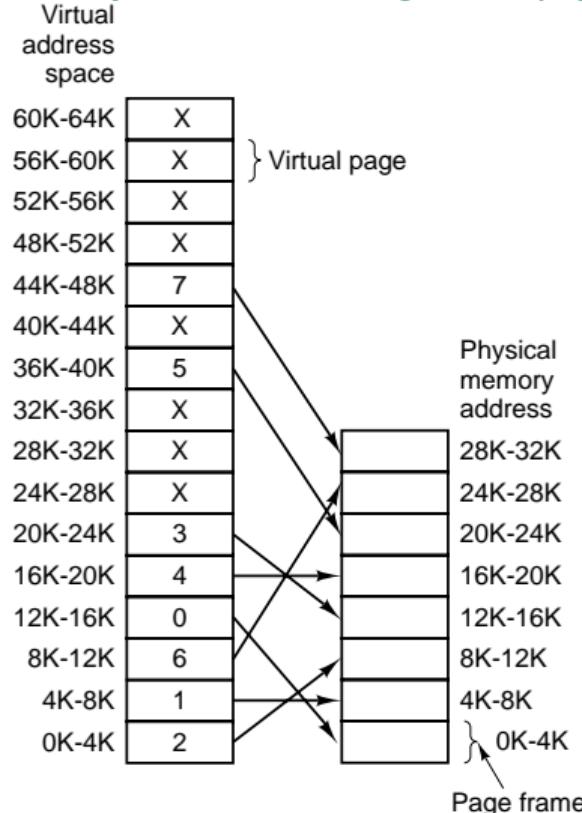
Reduce external fragmentation by

- ▶ **Compaction** is possible only if relocation is dynamic, and is done at execution time
- ▶ **Noncontiguous memory allocation**
  - ▶ Paging
  - ▶ Segmentation

## 14 Virtual Memory

# Virtual Memory

Logical memory can be much larger than physical memory



## Address translation

*virtual address*  $\xrightarrow{\text{page table}}$  *physical address*

*Page 0*  $\xrightarrow{\text{map to}}$  *Frame 2*

$0_{\text{virtual}}$   $\xrightarrow{\text{map to}}$   $8192_{\text{physical}}$

$20500_{\text{vir}}$   $\xrightarrow{\text{map to}}$   $12308_{\text{phy}}$   
 $(20k + 20)_{\text{vir}}$   $\xrightarrow{\text{map to}}$   $(12k + 20)_{\text{phy}}$

## 14.1 Paging

# Paging

## Address Translation Scheme

Address generated by CPU is divided into:

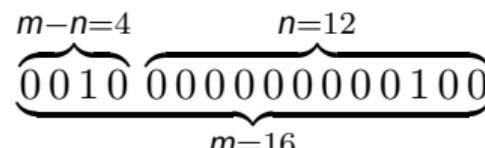
Page number(p): an index into a *page table*

Page offset(d): to be copied into memory

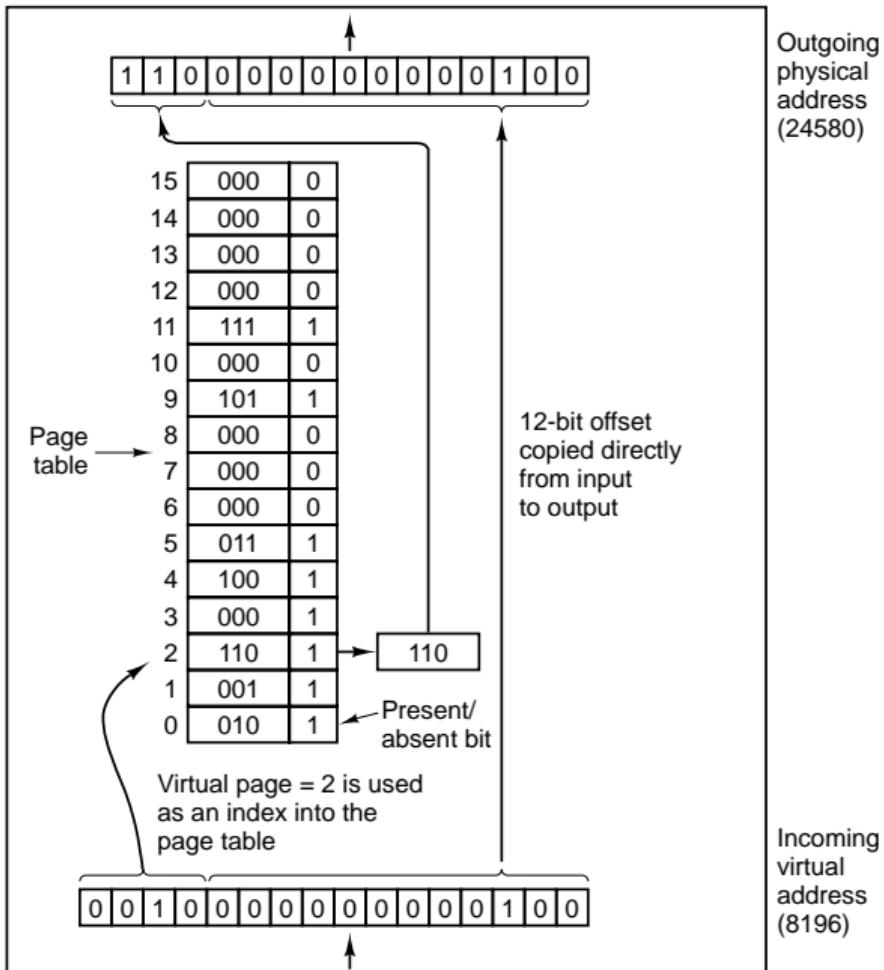
Given logical address space ( $2^m$ ) and page size ( $2^n$ ),

$$\text{number of pages} = \frac{2^m}{2^n} = 2^{m-n}$$

Example: addressing to 001000000000100



$$\text{page number} = 0010 = 2, \quad \text{page offset} = 0000000000100$$



Virtual pages: 16  
 Page size: 4k  
 Virtual memory: 64K  
 Physical frames: 8  
 Physical memory: 32K

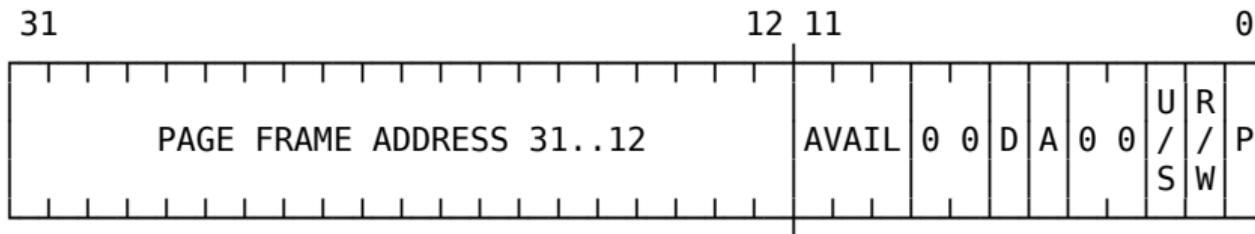
# Intel i386 Page Table Entry

- ▶ Commonly 4 bytes (32 bits) long
- ▶ Page size is usually 4k ( $2^{12}$  bytes). OS dependent

\$ getconf PAGESIZE

- ▶ Could have  $2^{32-12} = 2^{20} = 1M$  pages

Could address  $1M \times 4KB = 4GB$  memory



P – PRESENT

R/W – READ/WRITE

U/S – USER/SUPERVISOR

A – ACCESSED

D – DIRTY

AVAIL – AVAILABLE FOR SYSTEMS PROGRAMMER USE

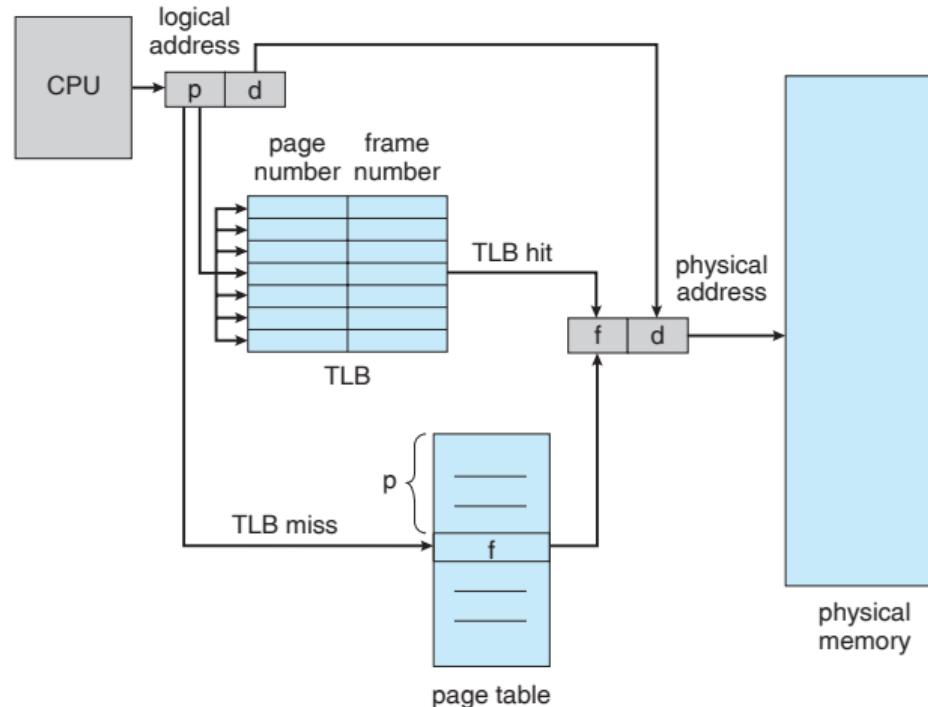
NOTE: 0 INDICATES INTEL RESERVED. DO NOT DEFINE.

## Page Table

- ▶ Page table is kept in main memory
- ▶ Usually one page table for each process
- ▶ **Page-table base register (PTBR):** A pointer to the page table is stored in PCB
- ▶ **Page-table length register (PRLR):** indicates size of the page table
- ▶ Slow
  - ▶ Requires two memory accesses. One for the page table and one for the data/instruction.
- ▶ TLB

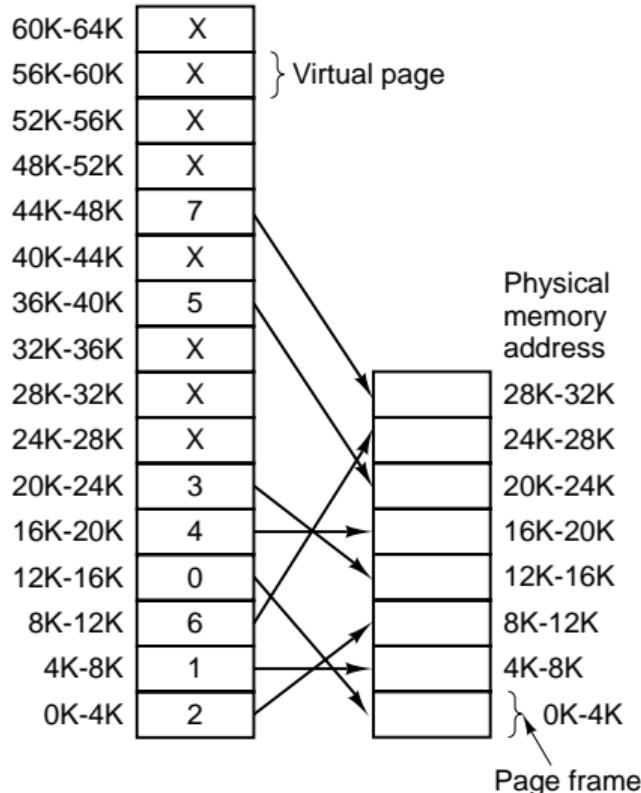
# Translation Lookaside Buffer (TLB)

80-20 rule Only a small fraction of the PTEs are heavily read; the rest are barely used at all



# Page Fault

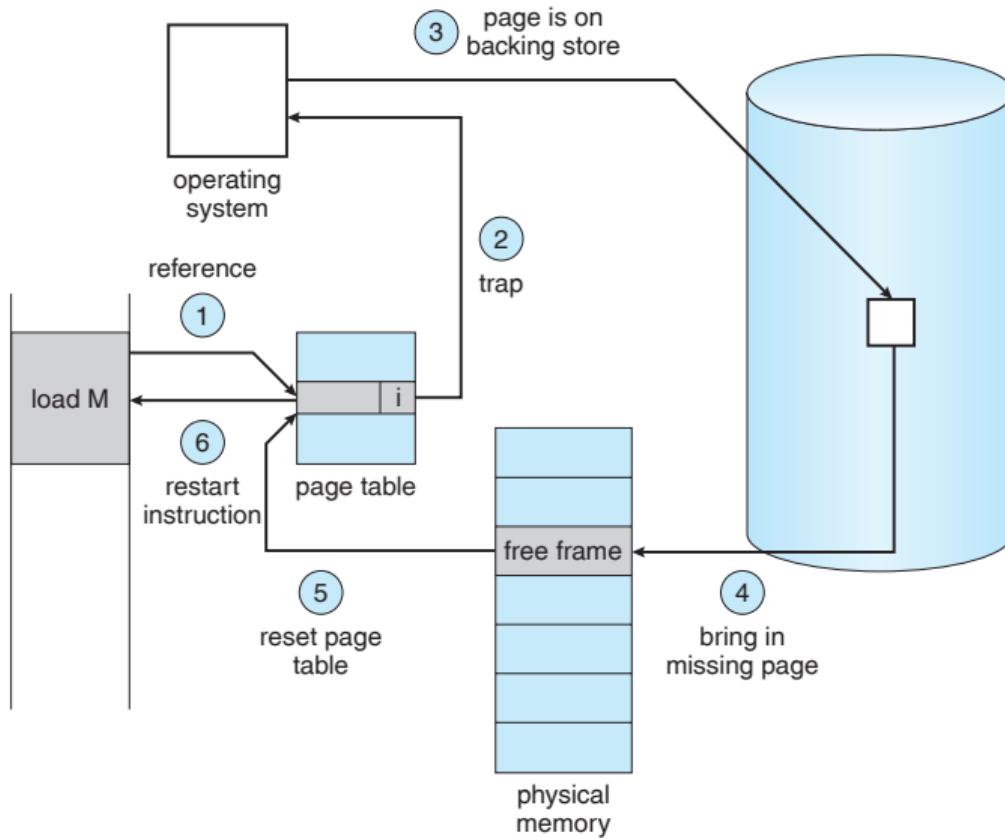
Virtual  
address  
space



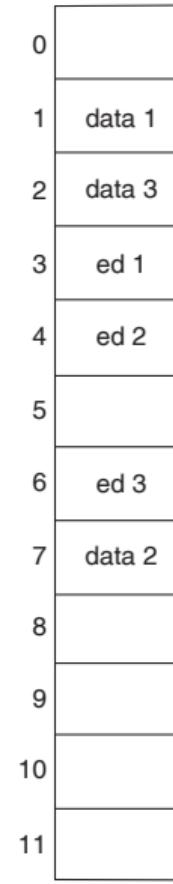
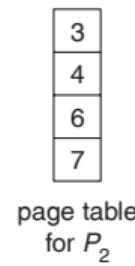
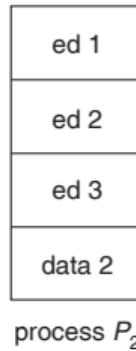
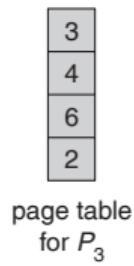
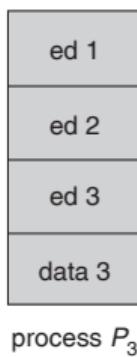
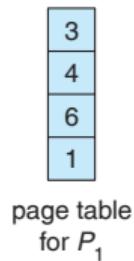
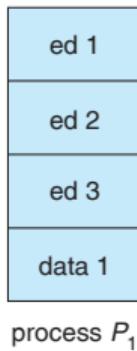
MOV REG, 32780?

➡ Page fault & swapping

# Page Fault Handling



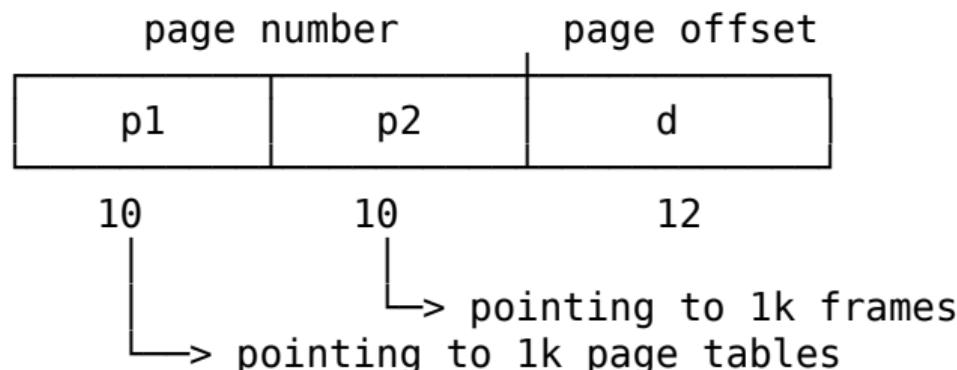
# Shared Pages



## Multilevel Page Tables

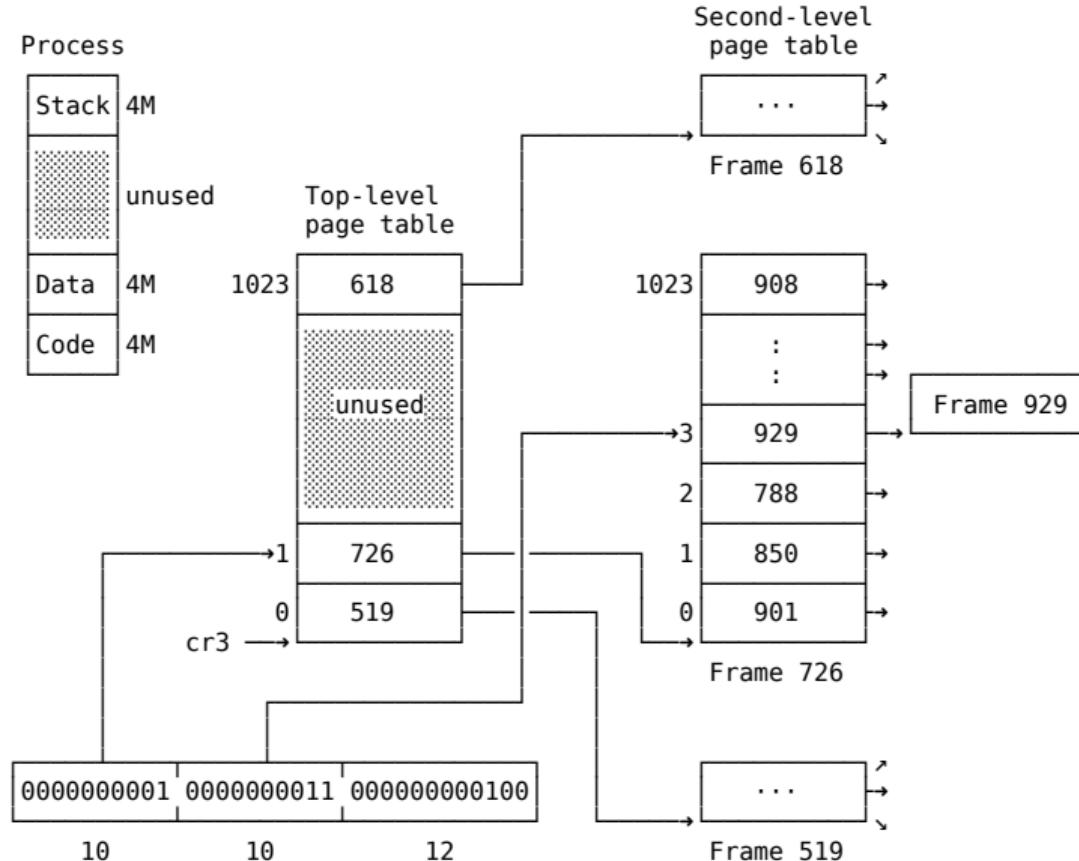
- ▶ a 1M-entry page table eats 4M memory
- ▶ while 100 processes running, 400M memory is gone for page tables
- ▶ avoid keeping all the page tables in memory all the time

### A two-level scheme



# Two-Level Page Tables

## Example



# Problem With 64-bit Systems

Given:

- ▶ virtual address space = 64 *bits*
- ▶ page size = 4 KB =  $2^{12}$  B

? How much space would a simple single-level page table take?

if Each page table entry takes 4 Bytes

then The whole page table ( $2^{64-12}$  entries) will take

$$2^{64-12} \times 4 \text{ B} = 2^{54} \text{ B} = 16 \text{ PB} \quad (\text{peta} \Rightarrow \text{tera} \Rightarrow \text{giga})!$$

And this is for ONE process!

Multi-level?

if 10 *bits* for each level

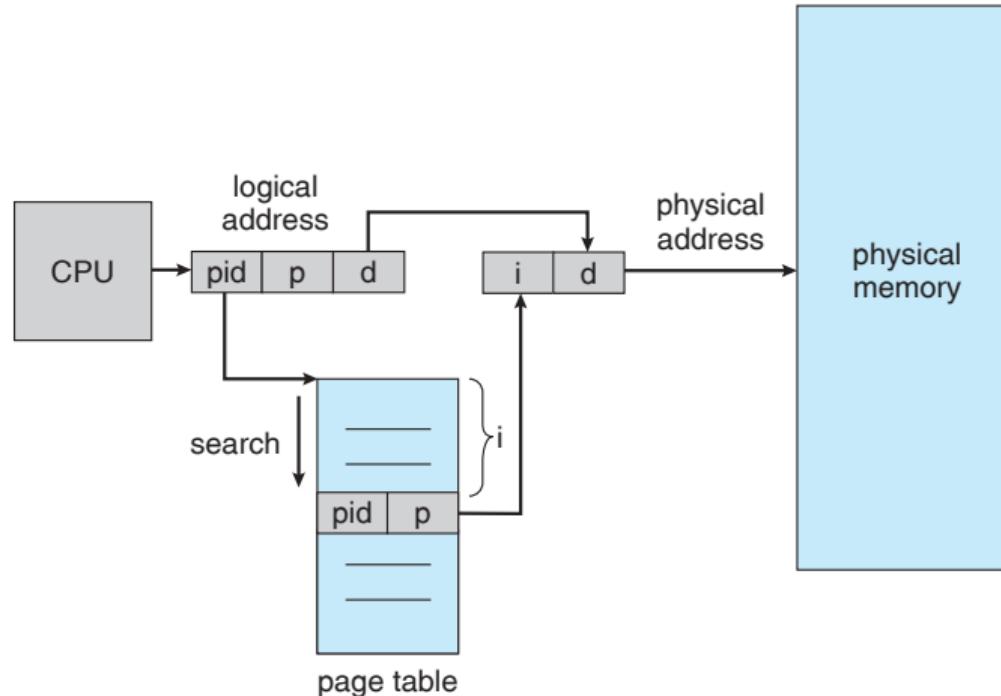
then  $\frac{64-12}{10} = 5$  levels are required

5 memory access for each address translation!

# Inverted Page Tables

Index with frame number

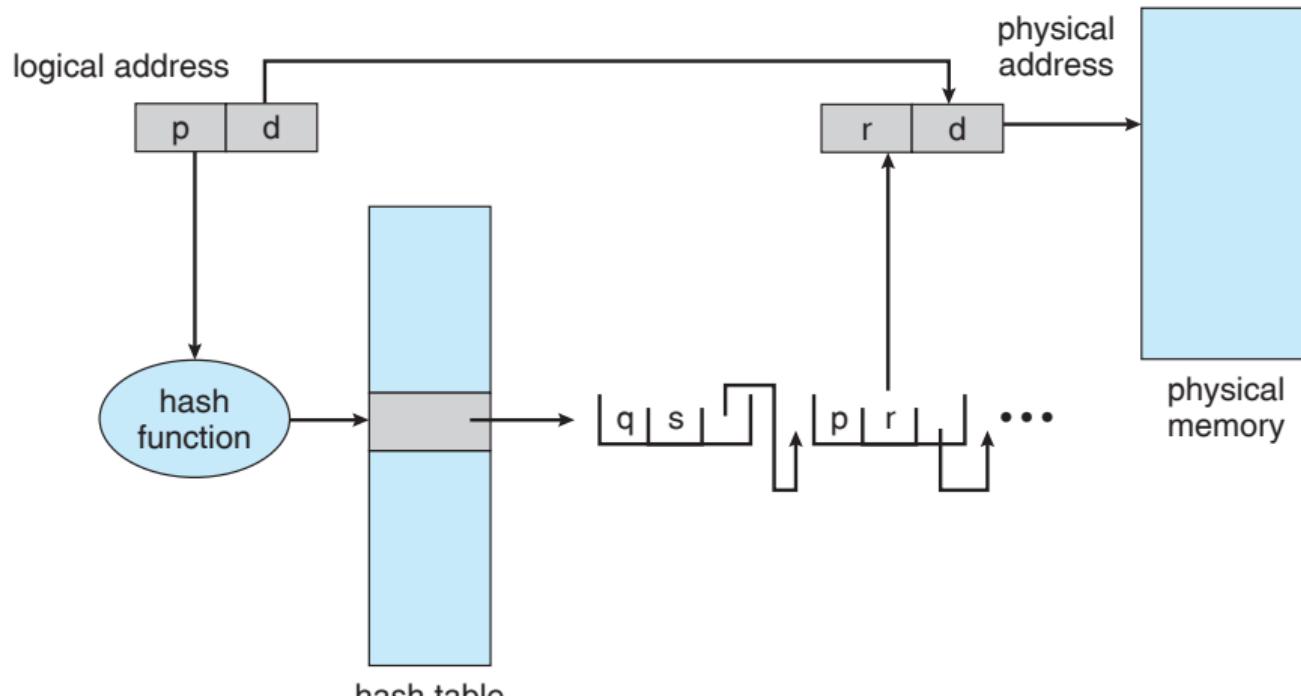
$(pid, p) \Rightarrow i$  Find index according to entry contents



# Hashed Inverted Page Tables

A hash anchor table — an extra level before the actual page table

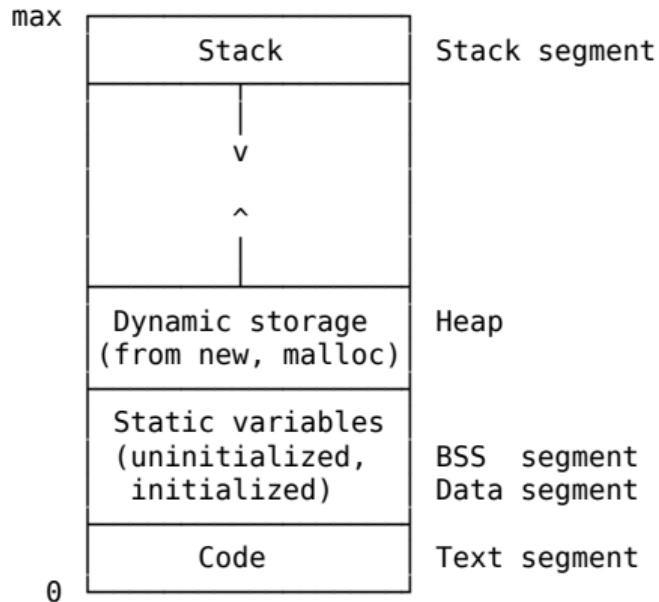
- ▶ maps virtual page numbers process IDs ⇒ page table entries
- ▶ Since collisions may occur, the page table must do chaining



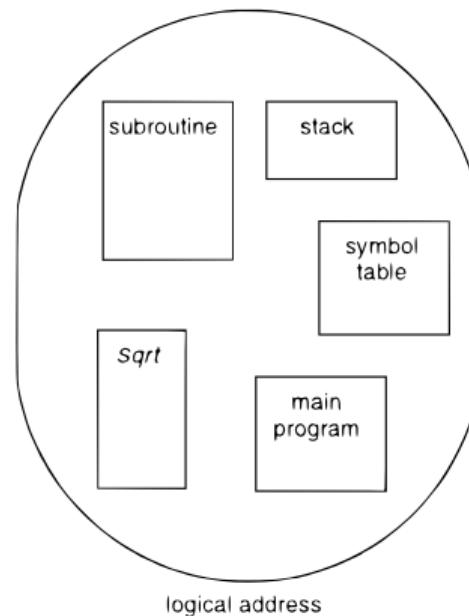
## 14.2 Segmentation

# Two Views of A Virtual Address Space

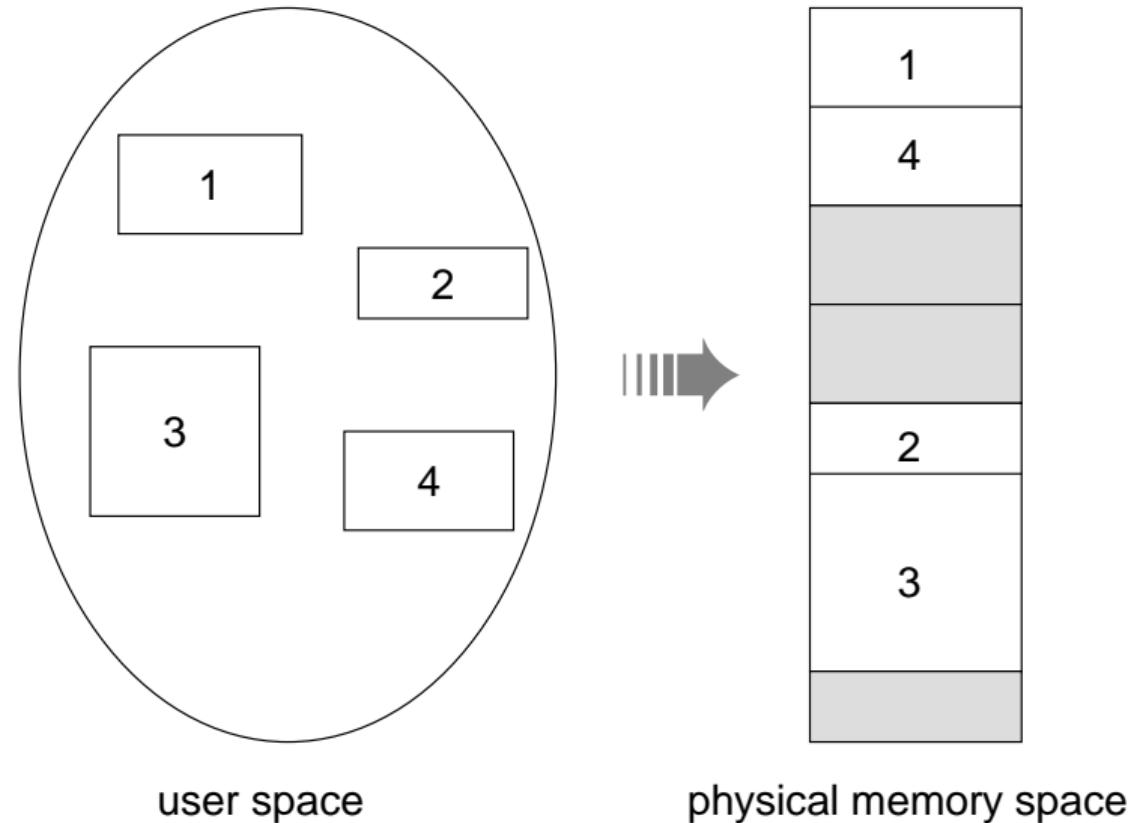
One-dimensional  
a linear array of bytes



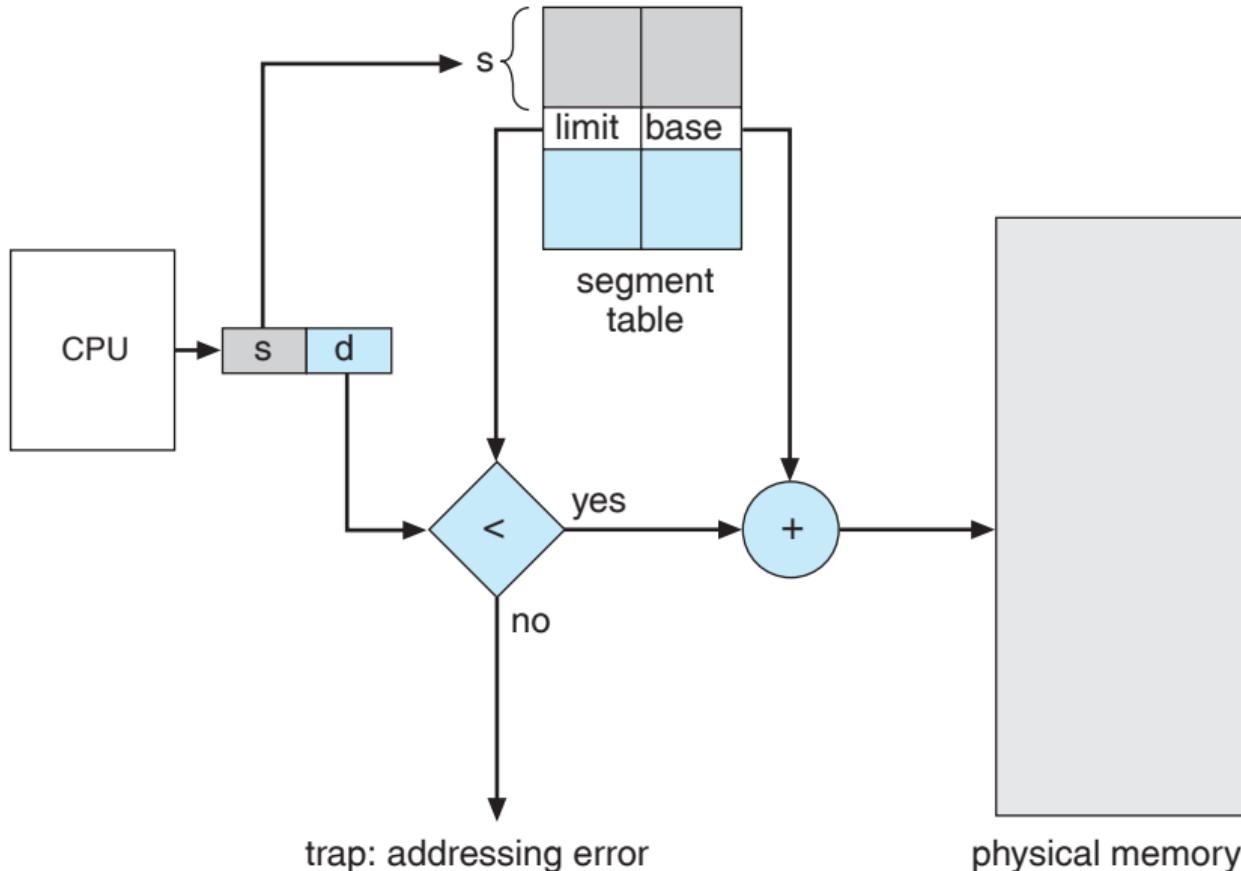
Two-dimensional  
a collection of variable-sized  
segments

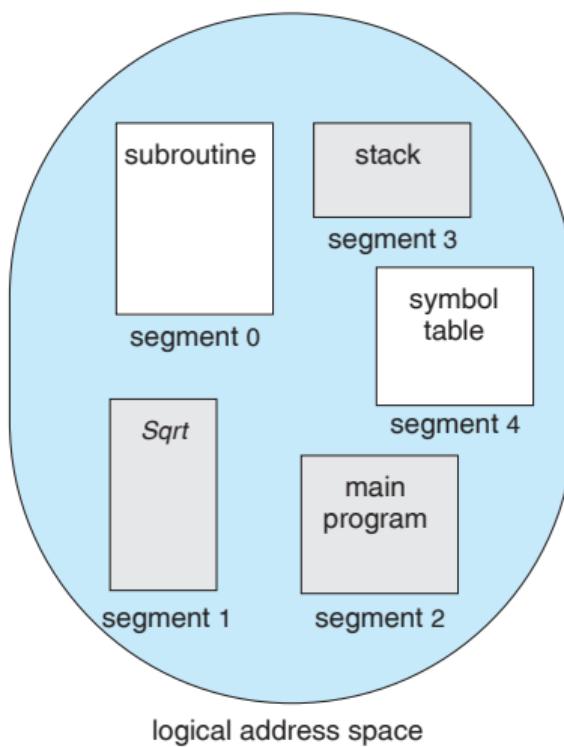


# Logical And Physical View of Segmentation



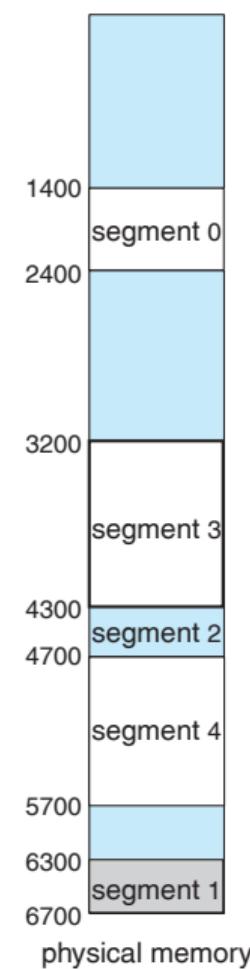
# Segmentation hardware





	limit	base
0	1000	1400
1	400	6300
2	400	4300
3	1100	3200
4	1000	4700

segment table



$$(2, 53) \Rightarrow 4300 + 53 = 4353$$

$$(3, 852) \Rightarrow 3200 + 852 = 4052$$

$$(0, 1222) \Rightarrow \text{Trap!}$$

## Advantages of Segmentation

- ▶ Each segment can be
  - ▶ located independently
  - ▶ separately protected
  - ▶ grow independently
- ▶ Segments can be shared between processes

## Problems with Segmentation

Variable allocation ⇒ Difficult to find holes in physical memory

- ▶ Must use one of non-trivial placement algorithm (first fit, best fit, worst fit)
- ▶ External fragmentation

## Linux prefers paging to segmentation

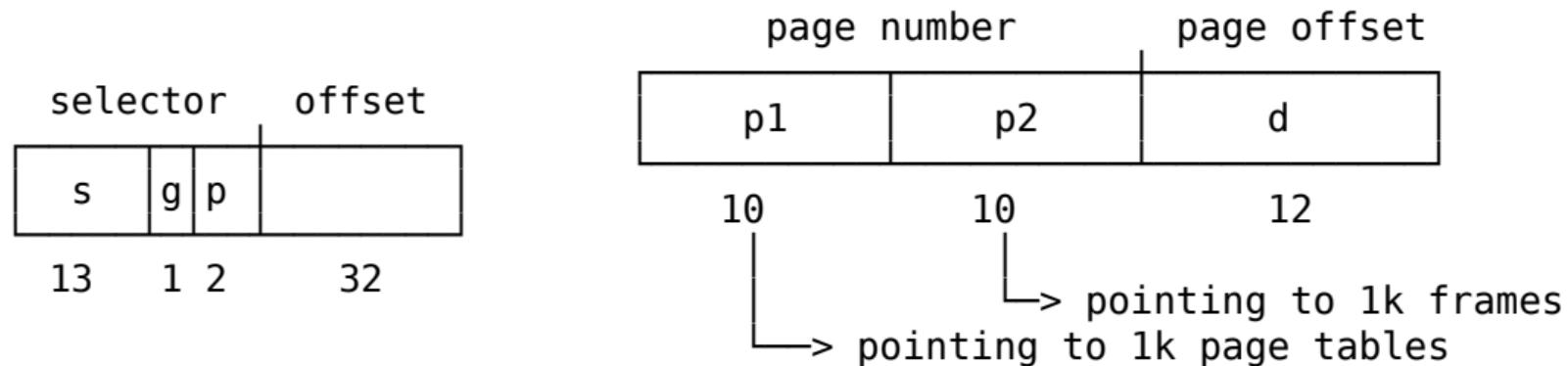
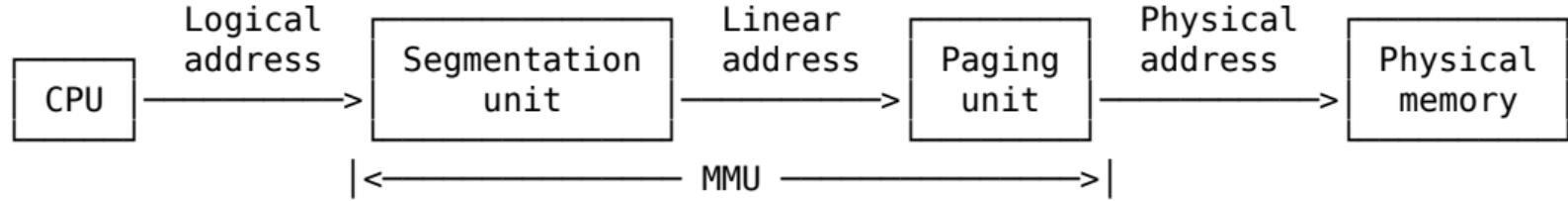
Because

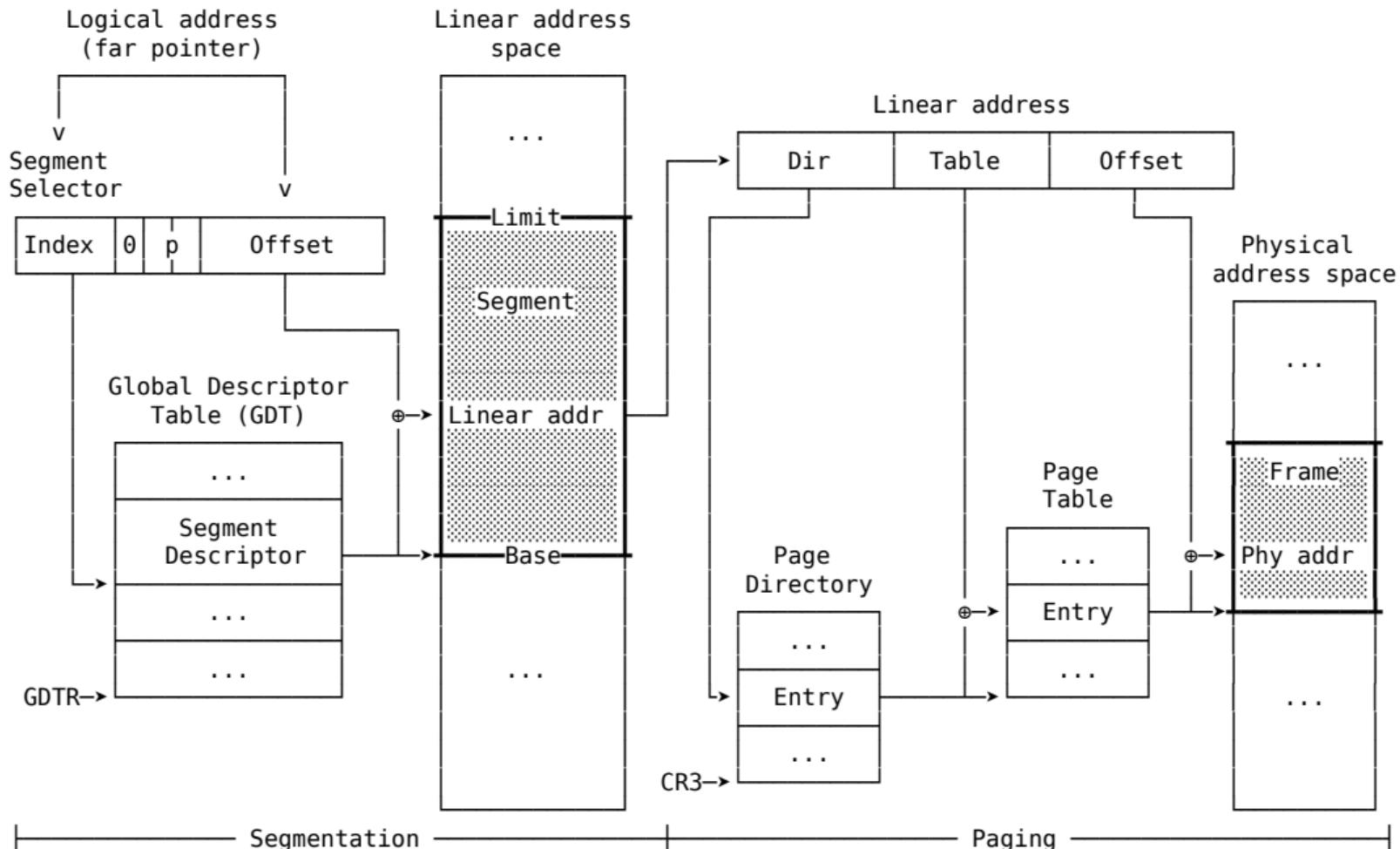
- ▶ Segmentation and paging are somewhat redundant
- ▶ Memory management is simpler when all processes share the same set of linear addresses
- ▶ Maximum portability. RISC architectures in particular have limited support for segmentation

The Linux 2.6 uses segmentation only when required by the 80x86 architecture.

# Case Study: The Intel Pentium

## Segmentation With Paging





# Segment Selector

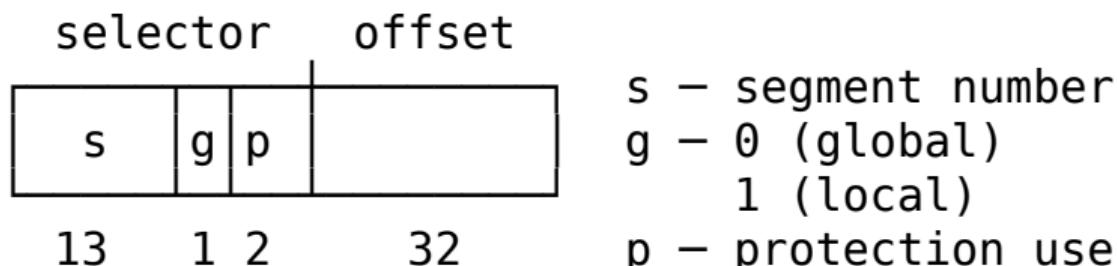
A logical address consists of two parts

Segment selector:Offset

16 bits

32 bits

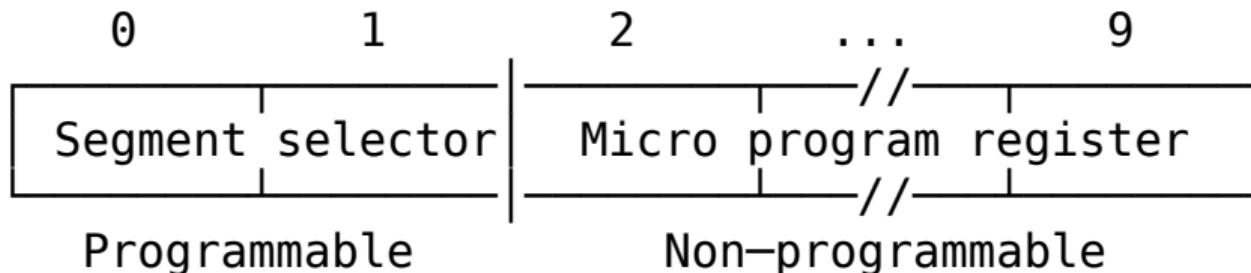
Segment selector is an index into GDT/LDT



# Segment Registers

The Intel Pentium has

- ▶ 6 segment registers, allowing 6 segments to be addressed at any one time by a process
  - ▶ Each segment register → an entry in LDT/GDT
- ▶ 6 8-byte micro program registers to hold descriptors from either LDT or GDT
  - ▶ avoid having to read the descriptor from memory for every memory reference



## Segment registers hold segment selectors

cs code segment register

CPL 2-bit, specifies the Current Privilege Level of the CPU

00 - Kernel mode

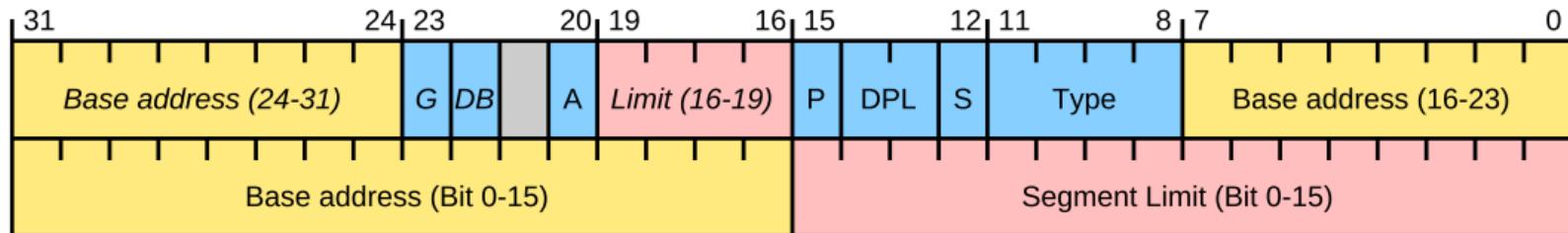
11 - User mode

ss stack segment register

ds data segment register

es/fs/gs general purpose registers, may refer to arbitrary data segments

## Example: A LDT entry for code segment



**Base:** Where the segment starts

**G:** Granularity flag  
0 - seg size in bytes  
1 - in 4096 bytes

**D/B:** 0 - 16-bit seg  
1 - 32-bit seg

**DPL:** Descriptor Privilege Level. 0 or 3

**AVL:** ignored by Linux

**Limit:** 20 bit,  $\Rightarrow 2^{20}$  in size

**S:** System flag  
0 - system seg, e.g. LDT  
1 - normal code/data seg

**Type:** seg type (cs/ds/tss)

**P:** Seg-Present flag  
0 - not in memory  
1 - in memory

# The Four Main Linux Segments

Every process in Linux has these 4 segments

Segment	Base	G	Limit	S	Type	DPL	D/B	P
user code	0x00000000	1	0xfffffff	1	10	3	1	1
user data	0x00000000	1	0xfffffff	1	2	3	1	1
kernel code	0x00000000	1	0xfffffff	1	10	0	1	1
kernel data	0x00000000	1	0xfffffff	1	2	0	1	1

- ▶ All processes share the same set of linear addresses
- ▶ Logical addresses coincide with linear addresses

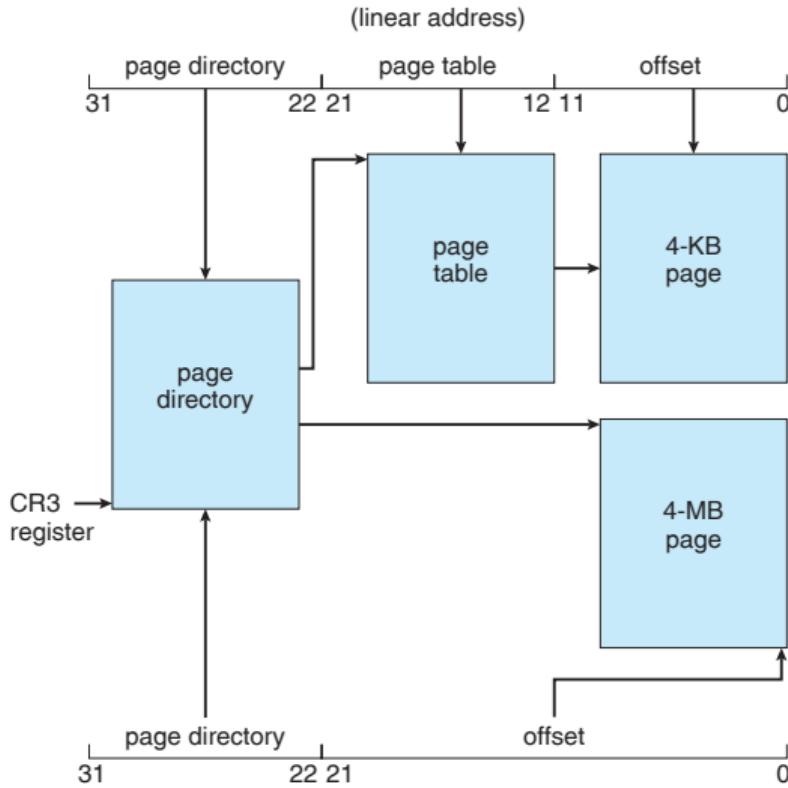
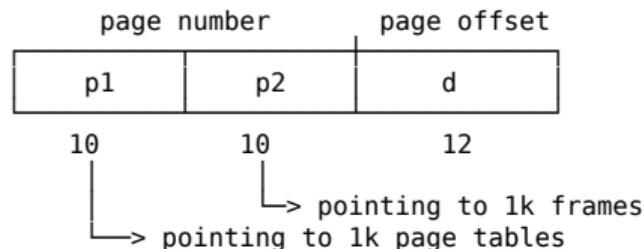
# Pentium Paging

Linear Address  $\Rightarrow$  Physical Address

Two page size in Pentium:

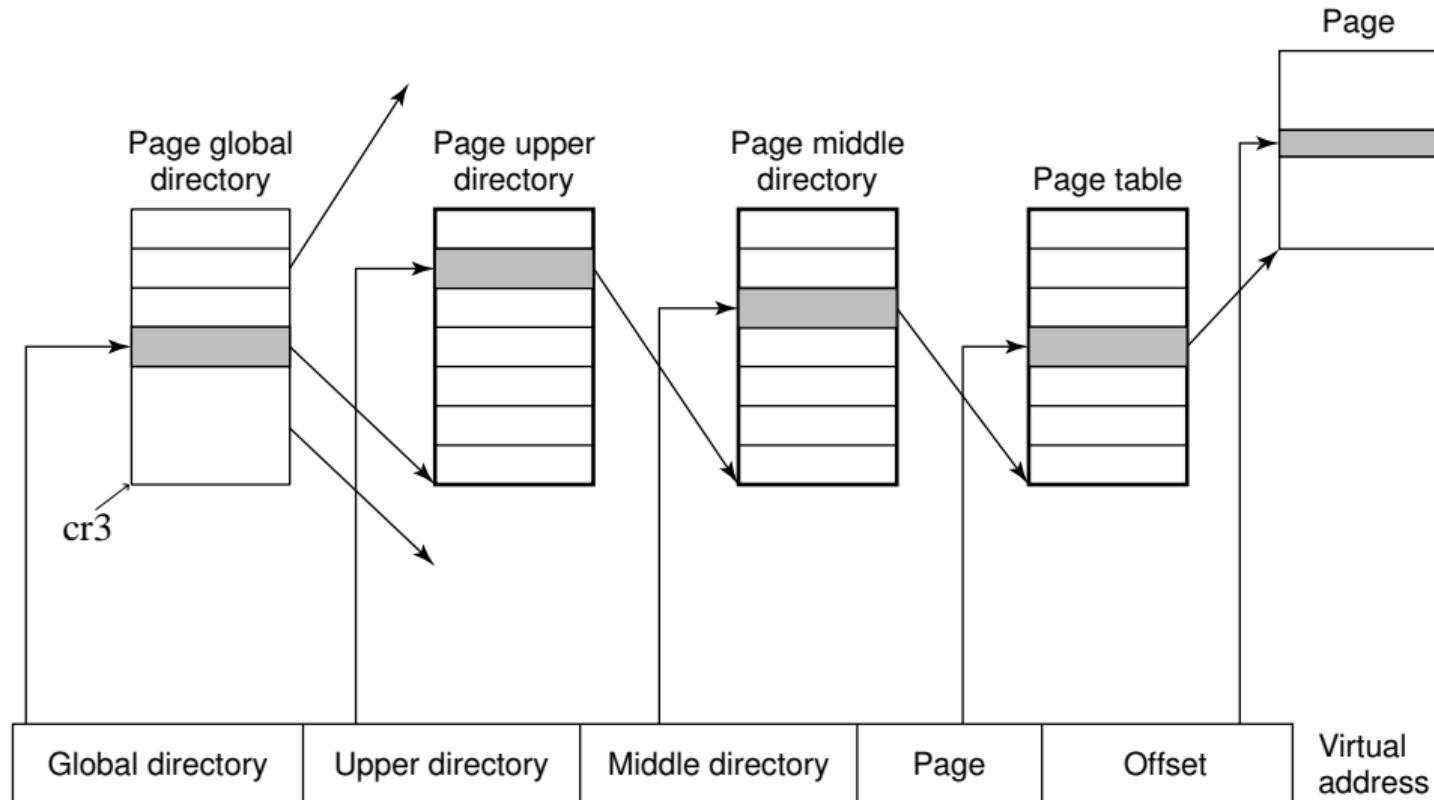
4K: 2-level paging

4M: 1-level paging



# Paging In Linux

4-level paging for both 32-bit and 64-bit



## 4-Level Paging For Both 32-Bit And 64-Bit

The same code can work on both 32-bit and 64-bit architectures

### 64-bit: 4-level paging

1. Page Global Directory
2. Page Upper Directory
3. Page Middle Directory
4. Page Table

### 32-bit: 2-level paging

1. Page Global Directory
2. Page Upper Directory — 0 bits; 1 entry
3. Page Middle Directory — 0 bits; 1 entry
4. Page Table

Arch	Page size	Address bits	Paging levels	Address splitting
x86	4KB(12bits)	32	2	10 + 0 + 0 + 10 + 12
x86-PAE	4KB(12bits)	32	3	2 + 0 + 9 + 9 + 12
x86-64	4KB(12bits)	48	4	9 + 9 + 9 + 9 + 12

## 14.3 Demand Paging

# Demand Paging

With demand paging, the size of the LAS is no longer constrained by physical memory

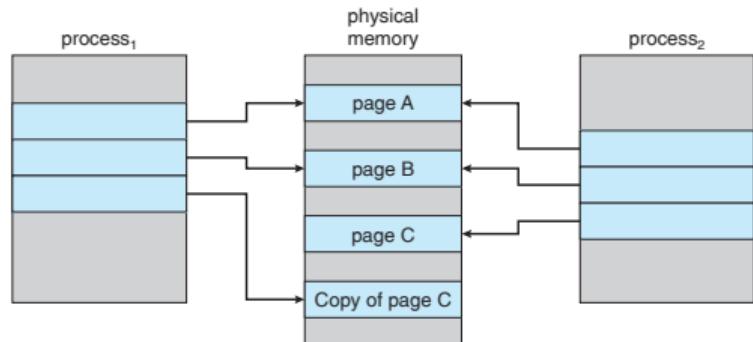
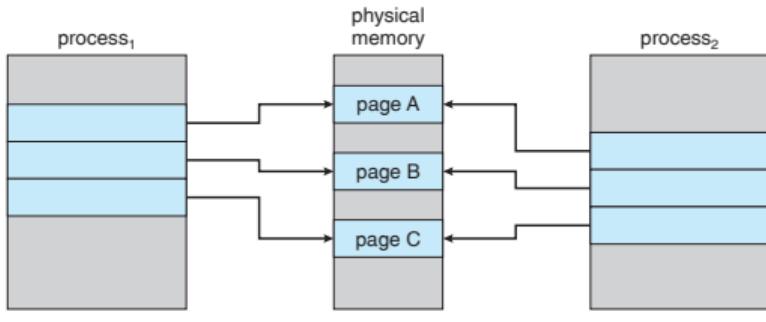
- ▶ Bring a page into memory only when it is needed
  - 😊 Less I/O needed
  - 😊 Less memory needed
  - 😊 Faster response
  - 😊 More users
- ▶ When page is needed (referenced)
  - ▶ invalid reference ⇒ abort
  - ▶ not-in-memory ⇒ bring to memory

## 14.4 Copy-on-Write

# Copy-on-Write

More efficient process creation

- ▶ Parent and child processes initially share the same pages in memory
- ▶ Only the modified page is copied upon modification occurs
- ▶ Free pages are allocated from a *pool* of zeroed-out pages

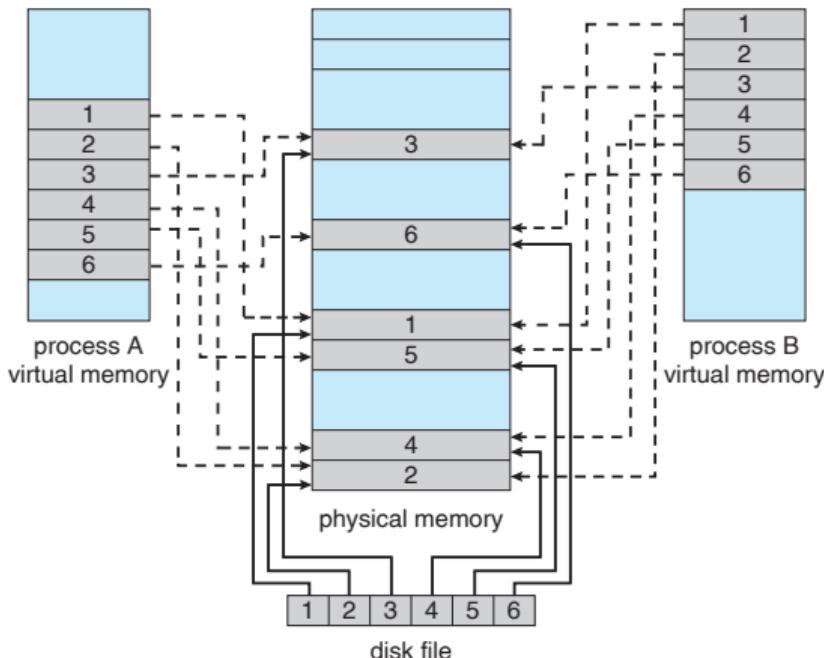


## 14.5 Memory mapped files

# Memory Mapped Files

Mapping a file (disk block) to one or more memory pages

- ▶ Improved I/O performance — much faster than `read()` and `write()` system calls
- ▶ Lazy loading (demand paging) — only a small portion of file is loaded initially
- ▶ A mapped file can be shared, like *shared library*



## 14.6 Page Replacement Algorithms

# Page Replacement

## Performance Concern

Because disk I/O is so expensive, we must solve two major problems to implement demand paging.

**Frame-allocation algorithm** If we have multiple processes in memory, we must decide how many frames to allocate to each process.

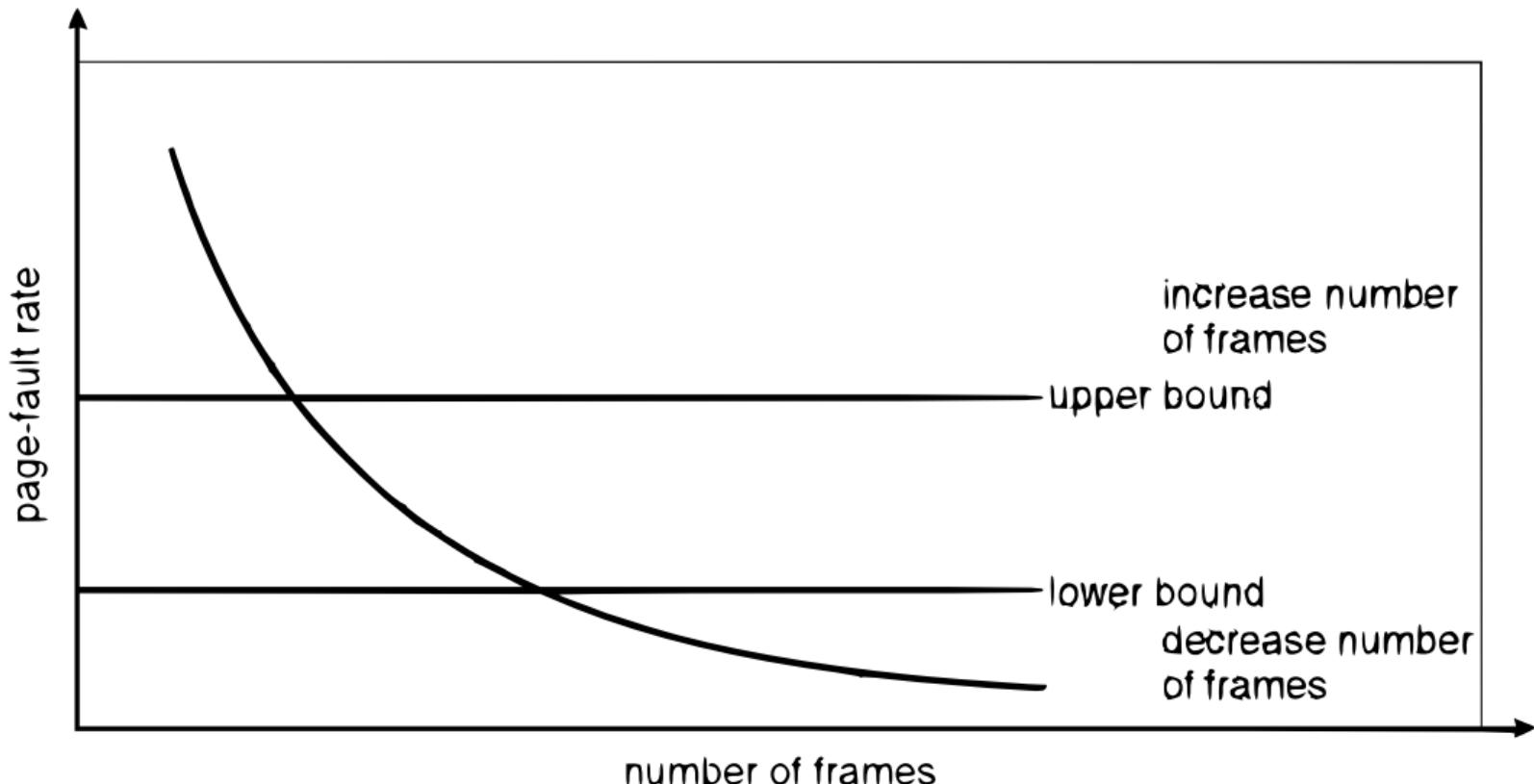
**Page-replacement algorithm** When page replacement is required, we must select the frames that are to be replaced.

We want an algorithm resulting in lowest page-fault rate

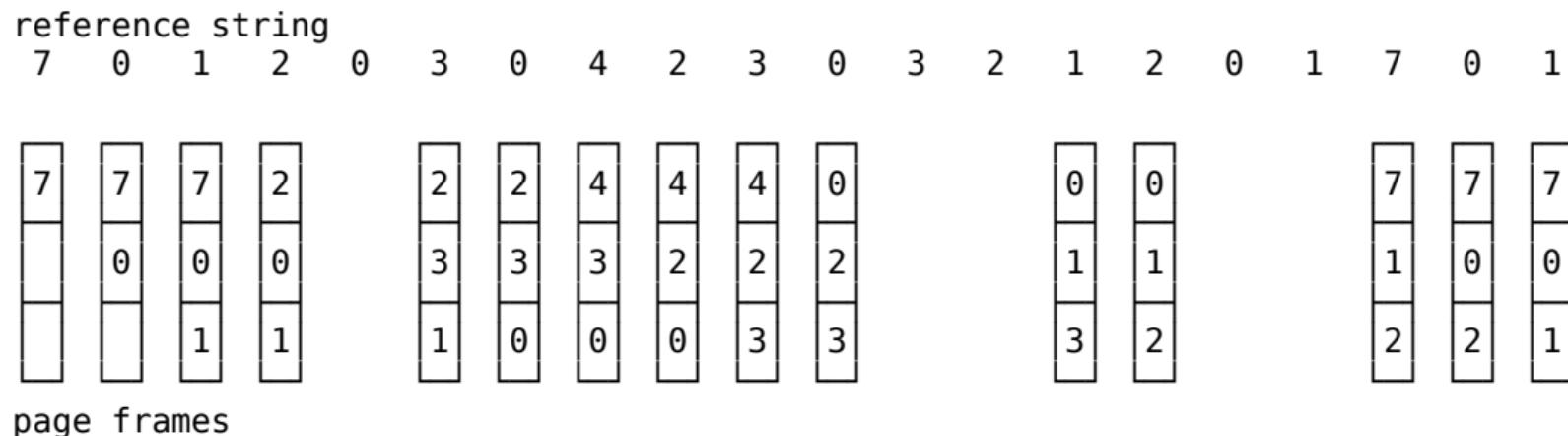
- ? Is the victim page modified?
- ? Pick a random page to swap out?
- ? Pick a page from the faulting process' own pages? Or from others?

# Page-Fault Frequency Scheme

Establish "acceptable" page-fault rate



# FIFO Page Replacement Algorithm



- ▶ Maintain a linked list (FIFO queue) of all pages
  - ▶ in order they came into memory
- ▶ Page at beginning of list replaced
- ▶ Disadvantage
  - ▶ The oldest page may be often used
  - ▶ Belady's anomaly

# FIFO Page Replacement Algorithm

## Belady's Anomaly

- ▶ Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- ▶ 3 frames (3 pages can be in memory at a time per process)

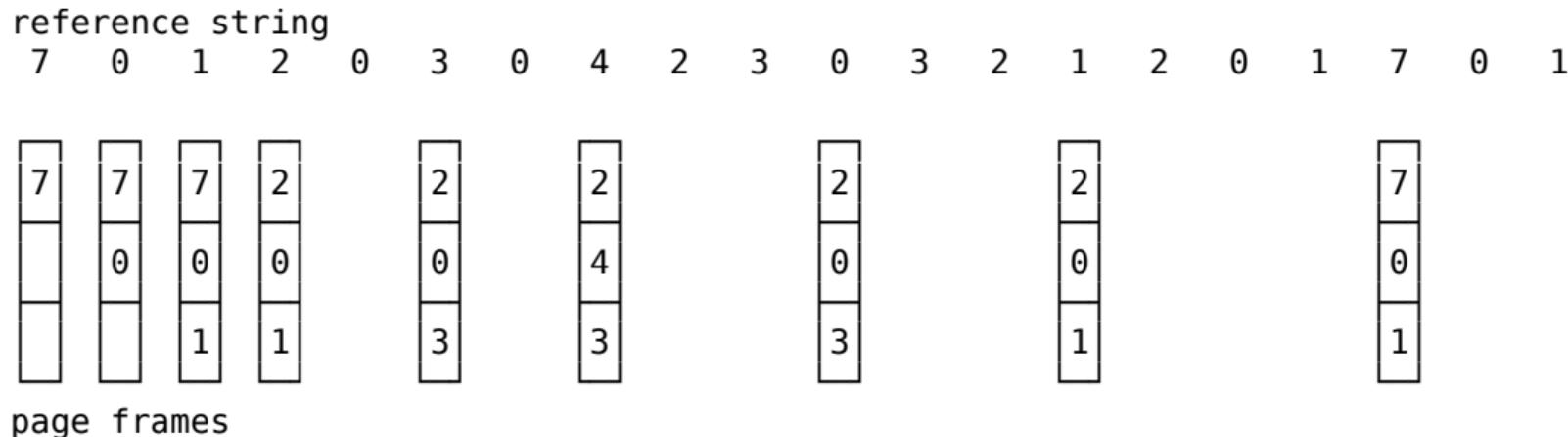
1	4	5	3	
2	1	<del>1</del>	4	9 page faults
3	2	<del>2</del>	<del>5</del>	

- ▶ 4 frames

1	<del>1</del>	2	
2	<del>2</del>	3	10 page faults
3	5	4	
4	1	5	

- ▶ Belady's Anomaly: more frames  $\Rightarrow$  more page faults

# Optimal Page Replacement Algorithm (OPT)



- ▶ Replace page needed at the farthest point in future
  - ▶ Optimal but not feasible
- ▶ Estimate by ...
  - ▶ logging page use on previous runs of process
  - ▶ although this is impractical, similar to SJF CPU-scheduling, it can be used for comparison studies

# Least Recently Used (LRU) Algorithm

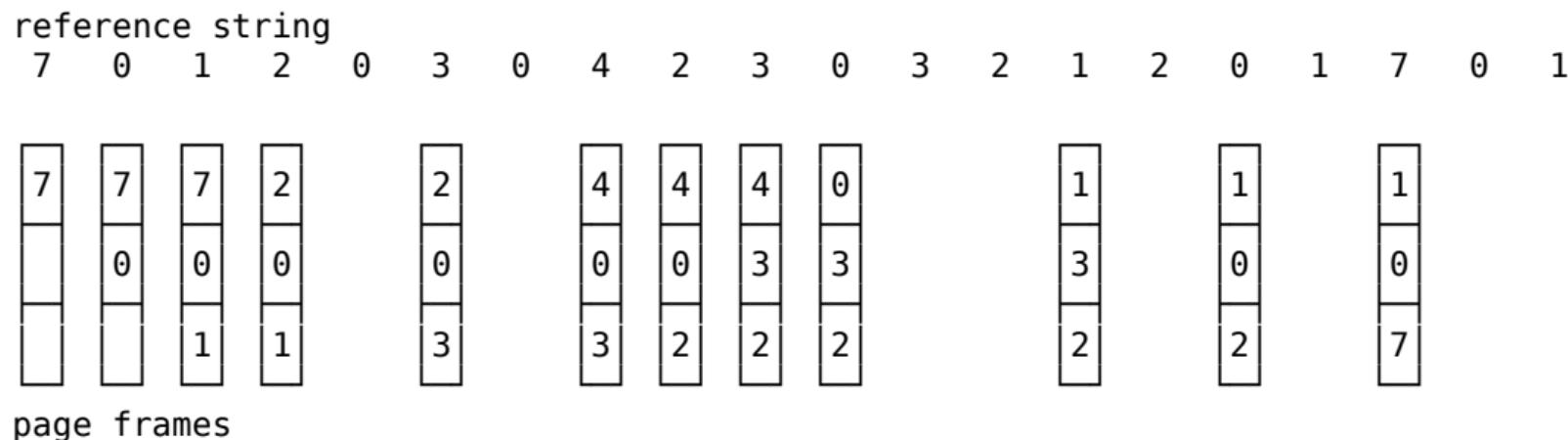
FIFO uses the time when a page was brought into memory

OPT uses the time when a page is to be used

LRU uses the recent past as an approximation of the near future

Replace the page that *has not been used* for the longest period of time

Assume recently-used-pages will be used again soon



# LRU Implementations

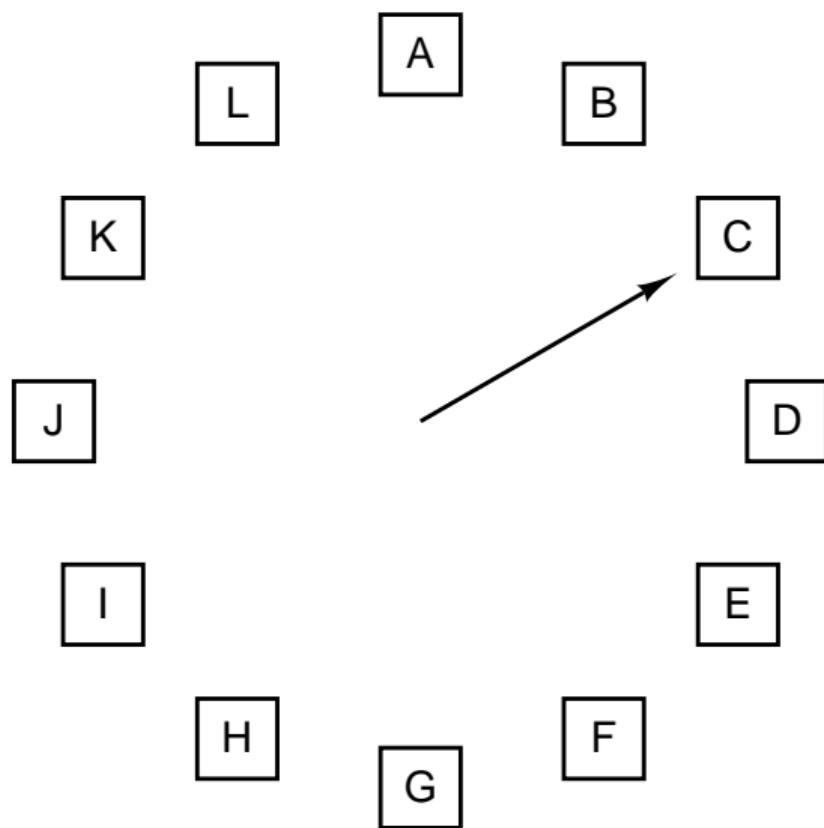
Counters: record the time of the last reference to each page

- ▶ choose page with lowest value counter
- ▶ Keep counter in each page table entry
- ▶ counter overflow — periodically zero the counter
- ▶ require a search of the page table to find the LRU page
- ▶ update time-of-use field in the page table every memory reference!

Stack: keep a linked list (stack) of pages

- ▶ most recently used at top, least (LRU) at bottom
  - ▶ no search for replacement
- ▶ whenever a page is referenced, it's removed from the stack and put on the top
  - ▶ update this list every memory reference!

## Second Chance Page Replacement Algorithm



When a page fault occurs,  
the page the hand is  
pointing to is inspected.  
The action taken depends  
on the R bit:

R = 0: Evict the page

R = 1: Clear R and advance hand

## 14.7 Allocation of Frames

## Allocation of Frames

- ▶ Each process needs minimum number of pages
- ▶ Fixed Allocation
  - ▶ Equal allocation — e.g., 100 frames and 5 processes, give each process 20 frames.
  - ▶ Proportional allocation — Allocate according to the size of process

$$a_i = \frac{s_i}{\sum s_i} \times m$$

$s_i$ : size of process  $p_i$

$m$ : total number of frames

$a_i$ : frames allocated to  $p_i$

- ▶ Priority Allocation — Use a proportional allocation scheme using priorities rather than size

$$\frac{\text{priority}_i}{\sum \text{priority}_i} \quad \text{or} \quad \left( \frac{s_i}{\sum s_i}, \frac{\text{priority}_i}{\sum \text{priority}_i} \right)$$

## Global vs. Local Allocation

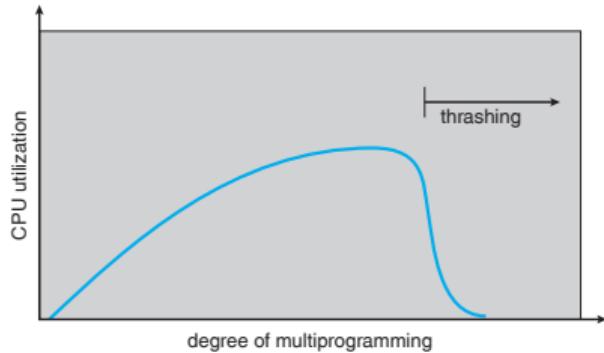
If process  $P_i$  generates a page fault, it can select a replacement frame

- ▶ from its own frames — **Local replacement**
- ▶ from the set of all frames; one process can take a frame from another — **Global replacement**
  - ▶ from a process with lower priority number

**Global replacement generally results in greater system throughput.**

## 14.8 Thrashing And Working Set Model

# Thrashing



1. CPU not busy  $\Rightarrow$  add more processes
2. a process needs more frames  $\Rightarrow$  faulting, and taking frames away from others
3. these processes also need these pages  $\Rightarrow$  also faulting, and taking frames away from others  $\Rightarrow$  chain reaction
4. more and more processes queueing for the paging device  $\Rightarrow$  ready queue is empty  $\Rightarrow$  CPU has nothing to do  $\Rightarrow$  add more processes  $\Rightarrow$  more page faults
5. MMU is busy, but no work is getting done, because processes are busy paging — **thrashing**

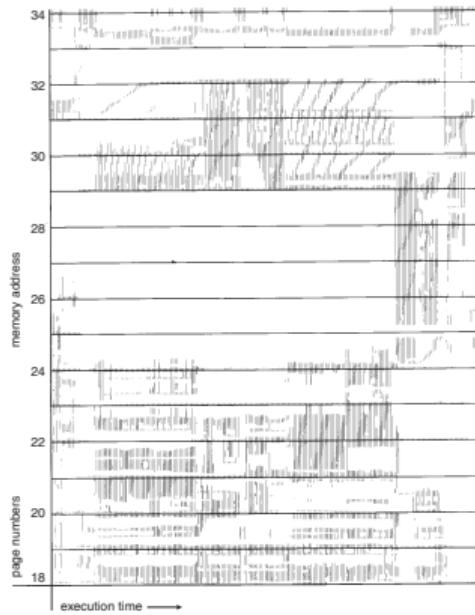
# Demand Paging and Thrashing

## Locality Model

- ▶ A **locality** is a set of pages that are actively used together
- ▶ Process migrates from one locality to another

Why does thrashing occur?

$$\sum_{i=(0,n)} Locality_i > \text{total memory size}$$

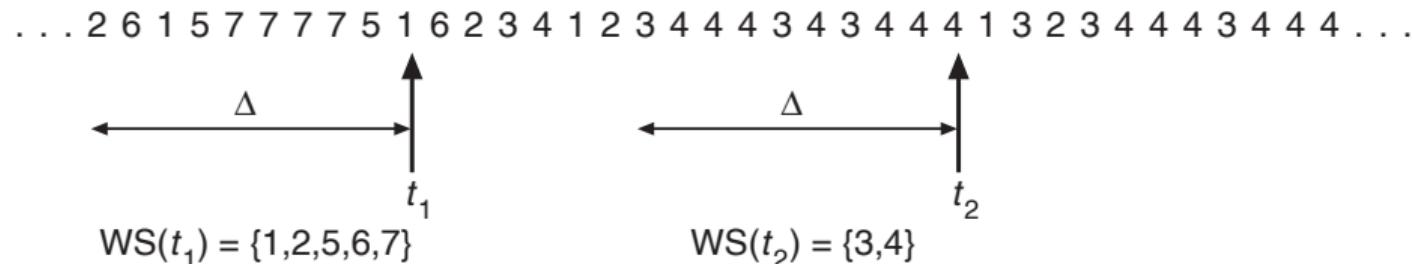


locality in a memory reference pattern

# Working-Set Model

**Working Set (WS)** The set of pages that a process is currently( $\Delta$ ) using.  
( $\approx$  locality)

page reference table



$\Delta$ : Working-set window. In this example,

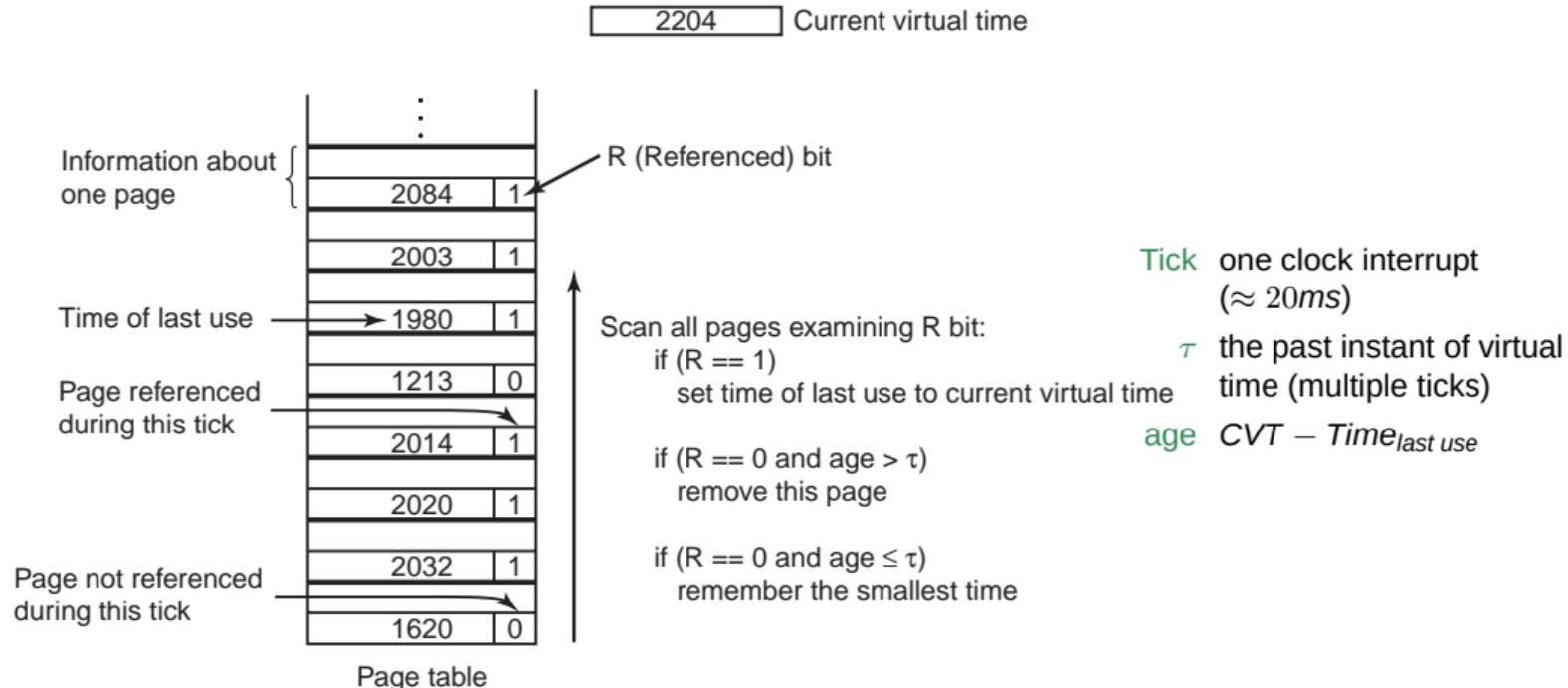
$$\Delta = 10 \text{ memory access}$$

**WSS:** Working-set size.  $WS(t_1) = \overbrace{\{1, 2, 5, 6, 7\}}^{WSS=5}$

- ▶ The accuracy of the working set depends on the selection of  $\Delta$
- ▶ Thrashing if  $\sum WSS_i > SIZE_{total\ memory}$

# The Working-Set Page Replacement Algorithm

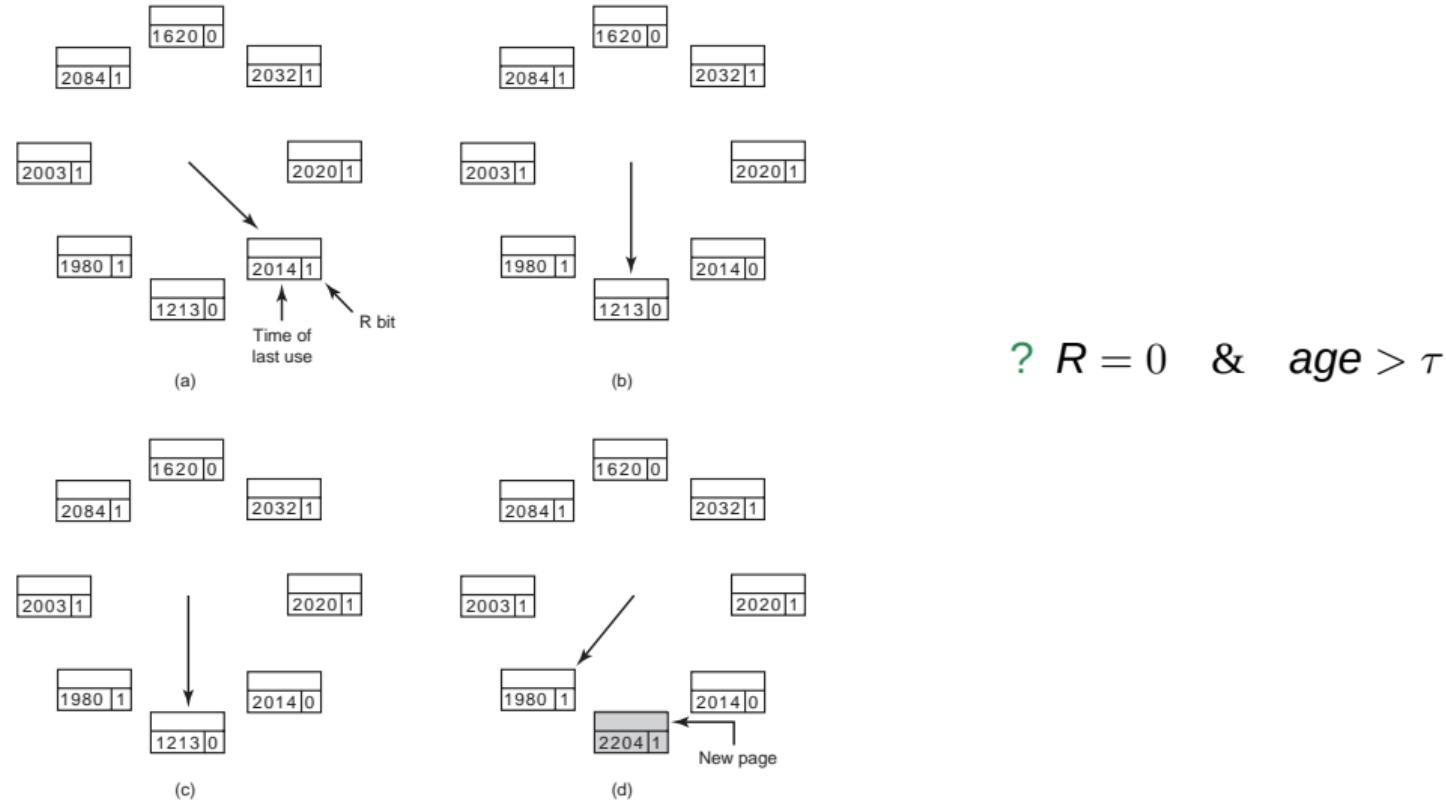
Evict a page not in the working set



# The WSClock Page Replacement Algorithm

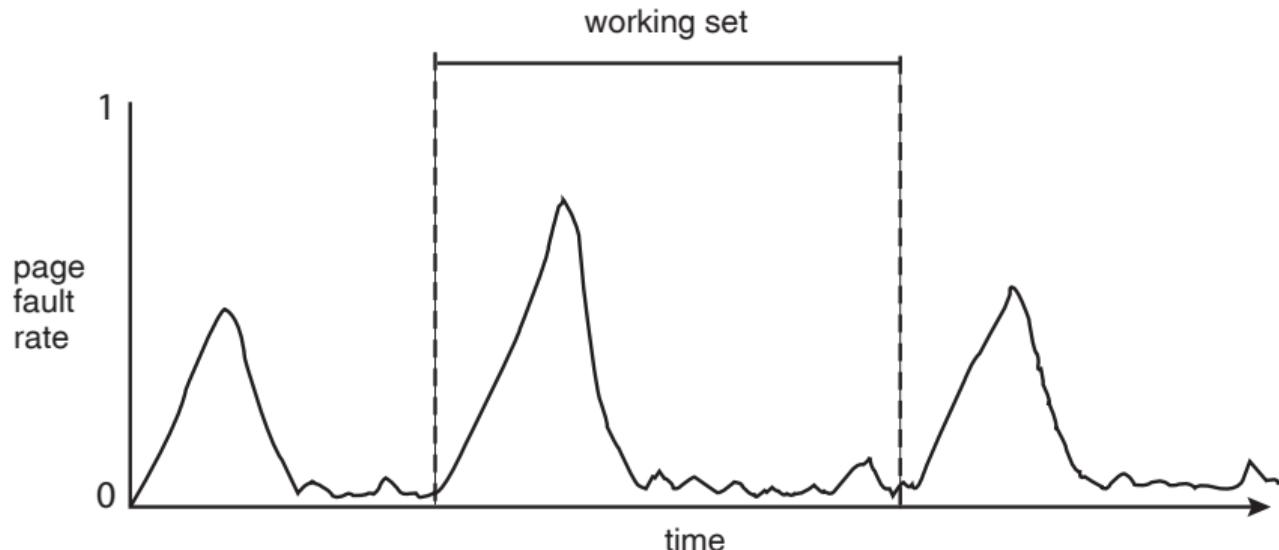
Combine Working Set Algorithm With Clock Algorithm

2204 Current virtual time



## 14.9 Other Issues

## Other Issues — Prepaging



- ▶ reduce faulting rate at (re)startup
  - ▶ remember working-set in PCB
- ▶ Not always work
  - ▶ if prepaged pages are unused, I/O and memory was wasted

## Other Issues — Page Size

Larger page size

- (⌚) Bigger internal fragmentation
- (⌚) longer I/O time

Smaller page size

- (⌚) Larger page table
- (⌚) more page faults
  - ▶ one page fault for each byte, if page size = 1 Byte
  - ▶ for a 200K process, with page size = 200K, only one page fault

No best answer

```
$ getconf PAGESIZE
```

## Other Issues — TLB Reach

- ▶ Ideally, the working set of each process is stored in the TLB
  - ▶ Otherwise there is a high degree of page faults
- ▶ **TLB Reach** — The amount of memory accessible from the TLB

$$TLB\ Reach = (TLB\ Size) \times (Page\ Size)$$

- ▶ Increase the page size
  - Internal fragmentation may be increased
- ▶ Provide multiple page sizes
  - ▶ This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation
    - ▶ UltraSPARC supports page sizes of 8KB, 64KB, 512KB, and 4MB
    - ▶ Pentium supports page sizes of 4KB and 4MB

## Other Issues — Program Structure

Careful selection of data structures and programming structures can increase locality, i.e. lower the page-fault rate and the number of pages in the working set.

### Example

- ▶ A stack has a good locality, since access is always made to the top
- ▶ A hash table has a bad locality, since it's designed to scatter references
- ▶ Programming language
  - ▶ Pointers tend to randomize access to memory
  - ▶ OO programs tend to have a poor locality

# Other Issues — Program Structure

## Example

- ▶ `int[i][j] = int[128][128]`
- ▶ Assuming page size is 128 words, then
- ▶ Each row (128 words) takes one page

If the process has fewer than 128 frames...

### Program 1:

```
1  for(j=0;j<128;j++)  
2      for(i=0;i<128;i++)  
3          data[i][j] = 0;
```

Worst case:

$$128 \times 128 = 16,384 \text{ page faults}$$

### Program 2:

```
1  for(i=0;i<128;i++)  
2      for(j=0;j<128;j++)  
3          data[i][j] = 0;
```

Worst case:

$$128 \text{ page faults}$$

## Other Issues — I/O interlock

Sometimes it is necessary to lock pages in memory so that they are not paged out.

### Example

- ▶ The OS
- ▶ I/O operation — the frame into which the I/O device was scheduled to write should not be replaced.
- ▶ New page that was just brought in — looks like the best candidate to be replaced because it was not accessed yet, nor was it modified.

## Other Issues — I/O interlock

### Case 1

Be sure the following sequence of events does not occur:

1. A process issues an I/O request, and then queueing for that I/O device
2. The CPU is given to other processes
3. These processes cause page faults
4. The waiting process' page is unluckily replaced
5. When its I/O request is served, the specific frame is now being used by another process

## Other Issues — I/O interlock

### Case 2

Another bad sequence of events:

1. A low-priority process faults
2. The paging system selects a replacement frame. Then, the necessary page is loaded into memory
3. The low-priority process is now ready to continue, and waiting in the ready queue
4. A high-priority process faults
5. The paging system looks for a replacement
  - 5.1 It sees a page that is in memory but not been referenced nor modified: perfect!
  - 5.2 It doesn't know the page is just brought in for the low-priority process

## References

- [1] Wikipedia. *Memory management — Wikipedia, The Free Encyclopedia*. 2015.  
[http://en.wikipedia.org/w/index.php?title=Memory%5C\\_management&oldid=647917932](http://en.wikipedia.org/w/index.php?title=Memory%5C_management&oldid=647917932).
- [2] Wikipedia. *Virtual memory — Wikipedia, The Free Encyclopedia*. 2015.  
[http://en.wikipedia.org/w/index.php?title=Virtual%5C\\_memory&oldid=644430956](http://en.wikipedia.org/w/index.php?title=Virtual%5C_memory&oldid=644430956).

# Part IV

## File Systems

## 15 File System Structure

## Long-term Information Storage Requirements

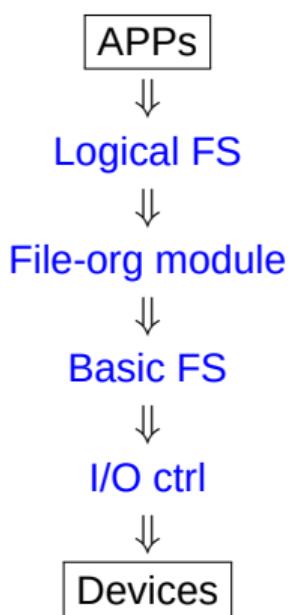
- ▶ Must store large amounts of data
- ▶ Information stored must survive the termination of the process using it
- ▶ Multiple processes must be able to access the information concurrently

# File-System Structure

File-system design addressing two problems:

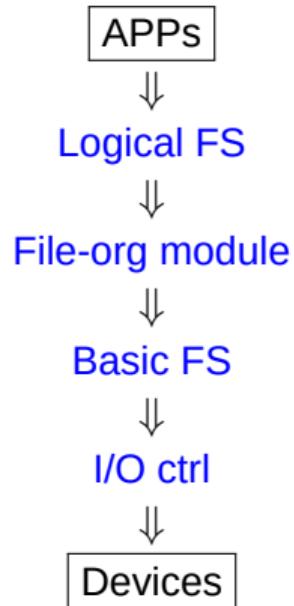
1. defining how the FS should look to the user
  - ▶ defining a file and its attributes
  - ▶ the operations allowed on a file
  - ▶ directory structure
2. creating algorithms and data structures to map the logical FS onto the physical disk

# File-System — A Layered Design



- ▶ **logical file system** — manages metadata information
  - maintains all of the file-system structure (directory structure, FCB)
  - responsible for protection and security
- ▶ **file-organization module**
  - logical block  $\xrightarrow{\text{translate}}$  physical block
    - address address
  - keeps track of free blocks
- ▶ **basic file system** issues generic commands to device driver, e.g
  - “read drive 1, cylinder 72, track 2, sector 10”
- ▶ **I/O Control** — device drivers, and INT handlers
  - **device driver:** high-level  $\xrightarrow{\text{translate}}$  hardware-specific commands

# The Operating Structure



## Example — To create a file

1. APP calls `creat()`
2. Logical FS
  - 2.1 allocates a new FCB
  - 2.2 updates the in-mem dir structure
  - 2.3 writes it back to disk
  - 2.4 calls the file-org module
3. file-organization module
  - 3.1 allocates blocks for storing the file's data
  - 3.2 maps the directory I/O into disk-block numbers

## Benefit of layered design

The I/O control and sometimes the basic file system code can be used by multiple file systems.

## 16 Files

# File

## A Logical View Of Information Storage

### User's view

A file is the smallest storage unit on disk.

- ▶ Data cannot be written to disk unless they are within a file

### UNIX view

Each file is a sequence of 8-bit bytes

- ▶ It's up to the application program to interpret this byte stream.

# File

## What Is Stored In A File?

Source code, object files, executable files, shell scripts, PostScript...

### Different type of files have different structure

- ▶ UNIX looks at contents to determine type

Shell scripts start with "#!"

PDF start with "%PDF..."

Executables start with **magic number**

- ▶ Windows uses file naming conventions

executables end with ".exe" and ".com"

MS-Word end with ".doc"

MS-Excel end with ".xls"

# File Naming

Vary from system to system

- ▶ Name length?
- ▶ Characters? Digits? Special characters?
- ▶ Extension?
- ▶ Case sensitive?

# File Types

Regular files: ASCII, binary

Directories: Maintaining the structure of the FS

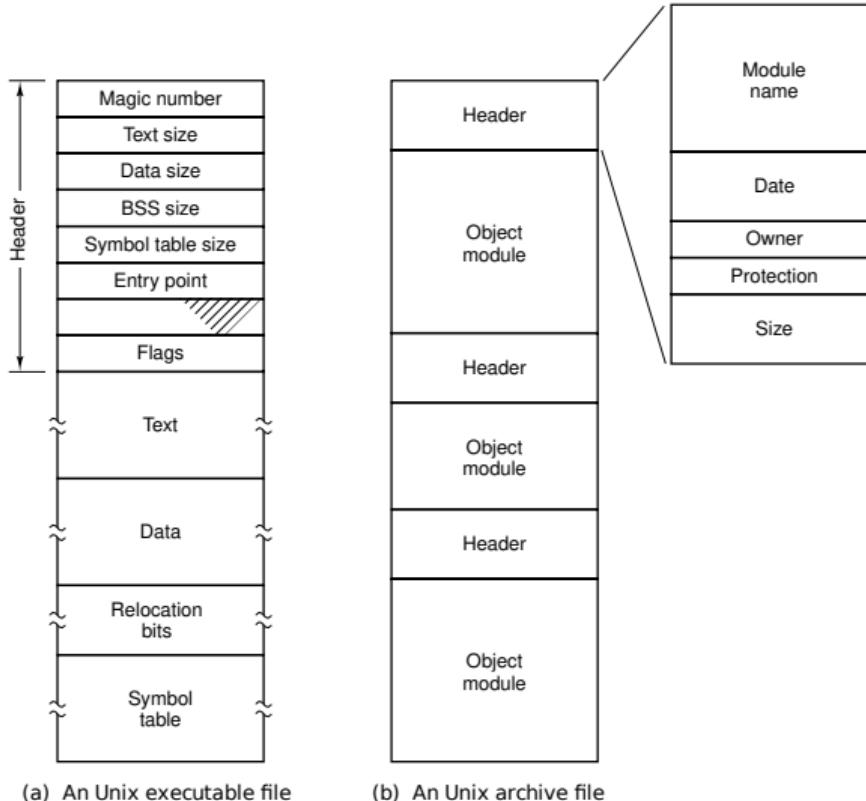
In UNIX, everything is a file

Character special files: I/O related, such as terminals, printers ...

Block special files: Devices that can contain file systems, i.e. disks

disks — logically, linear collections of blocks; disk driver translates them into physical block addresses

# Binary files



## File Attributes — Metadata

- ▶ **Name** - only information kept in human-readable form
- ▶ **Identifier** - unique tag (number) identifies file within file system
- ▶ **Type** - needed for systems that support different types
- ▶ **Location** - pointer to file location on device
- ▶ **Size** - current file size
- ▶ **Protection** - controls who can do reading, writing, executing
- ▶ **Time, date, and user identification** - data for protection, security, and usage monitoring

# File Operations

## POSIX file system calls

```
creat(name, mode)
open(name, flags)
close(fd)
link(oldname, newname)
unlink(name)
truncate(name, size)
ftruncate(fd, size)
stat(name, buffer)
fstat(fd, buffer)
```

```
read(fd, buffer, byte_count)
write(fd, buffer, byte_count)
lseek(fd, offset, whence)
chown(name, owner, group)
fchown(fd, owner, group)
chmod(name, mode)
fchmod(fd, mode)
utimes(name, times)
```

```
write()  
  
int main(void)  
{  
    write(1, "Hello, world!\n", 14);  
  
    return EXIT_SUCCESS;  
}
```

```
$ man 2 write  
$ man 3 write
```

```
read()  
  
int main(void)  
{  
    char buffer[10];  
  
    read(0, buffer, 10);  
  
    write(1, buffer, 10);  
  
    return EXIT_SUCCESS;  
}
```

```
$ man 2 read  
$ man 3 read
```

- ▶ No need to open() STDIN, STDOUT, and STDERR

cp

```
#define BUF_SIZE 4096
#define OUTPUT_MODE 0700

int main(int argc, char *argv[])
{
    int in, out, rbytes;
    char buf[BUF_SIZE];

    if (argc != 3) {}

    if ( (in = open(argv[1], O_RDONLY)) < 0 ) {}

    if ( (out = creat(argv[2], OUTPUT_MODE)) < 0 ) {}

    while (1) { /* Copy loop */
        if ( (rbytes = read(in, buf, BUF_SIZE)) <= 0 ) {}
        if ( write(out, buf, rbytes) <= 0 ) {}
    }

    close(in); close(out);

    exit (rbytes == 0 ? EXIT_SUCCESS : errno);
}
```

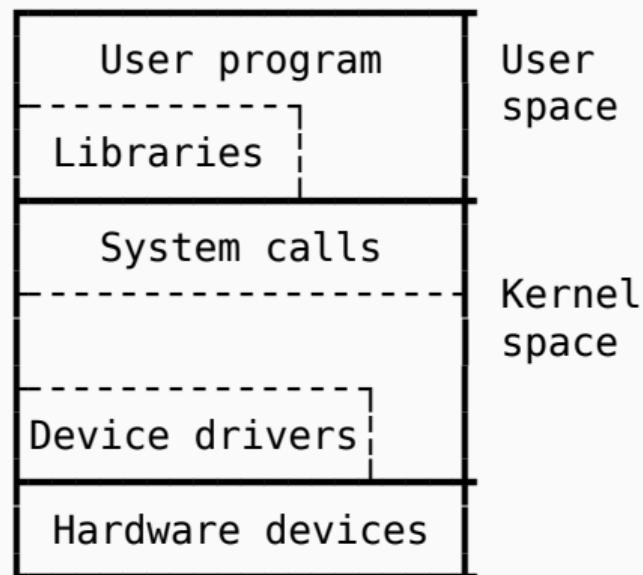
# stdio — The Standard I/O Library

System calls: `open()`, `read()`, `write()`, `close()`...

Library functions: `fopen()`, `fread()`, `fwrite`, `fclose()`...

Avoid calling syscalls directly as much as you can

- ▶ Portability
- ▶ Buffered I/O



## open() vs. fopen()

```
open()
```

```
int main(void)
{
    char c;
    int in;
    in = open("/tmp/1m.test", O_RDONLY);

    while ( read(in, &c, 1) == 1 );

    return EXIT_SUCCESS;
}
```

```
$ strace -c ./open
```

```
$ dd if=/dev/zero of=/tmp/1m.test bs=1k count=1024
```

### fopen() — Buffered I/O

```
int main(void)
{
    FILE *stream;

    stream = fopen("/tmp/1m.test", "r");

    while ( fgetc(stream) != EOF );

    fclose(stream);

    return EXIT_SUCCESS;
}
```

```
$ strace -c ./fopen
```

## cp — With stdio

```
int main(int argc, char *argv[])
{
    FILE *in, *out;
    int c=0;

    if (argc != 3) {}

    in = fopen(argv[1], "r");
    out = fopen(argv[2], "w");

    while( (c = fgetc(in)) != EOF )
        fputc(c, out);

    return EXIT_SUCCESS;
}
```

 Try `fread()`/`fwrite()` instead.

# open()

```
fd open(pathname, flags)
```

A per-process **open-file table** is kept in the OS

- ▶ upon a successful open() syscall, a new entry is added into this table
- ▶ indexed by **file descriptor (fd)**

To see files opened by a process, e.g. init

```
$ lsof -p 1
```

## Why open() is needed?

To avoid constant searching

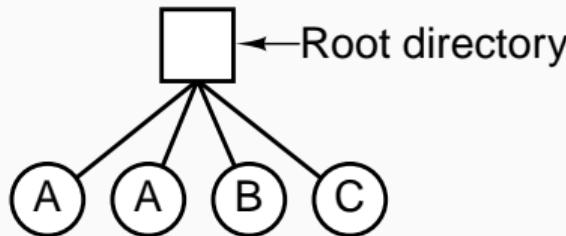
- ▶ Without open(), every file operation involves searching the directory for the file.

## 17 Directories

# Directories

## Single-Level Directory Systems

All files are contained in the same directory



- contains 4 files
- owned by 3 different people, A, B, and C

## Limitations

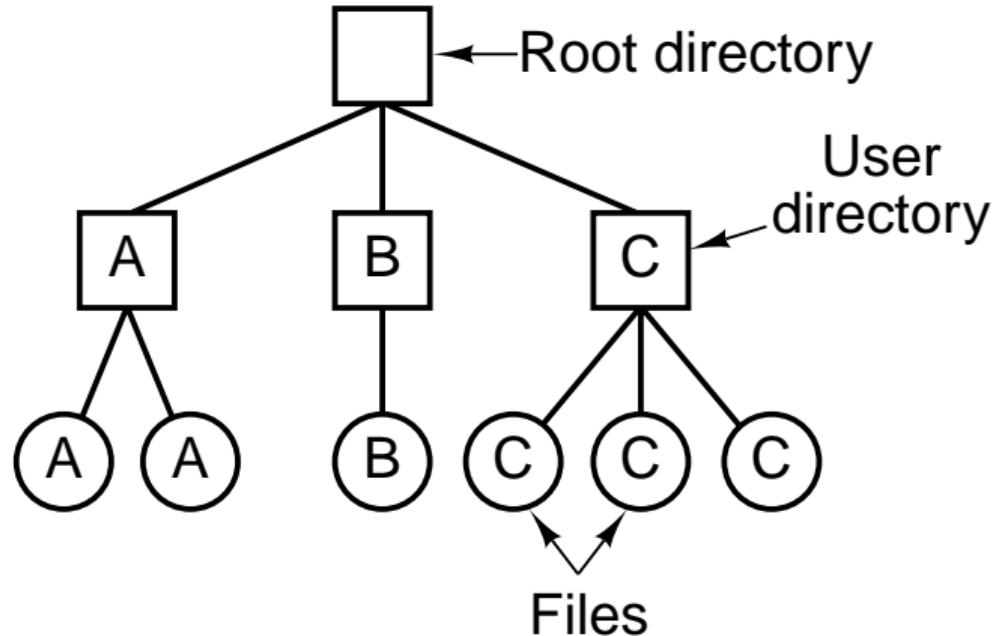
- name collision
- file searching

Often used on simple embedded devices, such as telephone, digital cameras...

# Directories

## Two-level Directory Systems

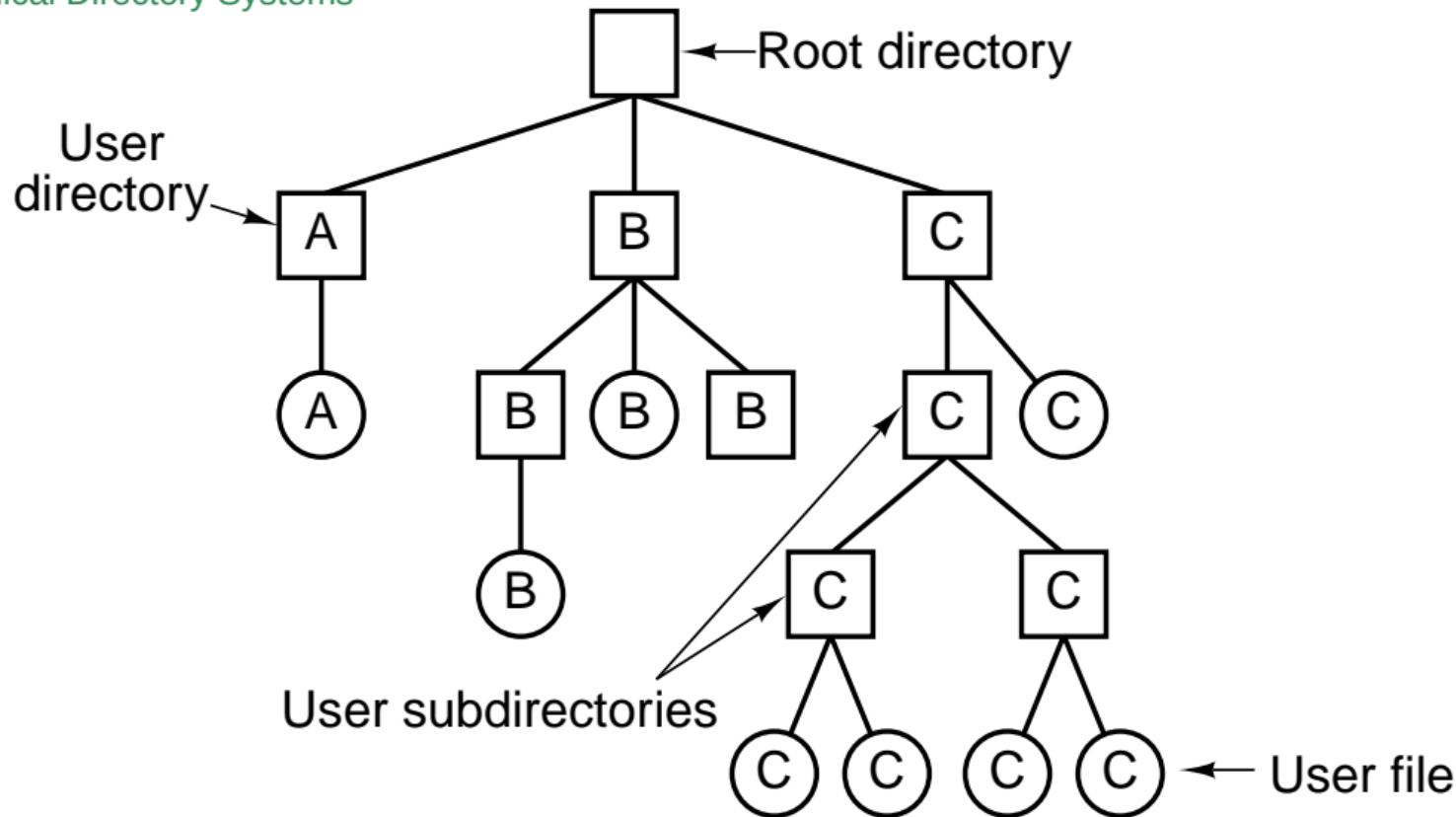
A separate directory for each user



Limitation: hard to access others files

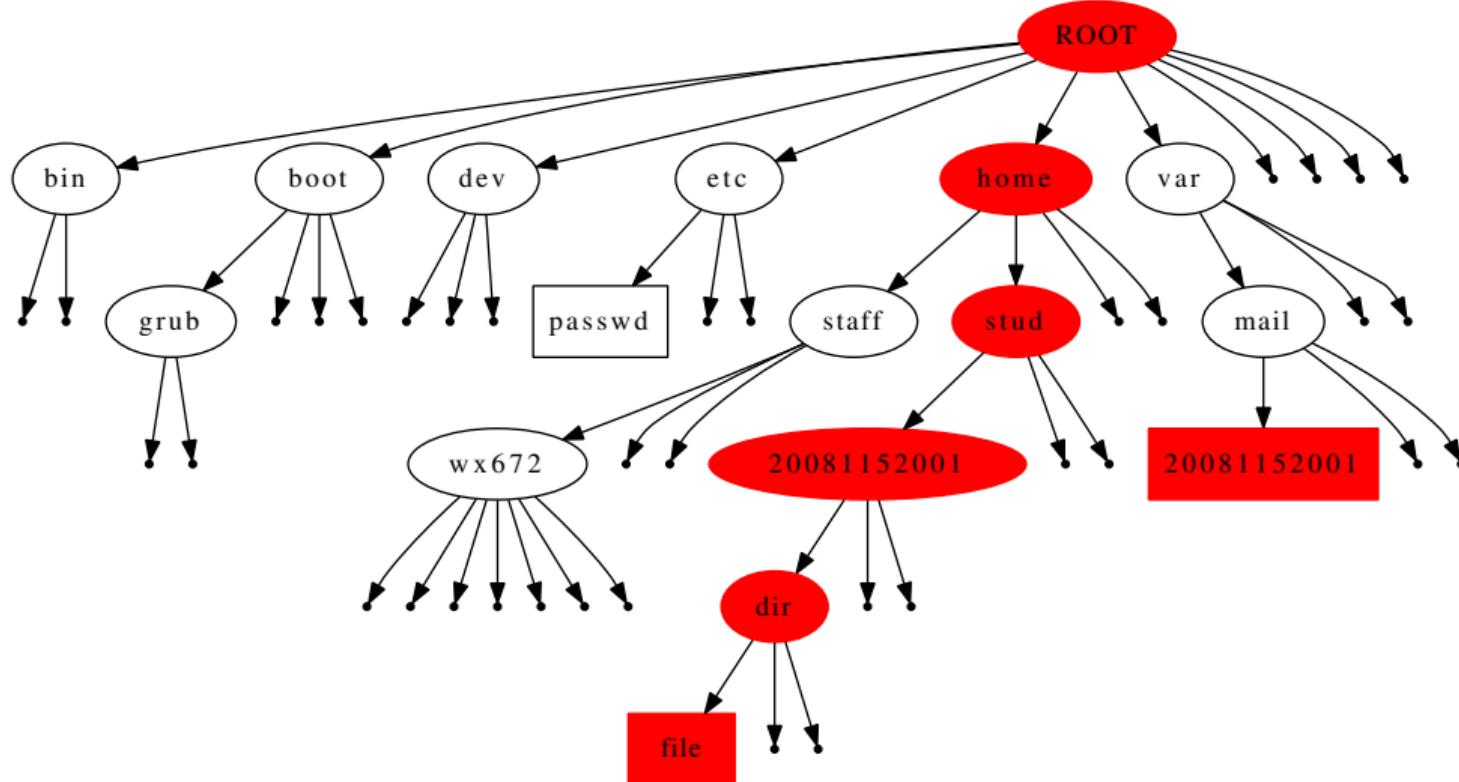
# Directories

## Hierarchical Directory Systems



# Directories

## Path Names



# Directories

## Directory Operations

```
opendir()    mkdir()    rename()    link()  
closedir()   rmdir()    readdir()   unlink()  
...  
...
```

ls

```
int main(int argc, char *argv[])
{
    DIR *dp;
    struct dirent *entry;

    if ( argc != 2 ) {}

    if ( (dp = opendir(argv[1])) == NULL ) {}

    while ( (entry = readdir(dp)) != NULL ) {
        printf("%s\n", entry->d_name);
    }

    closedir(dp);

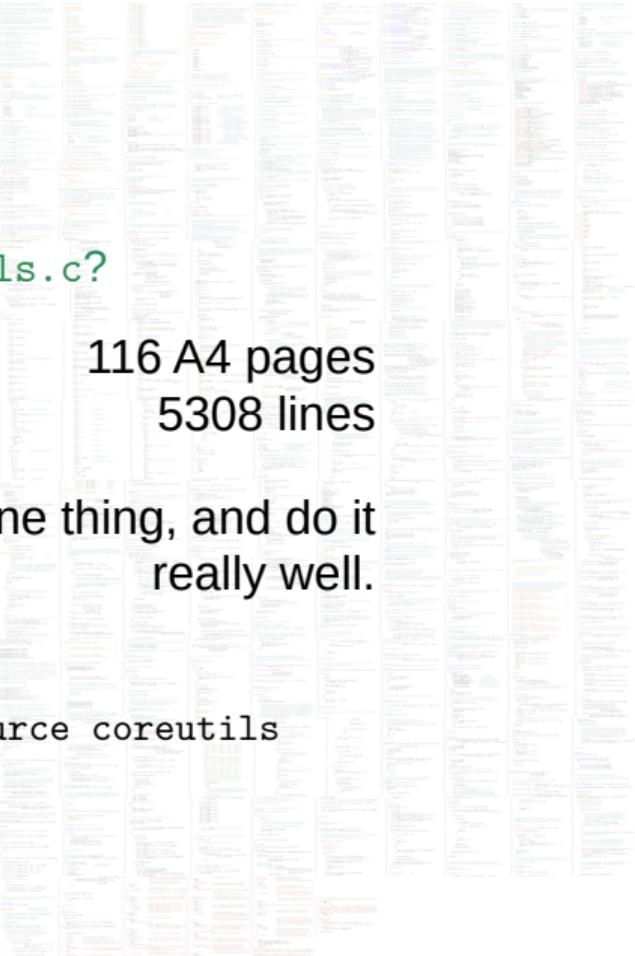
    return EXIT_SUCCESS;
}
```

The real ls.c?

116 A4 pages  
5308 lines

Do one thing, and do it  
really well.

\$ apt source coreutils



`mkdir()`, `chdir()`, `rmdir()`, `getcwd()`

```
int main(int argc, char *argv[])
{
    char s[100];

    if ( argc != 2 ) exit(EXIT_FAILURE);

    if ( mkdir(argv[1], S_IRUSR|S_IXUSR) != 0 ) {}

    if ( chdir(argv[1]) != 0 ) {}

    printf("PWD = %s\n", getcwd(s,100));

    /* chdir(".."); */

    if ( rmdir(argv[1]) != 0 ) {}

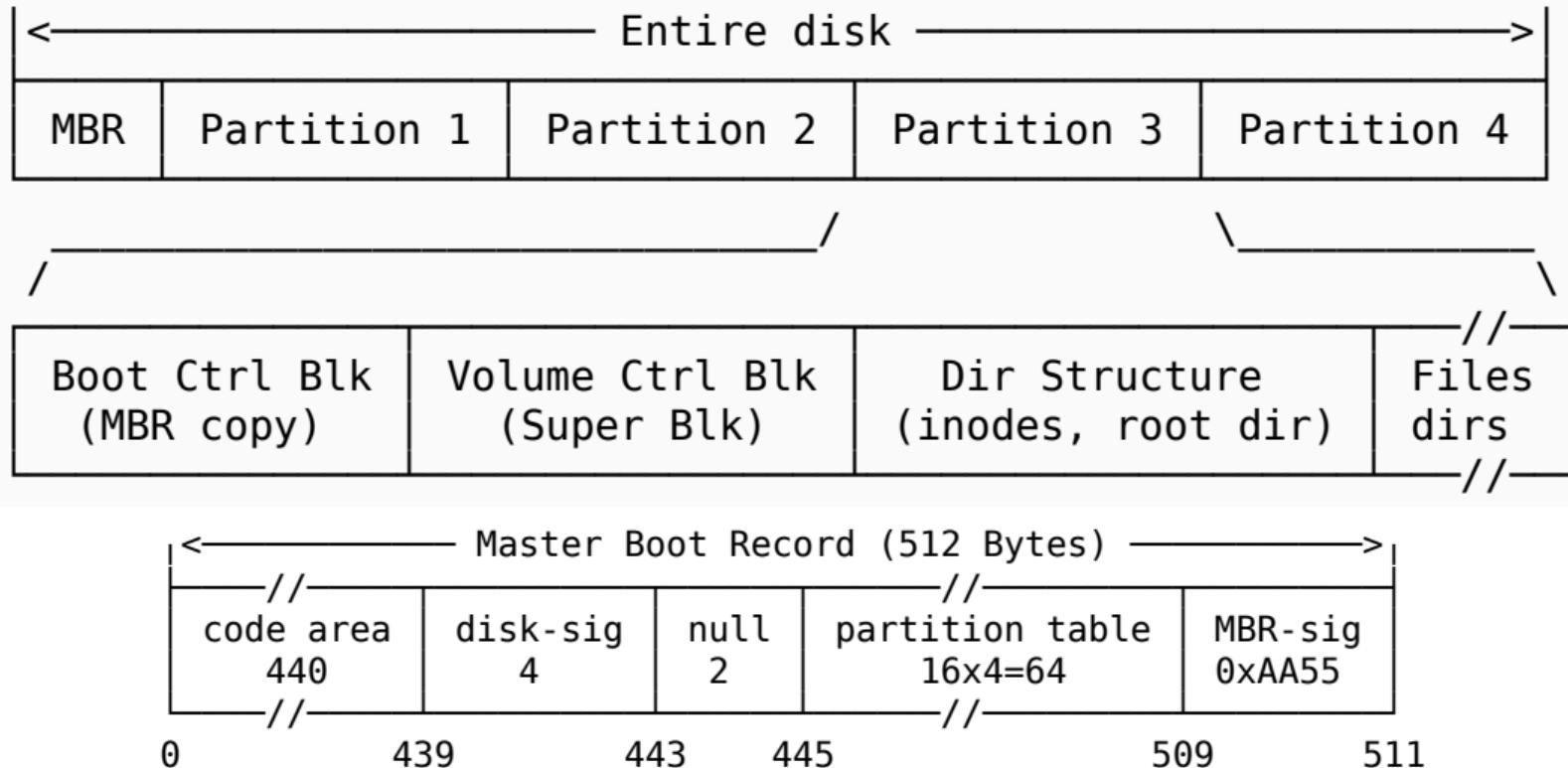
    return EXIT_SUCCESS;
}
```

## 18 File System Implementation

## 18.1 Basic Structures

# File System Implementation

## A typical file system layout



# On-Disk Information Structure

Boot control block a MBR copy

UFS: Boot block

NTFS: Partition boot sector

Volume control block Contains volume details

number of blocks	size of blocks
free-block count	free-block pointers
free FCB count	free FCB pointers

UFS: Superblock

NTFS: Master File Table

Directory structure Organizes the files **FCB**, **File control block**, contains file details (metadata).

UFS: I-node

NTFS: Stored in MFT using a relational database structure, with one row per file

# Each File-System Has a Superblock

## Superblock

Keeps information about the file system

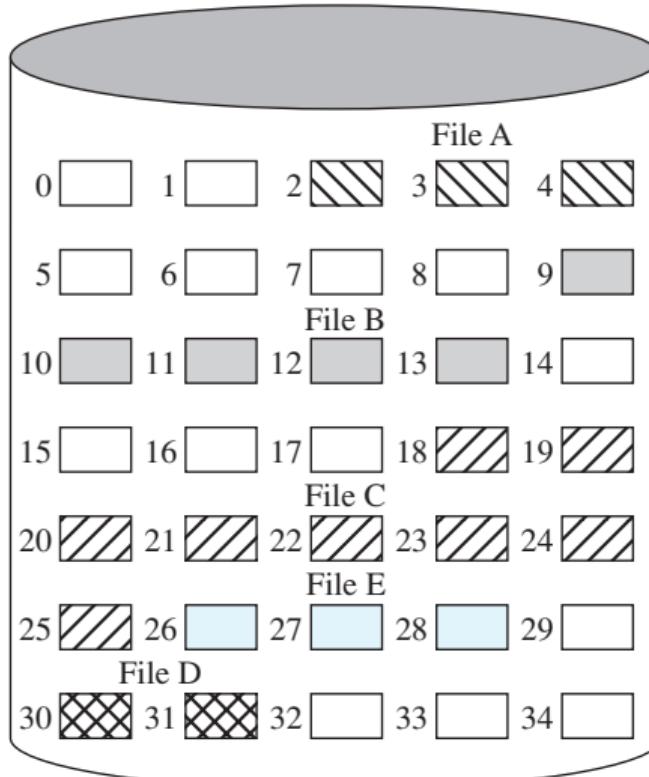
- ▶ Type — ext2, ext3, ext4...
- ▶ Size
- ▶ Status — how it's mounted, free blocks, free inodes, ...
- ▶ Information about other metadata structures

```
$ sudo dumpe2fs /dev/sda1 | less
```

## 18.2 Implementing Files

# Implementing Files

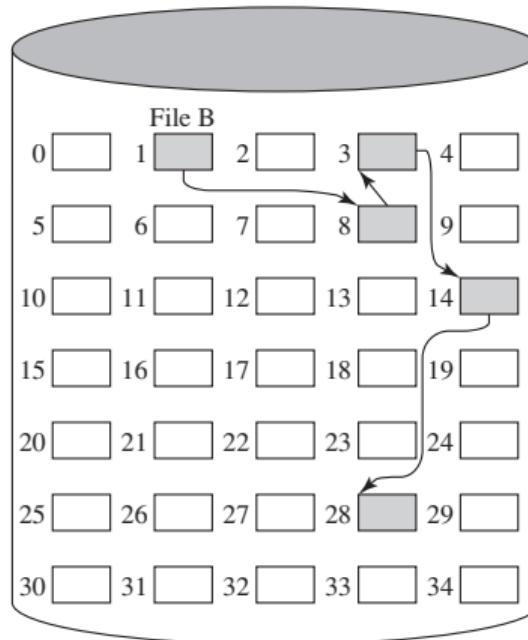
## Contiguous Allocation



File Allocation Table

File Name	Start Block	Length
File A	2	3
File B	9	5
File C	18	8
File D	30	2
File E	26	3

## Linked List (Chained) Allocation A pointer in each disk block

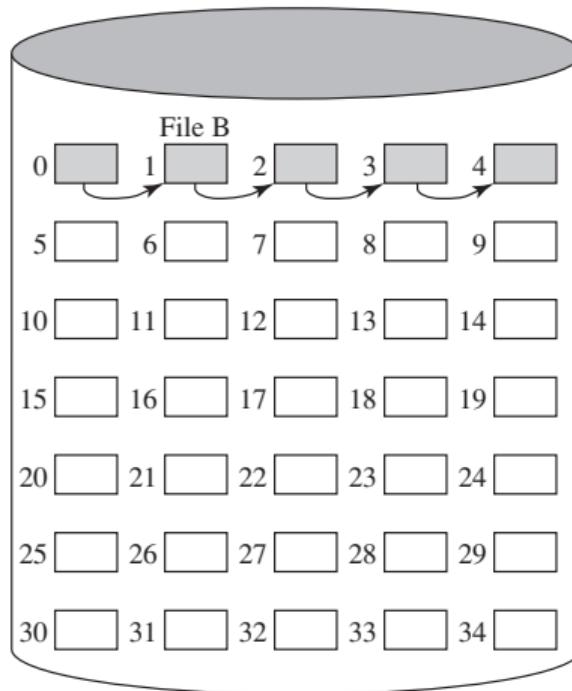


File Allocation Table

File Name	Start Block	Length
••• File B •••	••• 1 •••	••• 5 •••

- no waste block;
- slow random access;
- not  $2^n$

**Linked List (Chained) Allocation** Though there is no external fragmentation, consolidation is still preferred.



File Name	Start Block	Length
••• File B •••	••• 0 •••	••• 5 •••

## FAT: Linked list allocation with a table in RAM

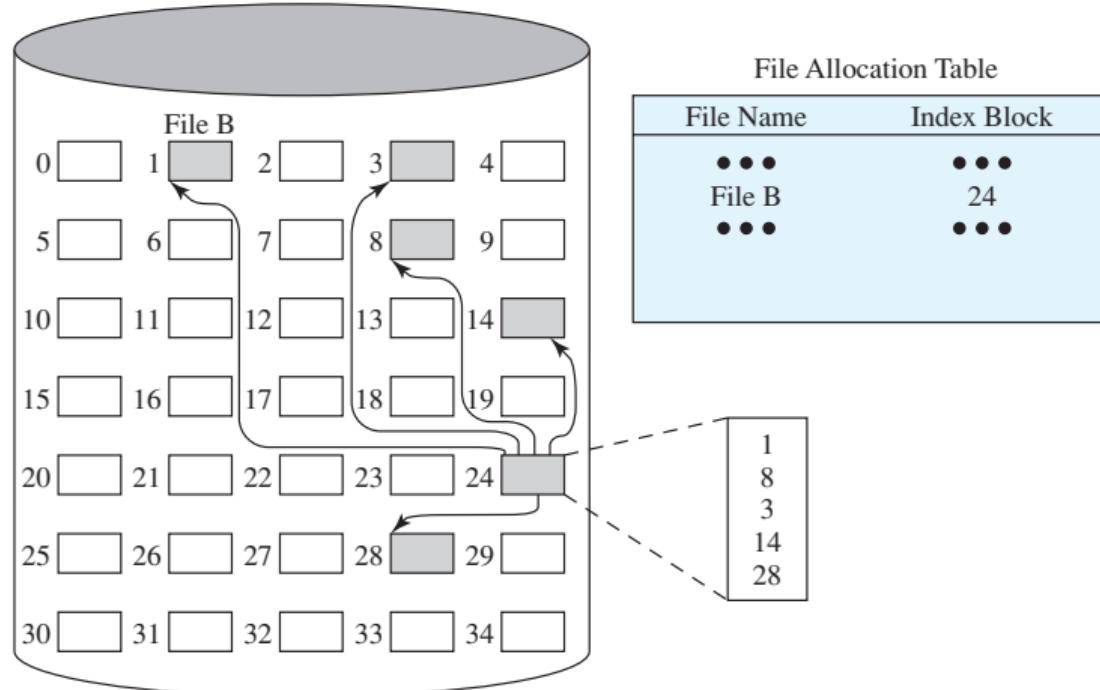
- ▶ Taking the pointer out of each disk block, and putting it into a table in memory
- ▶ fast random access (chain is in RAM)
- ▶ is  $2^n$
- ▶ the entire table must be in RAM

*disk ↗ ⇒ FAT ↗ ⇒ RAM<sub>used</sub> ↗*

Physical block
0
1
2 10
3 11
4 7
5
6 3
7 2
8
9
10 12
11 14
12 -1
13
14 -1
15

← File A starts here  
← File B starts here  
← Unused block

## Indexed Allocation

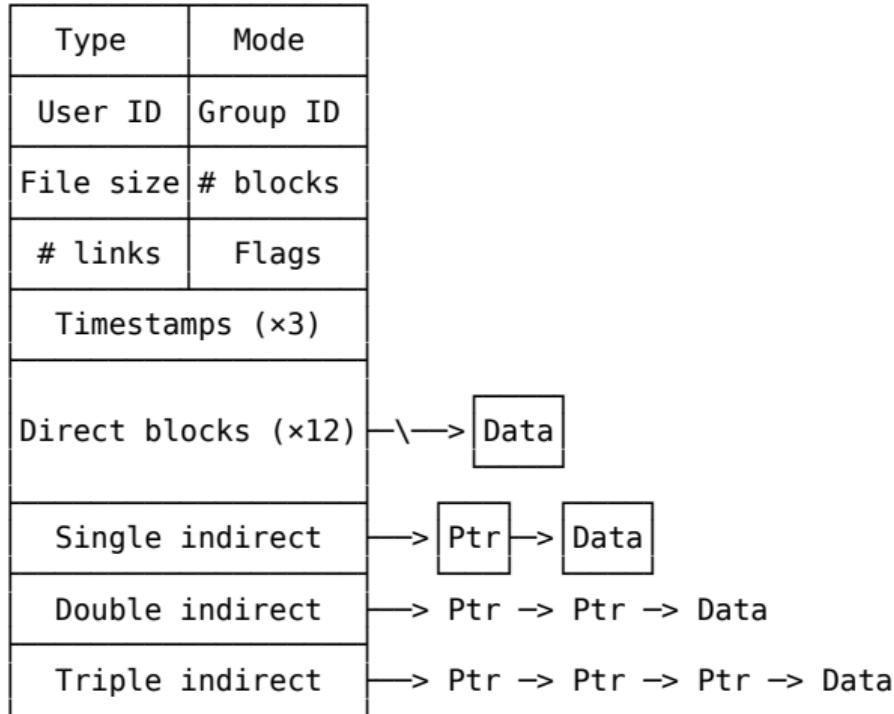


**I-node** A data structure for each file. An i-node is in memory *only if* the file is open

$$\text{files}_{\text{opened}} \nearrow \Rightarrow \text{RAM}_{\text{used}} \nearrow$$

# I-node — FCB in UNIX

File inode (128B)



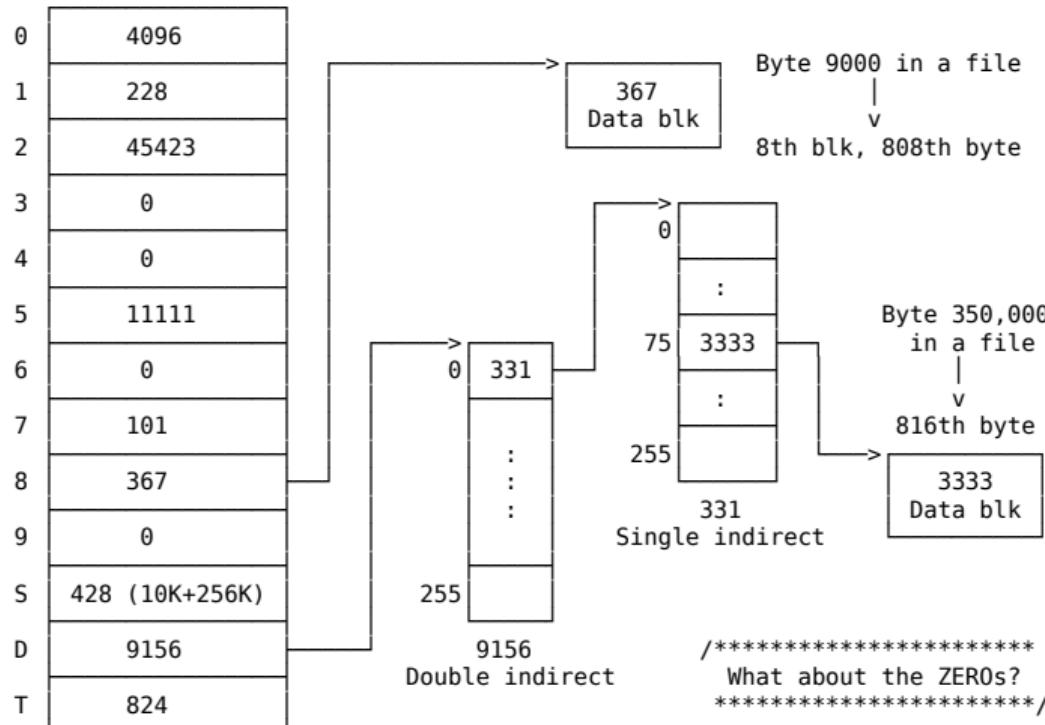
File type	Description
0	Unknown
1	Regular file
2	Directory
3	Character device
4	Block device
5	Named pipe
6	Socket
7	Symbolic link

Mode: 9-bit pattern

# Inode Quiz

Given: block size is 1KB; pointer size is 4B

Addressing: byte offset 9000; byte offset 350,000



# UNIX In-Core Data Structure

mount table — Info about each mounted FS

directory-structure cache — Dir-info of recently accessed dirs

inode table — An in-core version of the on-disk inode table

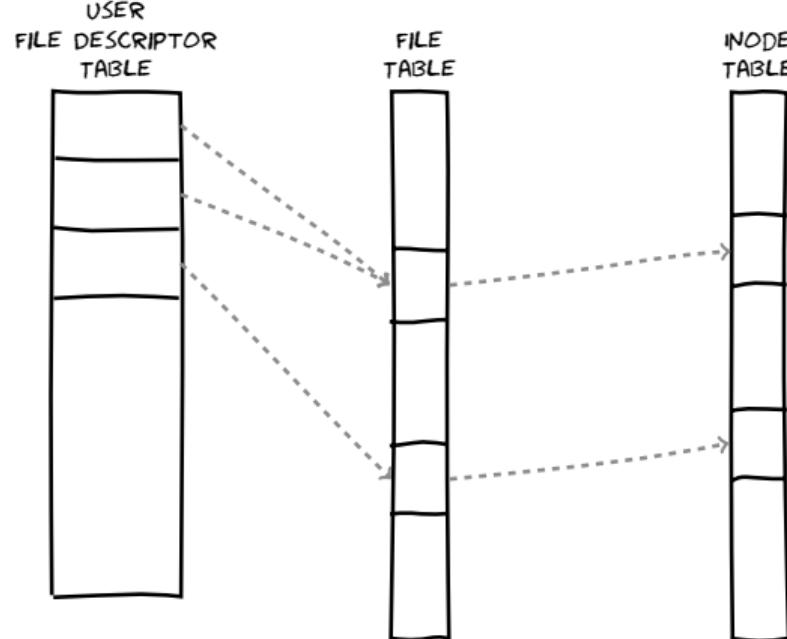
file table

- ▶ global
- ▶ keeps inode of each open file
- ▶ keeps track of
  - ▶ how many processes are associated with each open file
  - ▶ where the next read and write will start
  - ▶ access rights

user file descriptor table

- ▶ per process
- ▶ identifies all open files for a process

# UNIX In-Core Data Structure



`open()/creat()`

1. add entry in each table
2. returns a **file descriptor** — an index into the user file descriptor table

# The Tables

## Two levels of internal tables in the OS

A **per-process table** tracks all files that a process has open. Stores

- ▶ the current-file-position pointer (not really)
- ▶ access rights
- ▶ more...

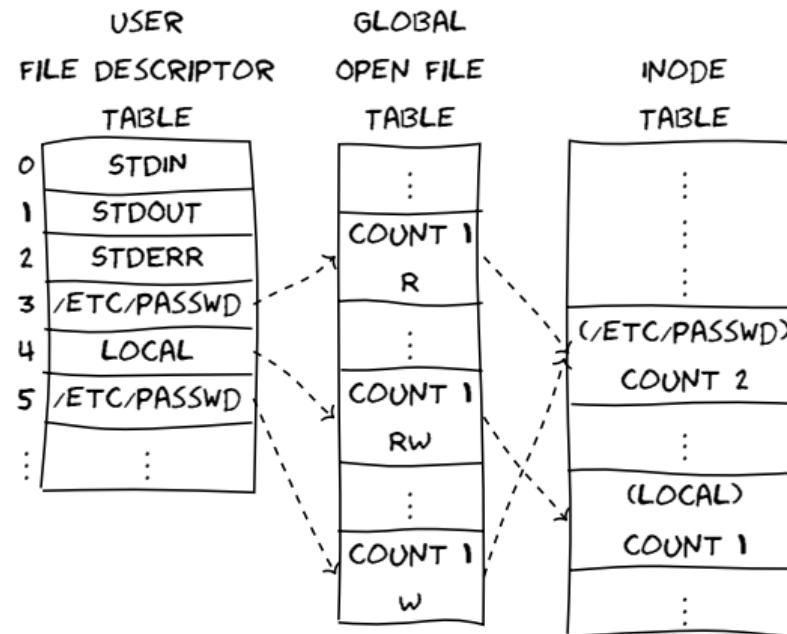
a.k.a file descriptor table

A **system-wide table** keeps process-independent information, such as

- ▶ the location of the file on disk
- ▶ access dates
- ▶ file size
- ▶ file open count — the number of processes opening this file

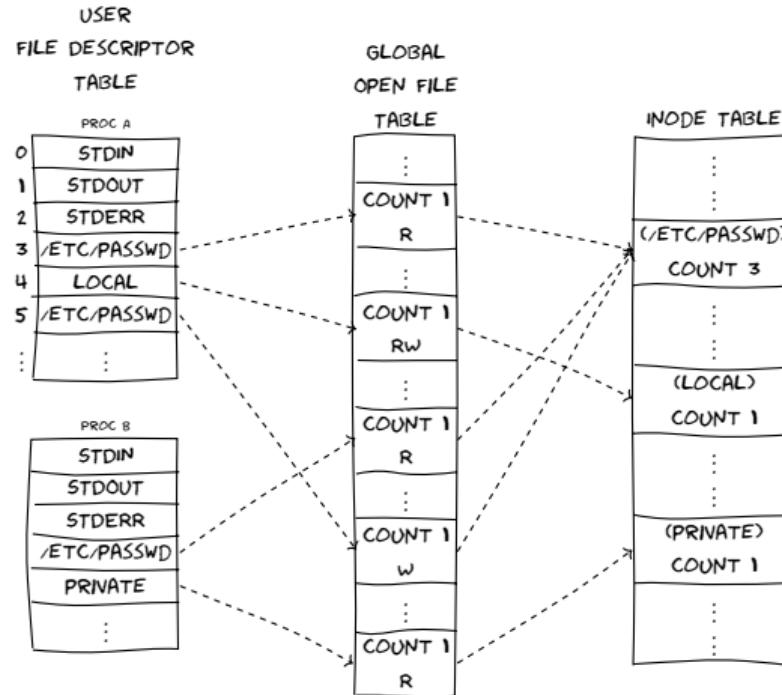
A process executes the following code:

```
fd1 = open("/etc/passwd", O_RDONLY);  
fd2 = open("local", O_RDWR);  
fd3 = open("/etc/passwd", O_WRONLY);
```



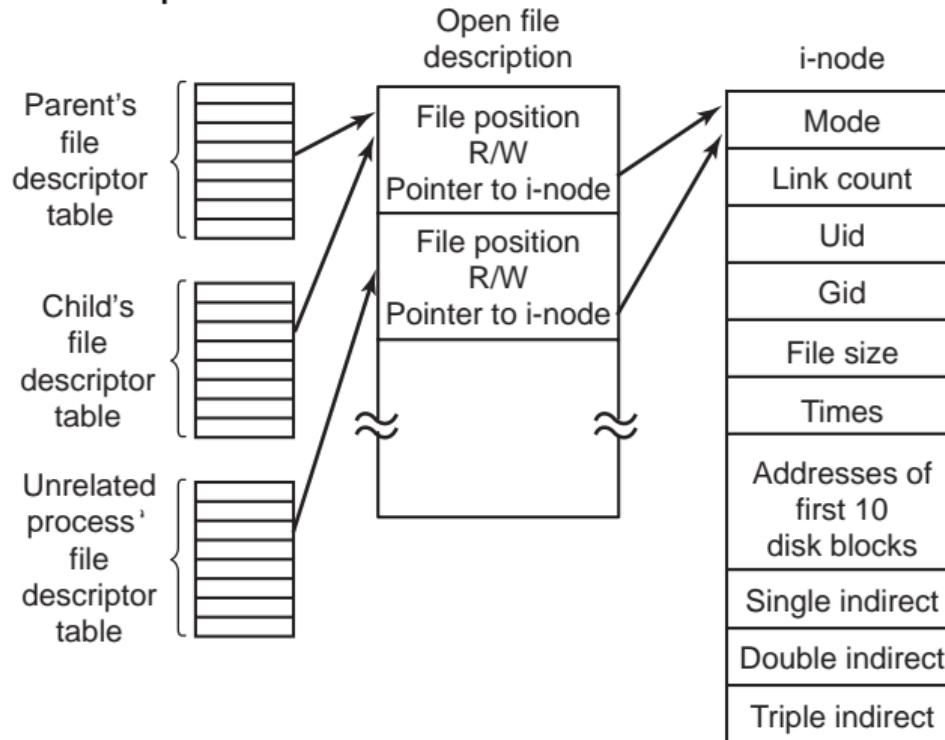
## One more process B:

```
fd1 = open("/etc/passwd", O_RDONLY);  
fd2 = open("private", O_RDONLY);
```



# Why File Table?

To allow a parent and child to share a file position, but to provide unrelated processes with their own values.



# Why File Table?

## Where To Put File Position Info?

Inode table? No. Multiple processes can open the same file. Each one has its own file position.

User file descriptor table? No. Trouble in file sharing.

## Example

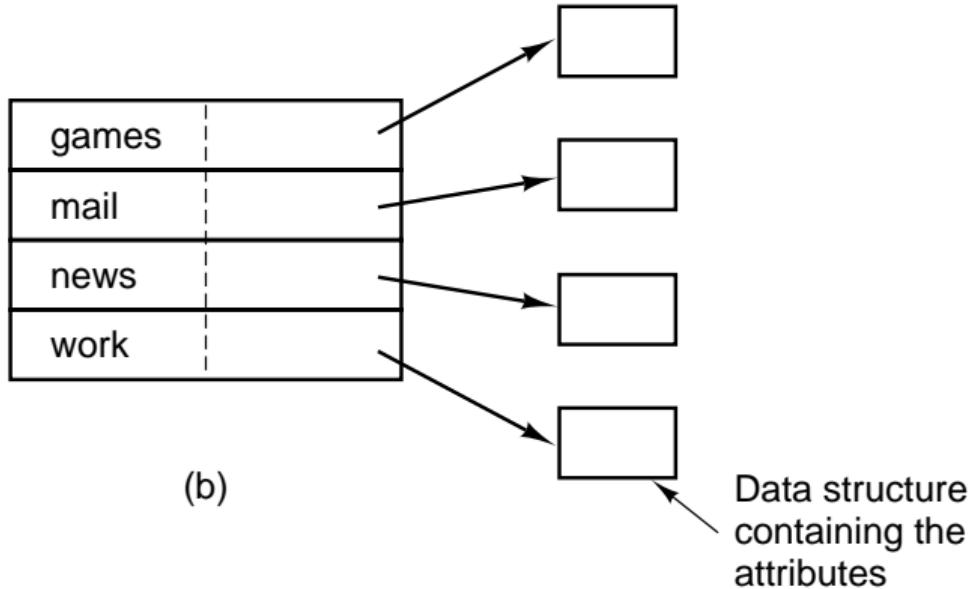
```
1 #!/bin/bash
2
3 echo hello           $ ./hello.sh > A
4 echo world          ? Where should the "world" be?
```

## 18.3 Implementing Directories

# Implementing Directories

games	attributes
mail	attributes
news	attributes
work	attributes

(a)



(a) A simple directory (Windows)

- ▶ fixed size entries
- ▶ disk addresses and attributes in directory entry

(b) Directory in which each entry just refers to an i-node (UNIX)

## Directory entry in glibc

```
1 struct dirent {  
2     ino_t          d_ino;           /* Inode number */  
3     off_t          d_off;          /* Not an offset; see below */  
4     unsigned short d_reclen;       /* Length of this record */  
5     unsigned char   d_type;         /* Type of file; not supported  
6                                by all filesystem types */  
7     char            d_name[256];    /* Null-terminated filename */  
8 };
```

```
$ man readdir
```

```
$ view /usr/include/x86_64-linux-gnu/bits/dirent.h
```

# How Long A File Name Can Be?

Entry for one file

File 1 entry length			
File 1 attributes			
p	r	o	j
e	c	t	-
b	u	d	g
e	t	☒	
File 2 entry length			
File 2 attributes			
p	e	r	s
o	n	n	e
l	☒		
File 3 entry length			
File 3 attributes			
f	o	o	☒
:			

(a)

Pointer to file 1's name

File 1 attributes

Pointer to file 2's name

File 2 attributes

Pointer to file 3's name

File 3 attributes

Entry for one file

Heap

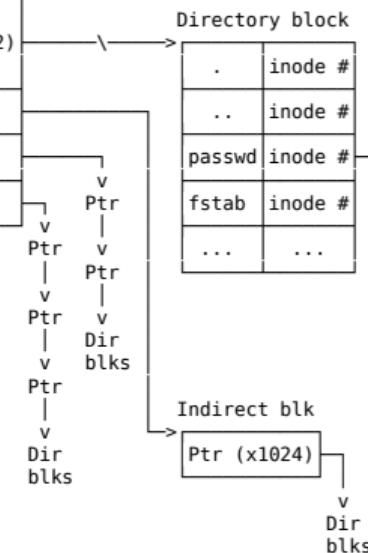
p	r	o	j
e	c	t	-
b	u	d	g
e	t	☒	p
e	r	s	o
n	n	e	l
☒	f	o	o
☒			

(b)

# UNIX Treats a Directory as a File

Directory inode (128B)

Type	Mode
User ID	Group ID
File size	# blocks
# links	Flags
Timestamps (x3)	
Direct blocks (x12)	
Single indirect	
Double indirect	
Triple indirect	



.	2
..	2
bin	11116545
boot	2
cdrom	12
dev	3
...	...

File inode (128B)

Type	Mode
User ID	Group ID
File size	# blocks
# links	Flags
Timestamps (x3)	
Direct blocks (x12)	
Single indirect	
Double indirect	
Triple indirect	

## The steps in looking up /usr/ast/mbox

Root directory

1	.
1	..
4	bin
7	dev
14	lib
9	etc
6	usr
8	tmp

Looking up  
usr yields  
i-node 6

I-node 6  
is for /usr

Mode	
size	
times	
132	

I-node 6  
says that  
/usr is in  
block 132

Block 132  
is /usr  
directory

6	•
1	..
19	dick
30	erik
51	jim
26	ast
45	bal

/usr/ast  
is i-node  
26

I-node 26  
is for  
/usr/ast

Mode	
size	
times	
406	

I-node 26  
says that  
/usr/ast is in  
block 406

Block 406  
is /usr/ast  
directory

26	•
6	..
64	grants
92	books
60	mbox
81	minix
17	src

/usr/ast/mbox  
is i-node  
60

## 18.4 Shared Files

# File Sharing

## Multiple Users

User IDs identify users, allowing permissions and protections to be per-user

Group IDs allow users to be in groups, permitting group access rights

### Example: 9-bit pattern

`rwxr-x---` means:

user	group	other
<code>rwx</code>	<code>r-x</code>	<code>---</code>
111	1-1	000
7	5	0

# File Sharing

## Remote File Systems

Networking — allows file system access between systems

- ▶ Manually via programs like FTP
- ▶ Automatically, seamlessly using distributed file systems
- ▶ Semi automatically, via the world wide web

C/S model — allows clients to *mount* remote file systems from servers

- ▶ NFS — standard UNIX client-server file sharing protocol
- ▶ CIFS — standard Windows protocol
- ▶ Standard system calls are translated into remote calls

Distributed Information Systems (distributed naming services)

- ▶ such as LDAP, DNS, NIS, Active Directory implement unified access to information needed for remote computing

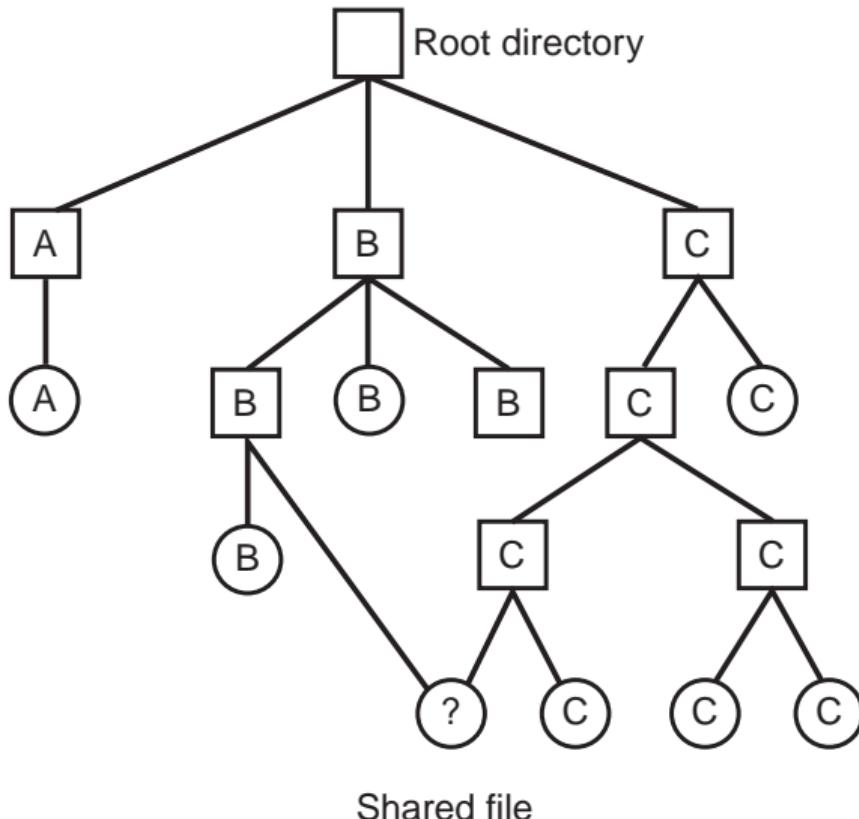
# File Sharing

## Protection

- ▶ File owner/creator should be able to control:
  - ▶ what can be done
  - ▶ by whom
- ▶ Types of access
  - ▶ Read
  - ▶ Write
  - ▶ Execute
  - ▶ Append
  - ▶ Delete
  - ▶ List

# Shared Files

## Hard Links vs. Soft Links

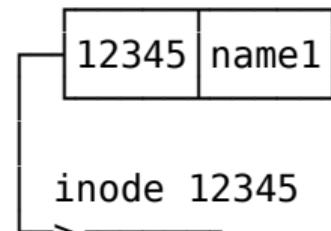


# Hard Links

Hard links ➔ the same inode

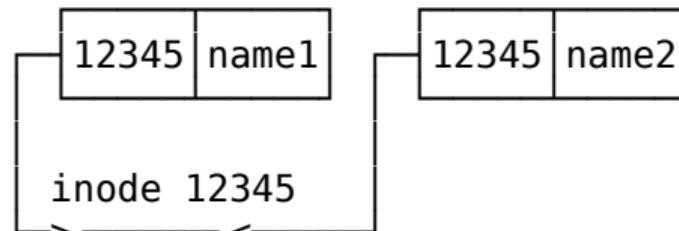
dir entry in /dirA

inode name



dir entry in /dirA

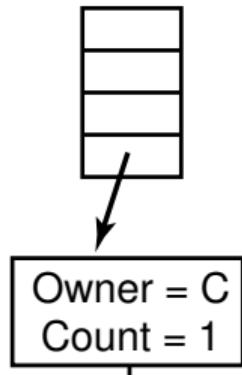
inode name



dir entry in /dirB

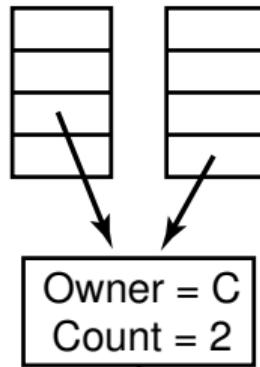
## Drawback

C's directory



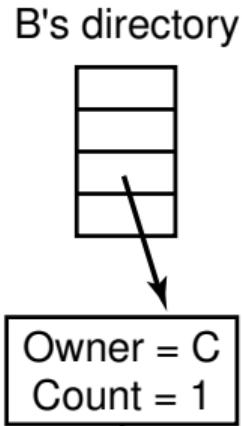
(a)

B's directory



(b)

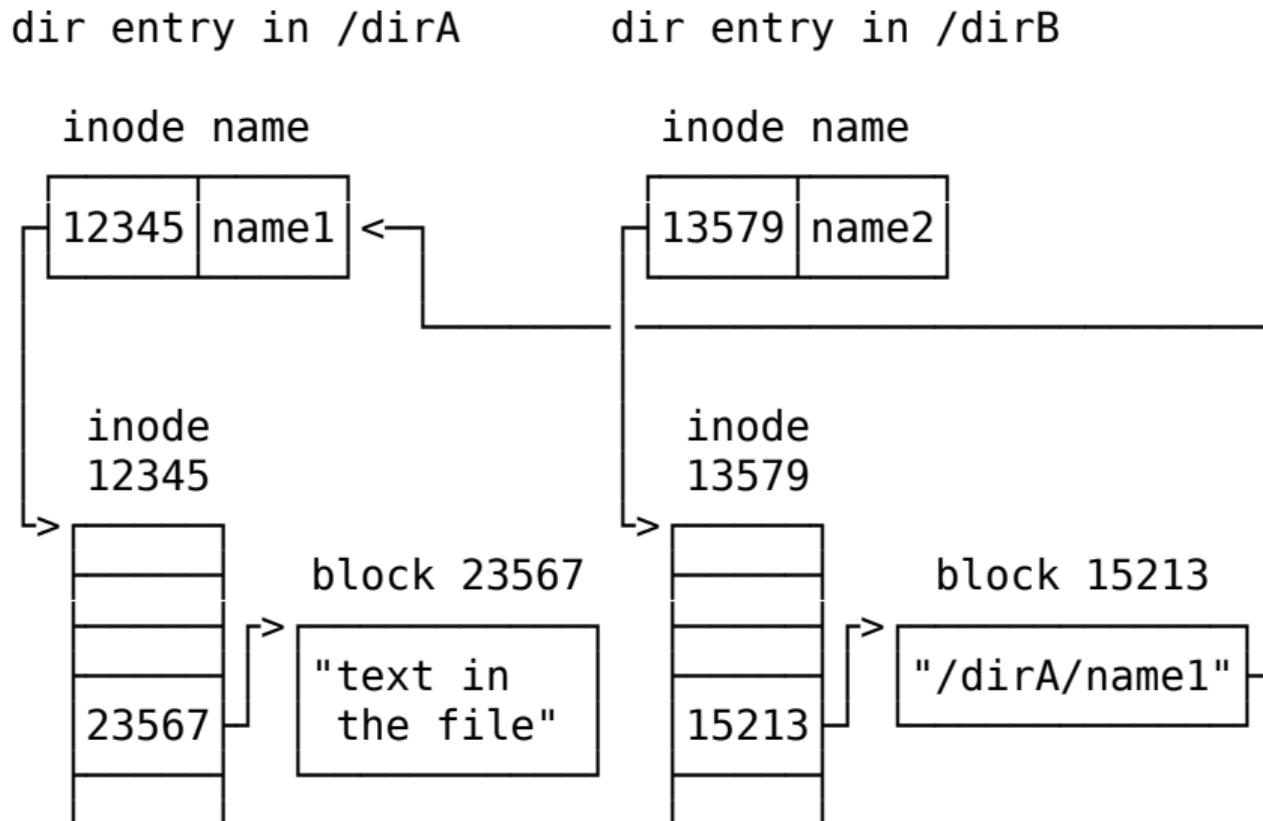
C's directory



(c)

# Symbolic Links

A symbolic link has its own inode ➔ a directory entry



## link(), unlink(), symlink()

```
int main(int argc, char *argv[])
{
    if ( argc !=3 ) { }

    if ( link(argv[1], argv[2]) ) { }

    return EXIT_SUCCESS;
}

/* symlink(argv[1], argv[2]); */
/* unlink(argv[1]); */
```

## 18.5 Disk Space Management

# Disk Space Management

## Statistics

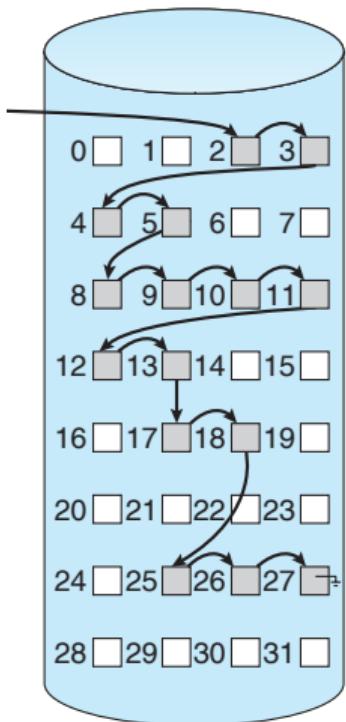
Length	VU 1984	VU 2005	Web
1	1.79	1.38	6.67
2	1.88	1.53	7.67
4	2.01	1.65	8.33
8	2.31	1.80	11.30
16	3.32	2.15	11.46
32	5.13	3.15	12.33
64	8.71	4.98	26.10
128	14.73	8.03	28.49
256	23.09	13.29	32.10
512	34.44	20.62	39.94
1 KB	48.05	30.91	47.82
2 KB	60.87	46.09	59.44
4 KB	75.31	59.13	70.64
8 KB	84.97	69.96	79.69

Length	VU 1984	VU 2005	Web
16 KB	92.53	78.92	86.79
32 KB	97.21	85.87	91.65
64 KB	99.18	90.84	94.80
128 KB	99.84	93.73	96.93
256 KB	99.96	96.12	98.48
512 KB	100.00	97.73	98.99
1 MB	100.00	98.87	99.62
2 MB	100.00	99.44	99.80
4 MB	100.00	99.71	99.87
8 MB	100.00	99.86	99.94
16 MB	100.00	99.94	99.97
32 MB	100.00	99.97	99.99
64 MB	100.00	99.99	99.99
128 MB	100.00	99.99	100.00

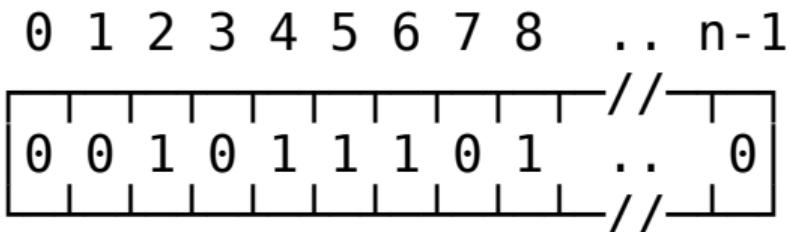
- ▶ Block size is chosen while creating the FS
  - ▶ Disk I/O performance is conflict with space utilization
    - ▶ smaller block size ⇒ better space utilization
    - ▶ larger block size ⇒ better disk I/O performance
- \$ dumpe2fs /dev/sda1 | grep "Block size"

# Keeping Track of Free Blocks

## 1. Linked List



## 2. Bit map (n blocks)


$$bit[i] = \begin{cases} 0 & \Rightarrow \text{block}[i] \text{ is free} \\ 1 & \Rightarrow \text{block}[i] \text{ is occupied} \end{cases}$$

# Journaling File Systems

Operations required to remove a file in UNIX:

1. Remove the file from its directory
  - set inode number to 0
2. Release the i-node to the pool of free i-nodes
  - clear the bit in inode bitmap
3. Return all the disk blocks to the pool of free disk blocks
  - clear the bits in block bitmap

What if crash occurs between 1 and 2, or between 2 and 3?

# Journaling File Systems

Keep a log of what the file system is going to do before it does it

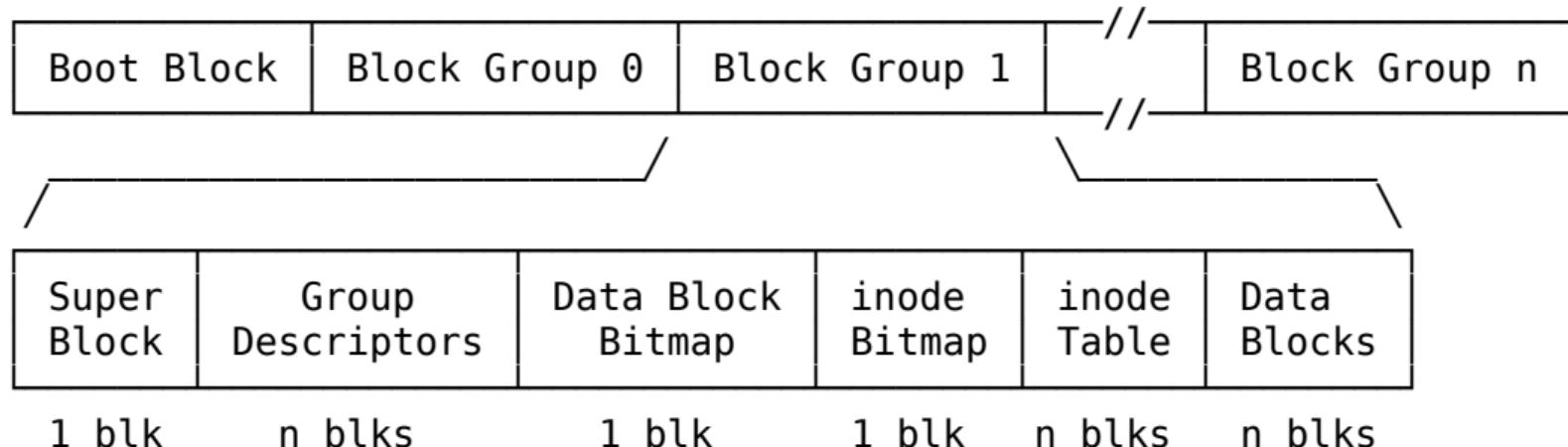
- ▶ so that if the system crashes before it can do its planned work, upon rebooting the system can look in the log to see what was going on at the time of the crash and finish the job.
- ▶ NTFS, EXT3/4, and ReiserFS use journaling among others

## 19 Ext2 File System

## 19.1 Ext2 File System Layout

# Ext2 File System

## Physical Layout



## 19.2 Ext2 Block groups

## Ext2 Block groups

### The partition is divided into Block Groups

- ▶ Block groups are same size — easy locating
- ▶ Kernel tries to keep a file's data blocks in the same block group — reduce fragmentation
- ▶ Backup critical info in each block group
- ▶ The Ext2 inodes for each block group are kept in the [inode table](#)
- ▶ The [inode-bitmap](#) keeps track of allocated and unallocated inodes

## Group descriptor

- ▶ Each block group has a group descriptor
- ▶ All the group descriptors together make the **group descriptor table**
- ▶ The table is stored along with the superblock
- ▶ **Block Bitmap:** tracks free blocks
- ▶ **Inode Bitmap:** tracks free inodes
- ▶ **Inode Table:** all inodes in this block group
  - ▶ Free blocks count
  - ▶ Free Inodes count
  - ▶ Used dir count

```
# dumpe2fs /dev/sda1
```

## Maths

Given  $\text{block size} = 4K$   
 $\text{block bitmap} = 1 \text{ blk}$ , then

$$\text{blocks per group} = 8 \text{ bits} \times 4K = 32K$$

How large is a group?

$$\text{group size} = 32K \times 4K = 128M$$

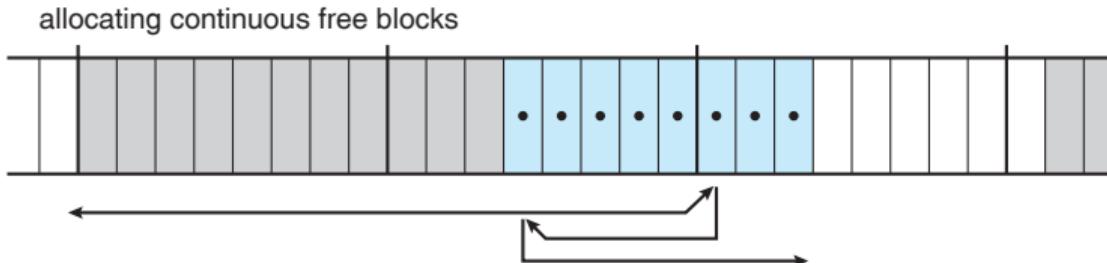
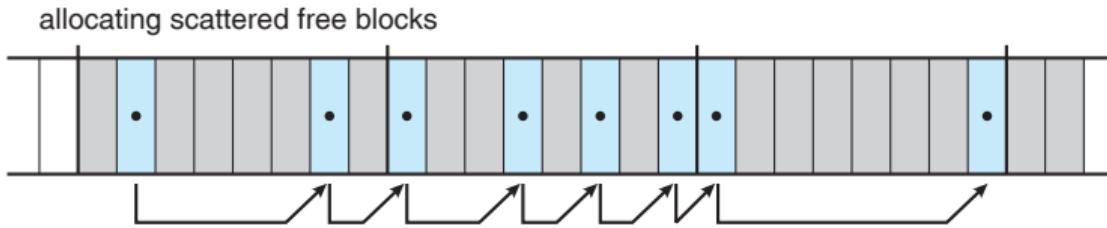
How many block groups are there?

$$\approx \frac{\text{partition size}}{\text{group size}} = \frac{\text{partition size}}{128M}$$

How many files can I have in max?

$$\approx \frac{\text{partition size}}{\text{block size}} = \frac{\text{partition size}}{4K}$$

# Ext2 Block Allocation Policies



block in use



block selected  
by allocator



free block

→ bitmap search



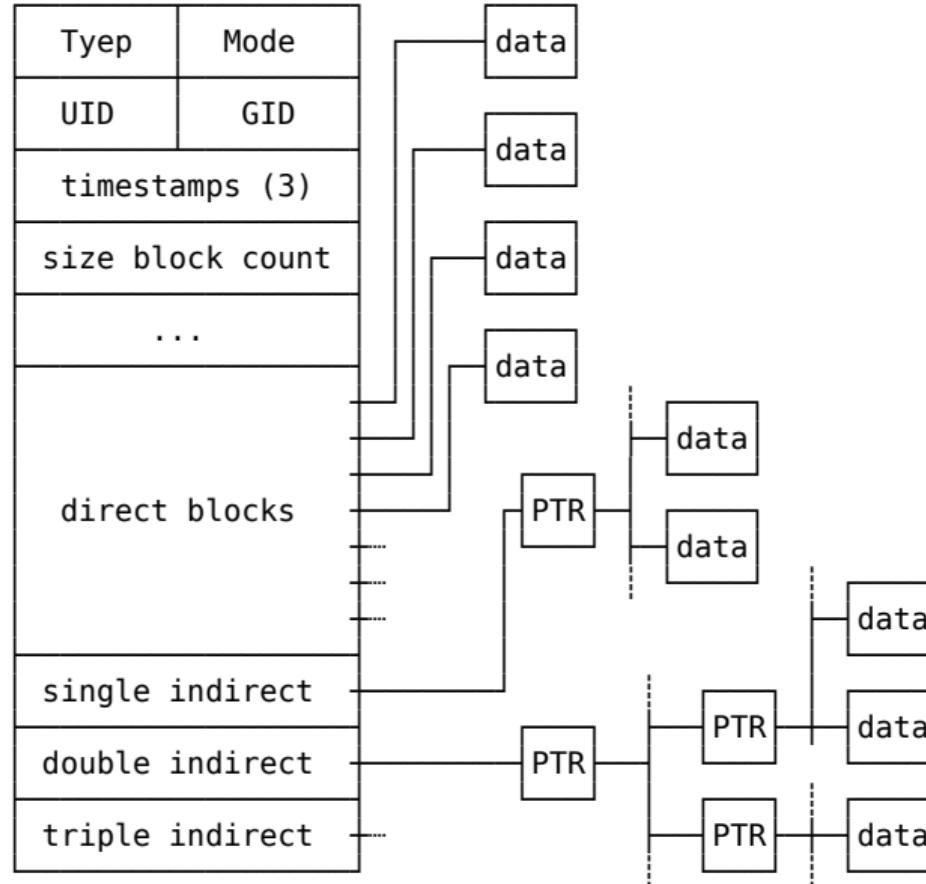
bit boundary



byte boundary

## 19.3 Ext2 Inode

# Ext2 inode



## Ext2 inode

Mode: holds two pieces of information

1. Is it a {file|dir|sym-link|blk-dev|char-dev|FIFO}?
2. Permissions

Owner info: Owners' ID of this file or directory

Size: The size of the file in bytes

Timestamps: Accessed, created, last modified time

Datablocks: 15 pointers to data blocks ( $12 + S + D + T$ )

## Max File Size

Given:

$$\begin{cases} \text{block size} = 4K \\ \text{pointer size} = 4B \end{cases},$$

We get:

$$\text{Max File Size} = \text{number of pointers} \times \text{block size}$$

$$\begin{aligned} &= (\underbrace{12}_{\text{direct}} + \underbrace{1K}_{\text{1-indirect}} + \underbrace{1K \times 1K}_{\text{2-indirect}} + \underbrace{1K \times 1K \times 1K}_{\text{3-indirect}}) \times 4K \\ &= 48K + 4M + 4G + 4T \end{aligned}$$

## 19.4 Ext2 Superblock

# Ext2 Superblock

Magic Number: 0xEF53

Revision Level: determines what new features are available

Mount Count and Maximum Mount Count: determines if the system should be fully checked

Block Group Number: indicates the block group holding this superblock

Block Size: usually 4K

Blocks per Group:  $8\text{bits} \times \text{block size}$

Free Blocks: System-wide free blocks

Free Inodes: System-wide free inodes

First Inode: First inode number in the file system

See more:

```
# dumpe2fs /dev/sda1
```

## Ext2 File Types

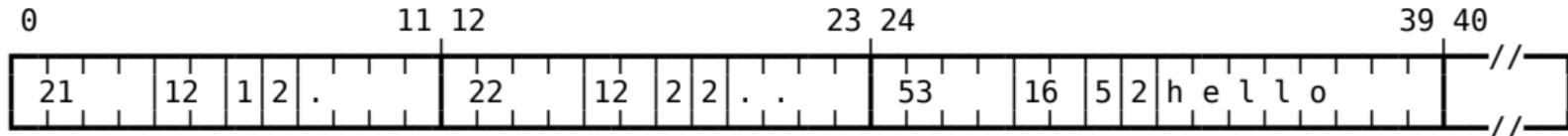
File type	Description
0	Unknown
1	Regular file
2	Directory
3	Character device
4	Block device
5	Named pipe
6	Socket
7	Symbolic link

**Device file, pipe, and socket:** No data blocks are required. All info is stored in the inode

**Fast symbolic link:** Short path name (< 60 chars) needs no data block. Can be stored in the 15 pointer fields

## 19.5 Ext2 Directory

# Ext2 Directories



→ inode number  
→ record length  
→ name length  
→ file type  
→ name



- ▶ Directories are special files
- ▶ “.” and “..” first
- ▶ Padding to 4 ×
- ▶ inode number is 0 — deleted file

## 20 Virtual File Systems

# Many different FS are in use

## Windows

uses drive letter (C:, D:, ...) to identify each FS

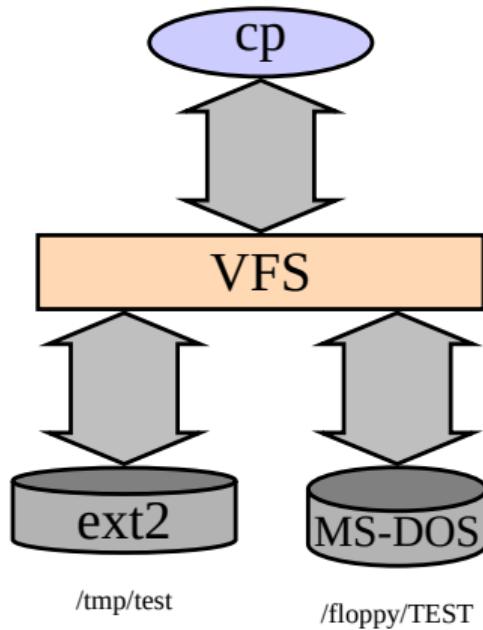
## UNIX

integrates multiple FS into a single structure

- ▶ From user's view, there is only one FS hierarchy

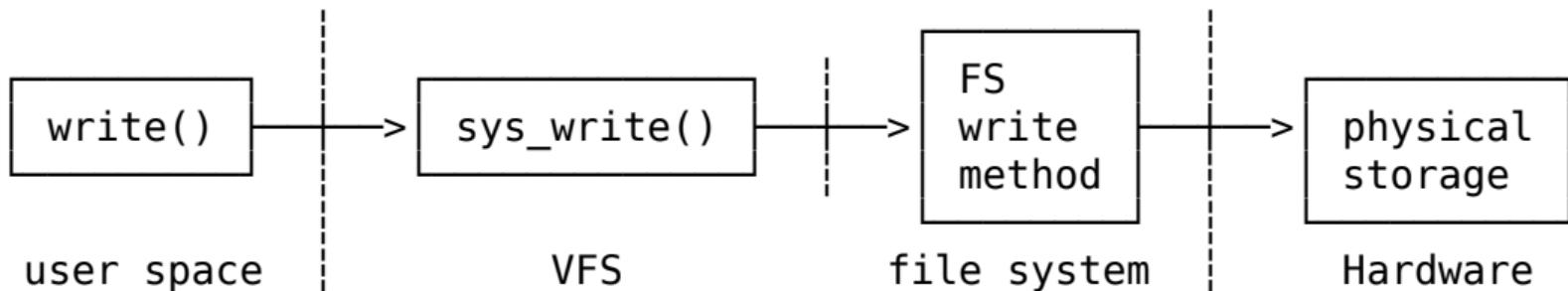
```
$ man fs
```

```
$ cp /floppy/TEST /tmp/test
```



```
1 inf = open("/floppy/TEST", O_RDONLY, 0);
2 outf = open("/tmp/test",
3                 O_WRONLY|O_CREAT|O_TRUNC, 0600);
4 do{
5     i = read(inf, buf, 4096);
6     write(outf, buf, i);
7 } while (i);
8 close(outf);
9 close(inf);
```

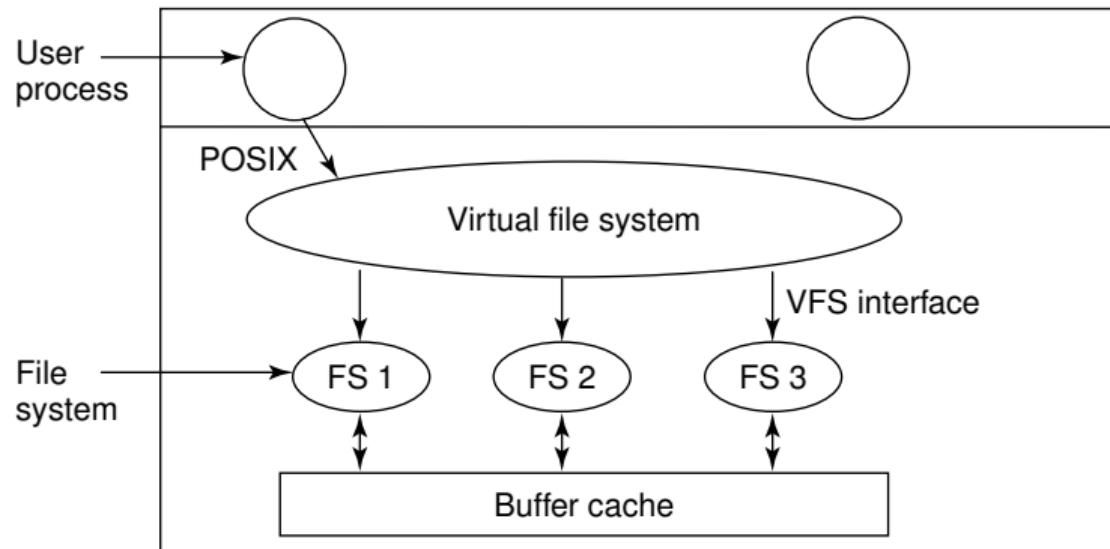
```
1| ret = write(fd, buf, len);
```



# Virtual File Systems

Put common parts of all FS in a separate layer

- ▶ It's a layer in the kernel
- ▶ It's a common interface to several kinds of file systems
- ▶ It calls the underlying concrete FS to actual manage the data



## Virtual File System

- ▶ Manages kernel level file abstractions in one format for all file systems
- ▶ Receives system call requests from user level (e.g. write, open, stat, link)
- ▶ Interacts with a specific file system based on mount point traversal
- ▶ Receives requests from other parts of the kernel, mostly from memory management

## Real File Systems

- ▶ managing file & directory data
- ▶ managing meta-data: timestamps, owners, protection, etc.
- ▶ 

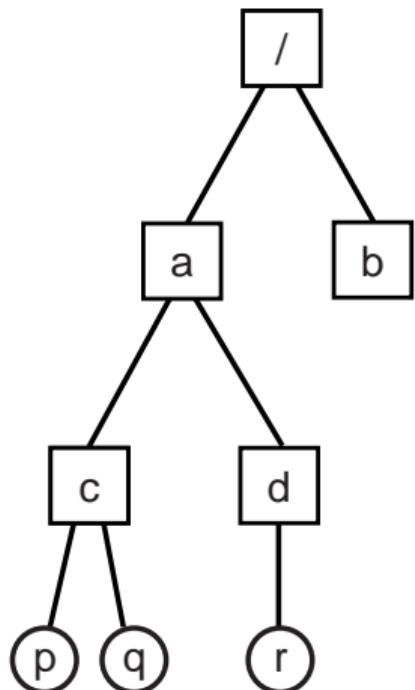
disk data, NFS data...

 $\xleftarrow{\text{translate}}$ 

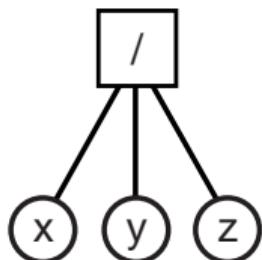
VFS data

# File System Mounting

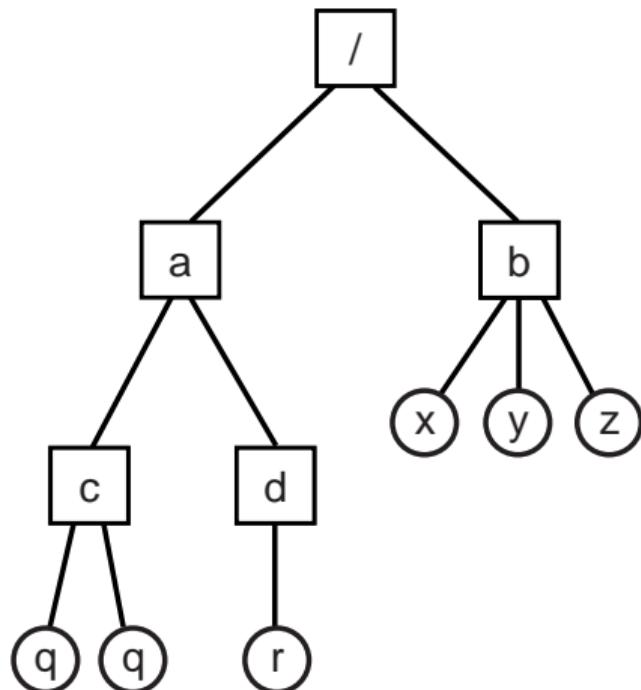
Hard disk



Diskette



Hard disk



## A FS must be mounted before it can be used

### Mount — The file system is registered with the VFS

- ▶ The superblock is read into the VFS superblock
- ▶ The table of addresses of functions the VFS requires is read into the VFS superblock
- ▶ The FS' topology info is mapped onto the VFS superblock data structure

The VFS keeps a list of the mounted file systems together with their superblocks

The VFS superblock contains:

- ▶ Device, blocksize
- ▶ Pointer to the **root inode**
- ▶ Pointer to a set of superblock routines
- ▶ Pointer to `file_system_type` data structure
- ▶ more...

## V-node

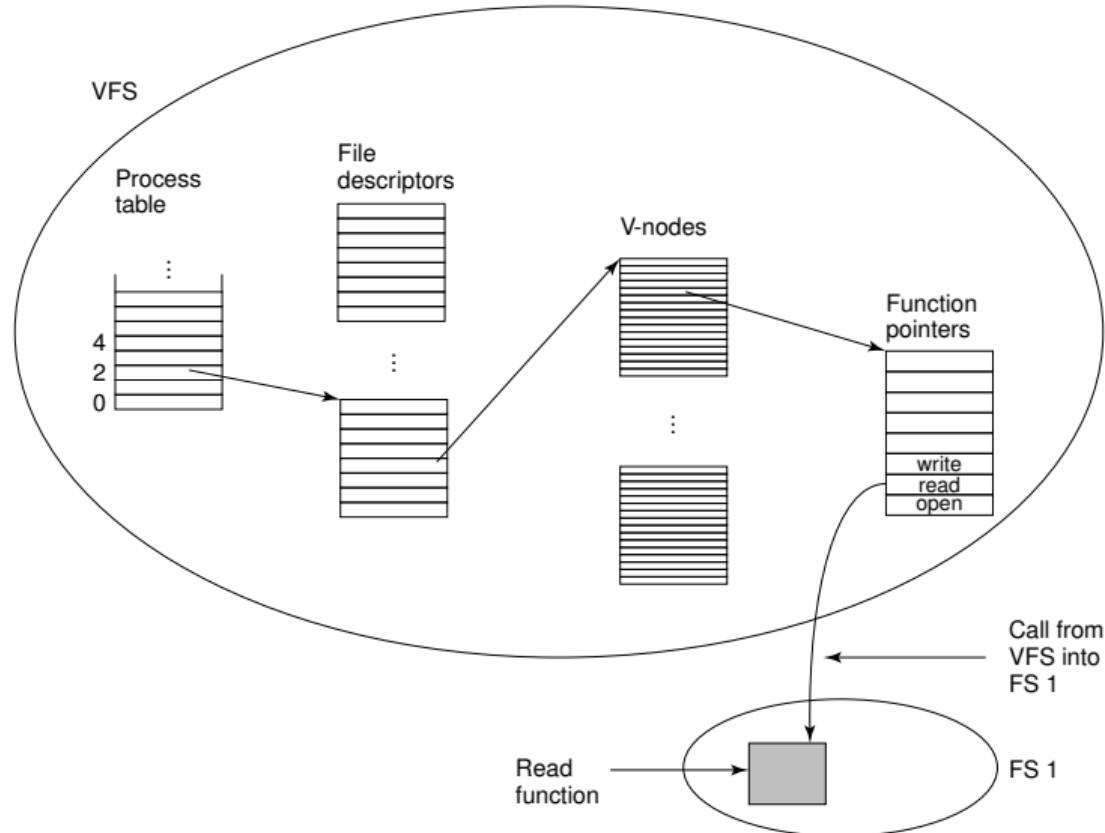
- ▶ Every file/directory in the VFS has a VFS inode, kept in the VFS [inode cache](#)
- ▶ The real FS builds the VFS inode from its own info

Like the EXT2 inodes, the VFS inodes describe

- ▶ files and directories within the system
- ▶ the contents and topology of the Virtual File System

# VFS Operation

read()



## The Common File Model

All other filesystems must map their own concepts into the common file model

For example, FAT filesystems do not have inodes.

- ▶ The main components of the common file model are
  - superblock** – information about mounted filesystem
  - inode** – information about a specific file
  - file** – information about an open file
  - dentry** – information about directory entry
- ▶ Geared toward Unix FS

## The Superblock Object

- ▶ is implemented by each FS and is used to store information describing that specific FS
- ▶ usually corresponds to the **filesystem superblock** or the **filesystem control block**
- ▶ Filesystems that are not disk-based (such as sysfs, proc) generate the superblock on-the-fly and store it in memory
- ▶ `struct super_block` in `<linux/fs.h>`
- ▶ `s_op` in `struct super_block` → `struct super_operations` — the superblock operations table
  - ▶ Each item in this table is a pointer to a function that operates on a superblock object

## The Inode Object

- ▶ For Unix-style filesystems, this information is simply read from the on-disk inode
- ▶ For others, the inode object is constructed in memory in whatever manner is applicable to the filesystem
- ▶ `struct inode` in `<linux/fs.h>`
- ▶ An inode represents each file on a FS, but the inode object is constructed in memory only as files are accessed
  - ▶ includes special files, such as device files or pipes
- ▶ `i_op` → `struct inode_operations`

## The Dentry Object

- ▶ components in a path
- ▶ makes path name lookup easier
- ▶ struct dentry in <linux/dcache.h>
- ▶ created on-the-fly from a string representation of a path name

## Dentry State

- ▶ used
- ▶ unused
- ▶ negative

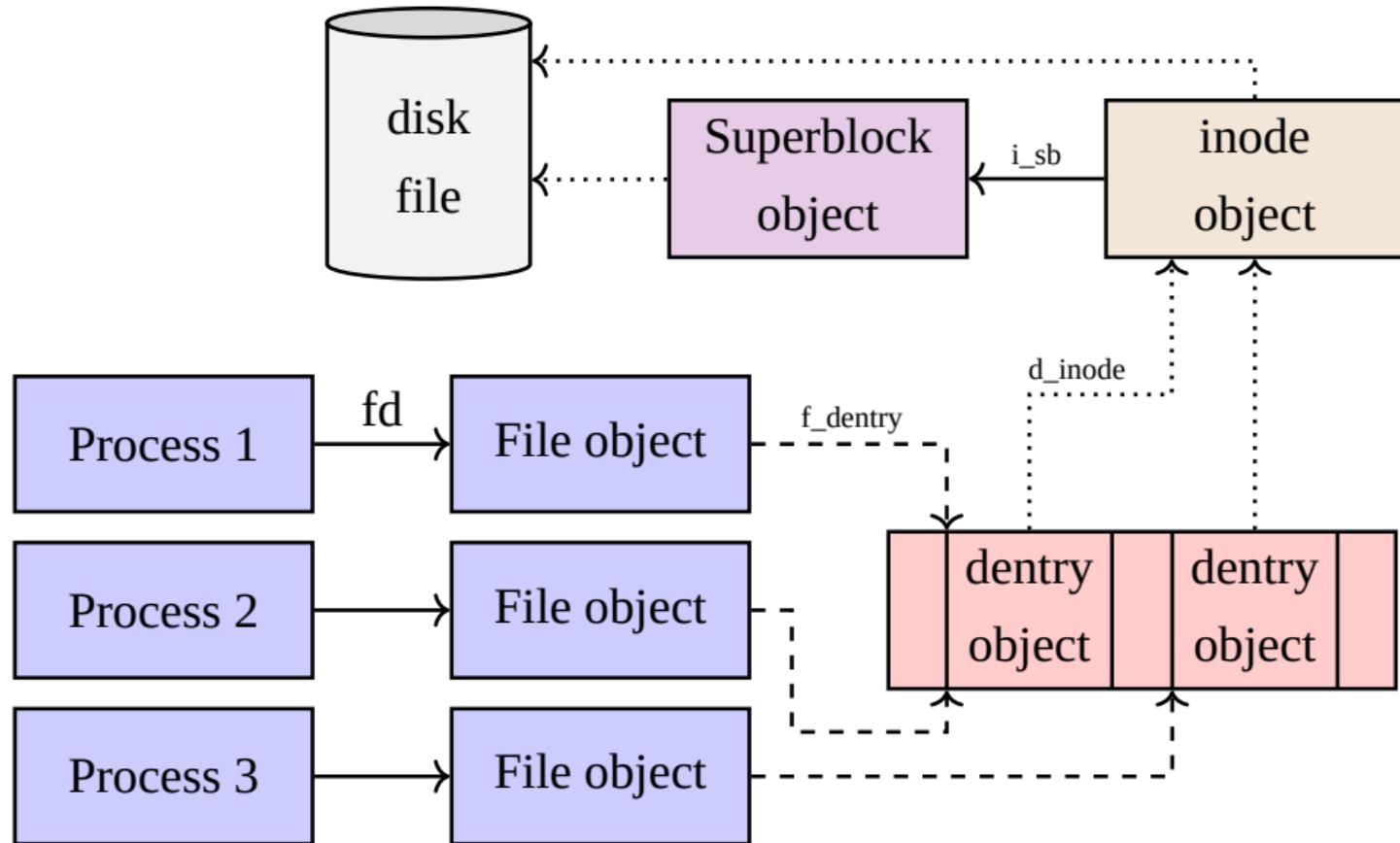
## Dentry Cache

consists of three parts:

1. Lists of “used” dentries
2. A doubly linked “least recently used” list of unused and negative dentry objects
3. A hash table and hashing function used to quickly resolve a given path into the associated dentry object

## The File Object

- ▶ is the in-memory representation of an open file
- ▶ `open()` ⇒ create; `close()` ⇒ destroy
- ▶ there can be multiple file objects in existence for the same file
  - ▶ Because multiple processes can open and manipulate a file at the same time
- ▶ `struct file` in `<linux/fs.h>`



## References

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[http://en.wikipedia.org/w/index.php?title=File%5C\\_system&oldid=646603121](http://en.wikipedia.org/w/index.php?title=File%5C_system&oldid=646603121).
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[http://en.wikipedia.org/w/index.php?title=Virtual%5C\\_file%5C\\_system&oldid=640354992](http://en.wikipedia.org/w/index.php?title=Virtual%5C_file%5C_system&oldid=640354992).