

OS Condensed Summary Notes For Quick In-Exam Strategic Fact Deployment

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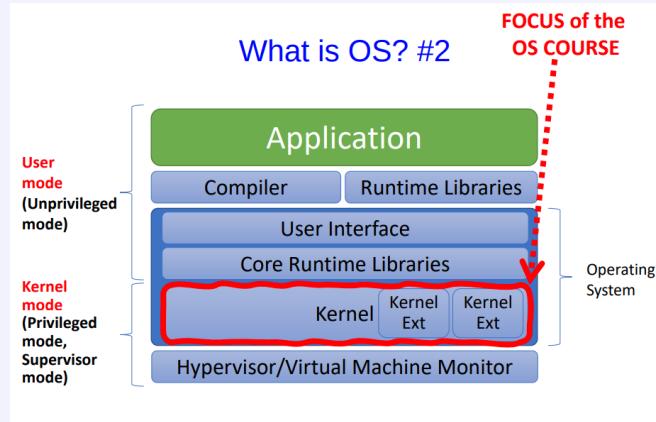
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OS

Introduction & Structure

OS

An intermediary between the user of a computer and computer hardware. A program itself most intimately connected to the hardware. Everything you don't need to write in order to run your application. Library, all operations on I/O, syscalls. The OS can be an invisible intermediary



Main benefits of OS abstraction:

- Application benefits
 - programming simplicity - see high level abstraction (files) instead of low level hardware details (device registers)
 - abstractions are **reusable** across many platforms
 - **portability** (across machine configurations or architectures) - device independence: 3com or intel card?
- User benefits
 - safety: program sees its own virtual machine, can believe it owns the computer
 - OS **protects** programs from each other
 - OS **fairly multiplexes** resources across programs
 - efficiency - **share** one computer across many users. **Concurrent** execution of multiple programs

Basic OS Concepts

Multiprogramming : ability to keep multiple programs running in parallel (almost). This is done by keeping all possible jobs in the **job pool** on the disk, when a job is ready to take its turn to execute, it's brought to main memory and run for a bit until the OS decides to switch it for another (because of an interrupt) or it completes.

Multitasking/timesharing : while multiprogramming makes the OS efficient, it does not facilitate for user interaction! For the user to be able to run multiple tasks simultaneously and have a smooth experience, the CPU needs to actually switch jobs much more frequently so as it appears that all of them are being processed simultaneously. A system which facilitates **timesharing** is **interactive** - it frequently awaits user input and has short response time. A time-shared system enables the system to be used by **multiple** users simultaneously.

Process : a program which is loaded in main memory. This may be a full program, or a printer job. Processes may spawn sub-processes if they wish to use syscalls. This is the **unit of work in a system**.

Job scheduling : prioritising which jobs should be in main memory at any time.

CPU scheduling : prioritising which jobs in main memory should be executed first.

Virtual memory : a technique that allows each program to see the entire memory as theirs and not mess with other processes as well as running programs which require more memory than is **physically available**

Logical memory : memory as seen by the programmer, abstracted away from the nitty-gritty mechanical details of the OS.

Interrupt driven : if there's no demand for action from the OS, it will IDLE. Events are almost always signalled by the occurrence of an interrupt or a trap

Trap : (exception) is a software generated interrupt caused by either an error or a syscall.

Dual-mode/multimode operation : in a multiprogramming system processes are run in parallel, hence protections must be put into place so that processes cannot impede other processes. Most commonly this is done via introduction of **user mode** and **kernel mode**. In user mode certain possibly harmful **privileged instructions** are forbidden by the **hardware itself** which sends a trap signal (switch to kernel mode, timer management, I/O control)

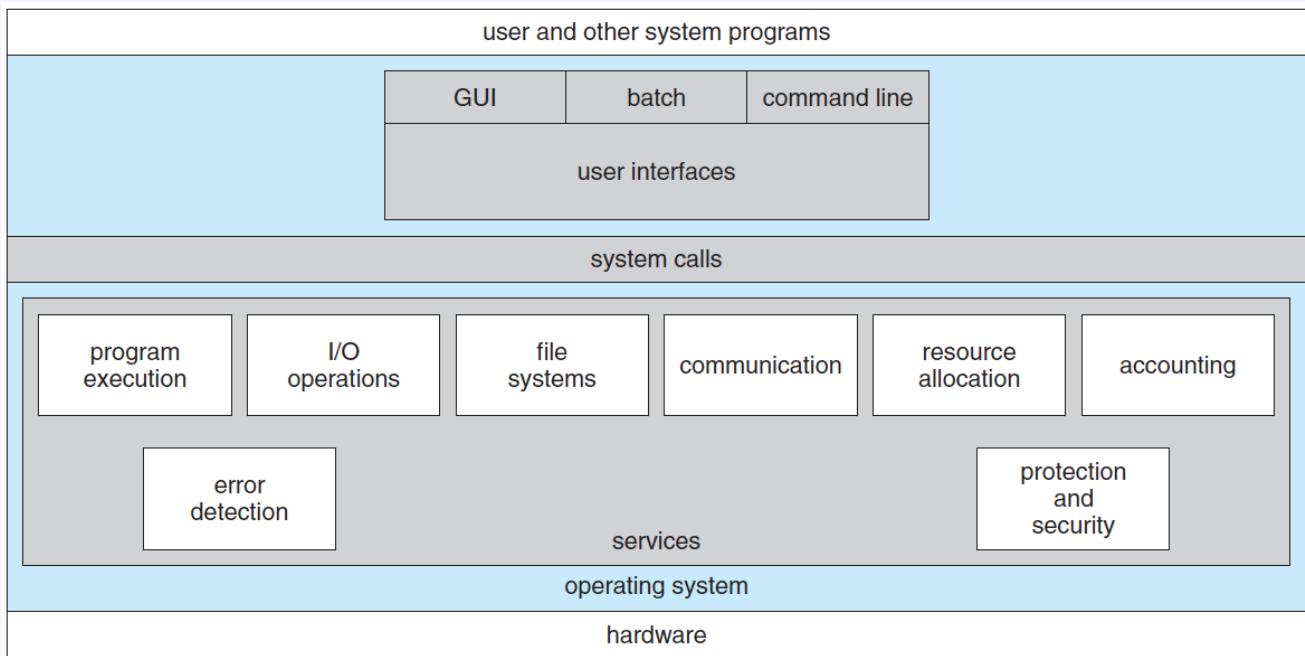
Virtual machine manager : virtual machine management software which can be set to run on a third mode (which requires more mode bits), giving it less power than the kernel but more than the user. Virtualisation does not necessarily require its own privilege level

Mode bits : reserved bits in the hardware which signify which mode we're in. Typically 0 = user mode and 1 = kernel mode. Always set

before passing control to the user program.

File : abstract memory concept which is mapped to physical storage space. Each file may contain absolutely any data. The OS is responsible for creating/removing files, creating removing directories to organise files, supporting primitives for manipulating files and directories, mapping files onto secondary storage, backing up files on stable (nonvolatile) storage media.

OS Services



User Interface : can appear in many different forms, CLI, GUI or batch - where commands and directives run directly from files.

Program execution : the OS loads programs into memory and runs their instructions, then halts them.

IO Operations : interactions with external devices such as the keyboard or mouse.

File-system manipulation : search through files and directories, creation and deletion of files, permission management.

Communications : facilities for exchanging information between different processes on the same computer or via network. I.e. **Shared memory** or perhaps **message passing**.

Error detection : the OS needs to be aware of errors which occur and correct them as they appear. These can happen anywhere in the system, including hardware and software.

Resource allocation : distribution of resources available to different jobs and users at the same time efficiently.

Accounting : keeping track of who used what resources for either economic purposes or analytics.

Protection and security : all data needs to be securely stored and only available to the users who have the correct permissions. Several processes cannot interfere with each other or harm the system.

Command interpreter : allows the user to directly interface with the system via commands either in the form of a GUI or CLI or in other forms. When multiple are available these are shown as **shells**. The commands themselves may be stored by the shell, or the shell might simply direct the appropriate loading of file-stored directives which run the appropriate commands (i.e. PATH resolution)

System calls : calls to the OS to develop certain specific functions such as opening files or starting sub-processes. Many OS use API's on top of system calls to make portability more achievable.

System-call interface : the interface provided by programming languages to interface with the system calls in different OS' which the compiler knows the specifics of.

Syscalls

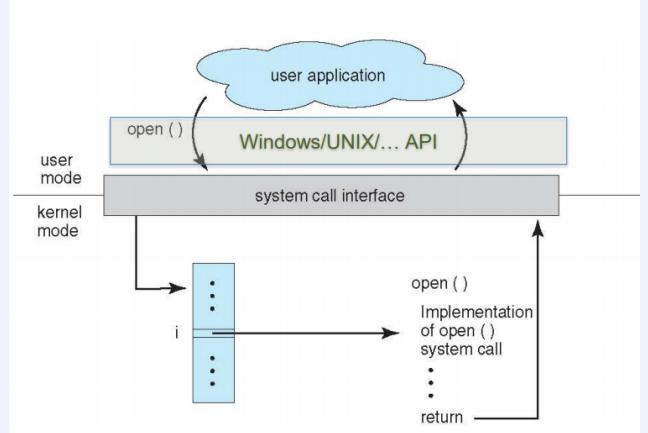
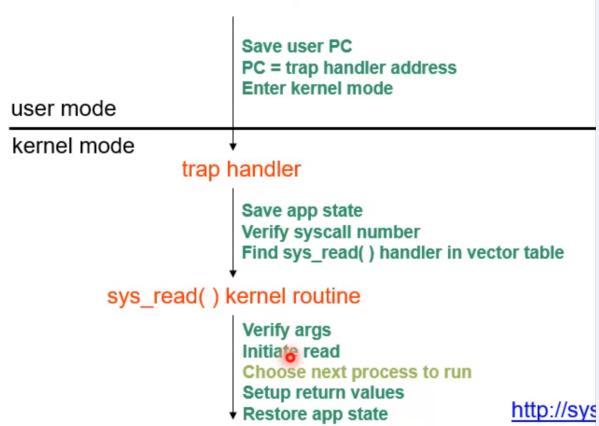
The user cannot perform IO operations by himself, he must ask the OS to do it for them.

Syscalls define procedures which the OS performs for the user in privileged mode.

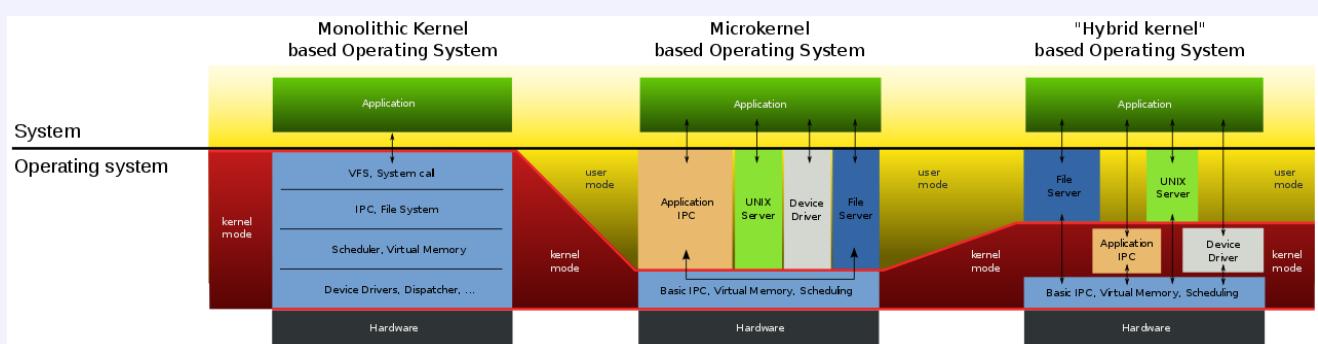
Usually implemented as vectors, where each syscall is simply an offset to a base address.

Mechanically just a procedure call (but is not one! in a normal procedure call the caller knows the location of the procedure, in this case a syscall is just an ID), the caller puts arguments in a place the callee expects, then retrieves output from known place. Usually each system call will have wrapper functions provided by each programming language, i.e. the **system call interface**, which the compiler understands.

Firefox: `read(int fileDescriptor, void *buffer, int numBytes)`



OS Structures



Monolithic Kernel

All major subsystems implemented in kernel.

- + low system interaction cost (procedure call)
- hard to understand and modify
- unreliable (no isolation between system modules)
- hard to maintain

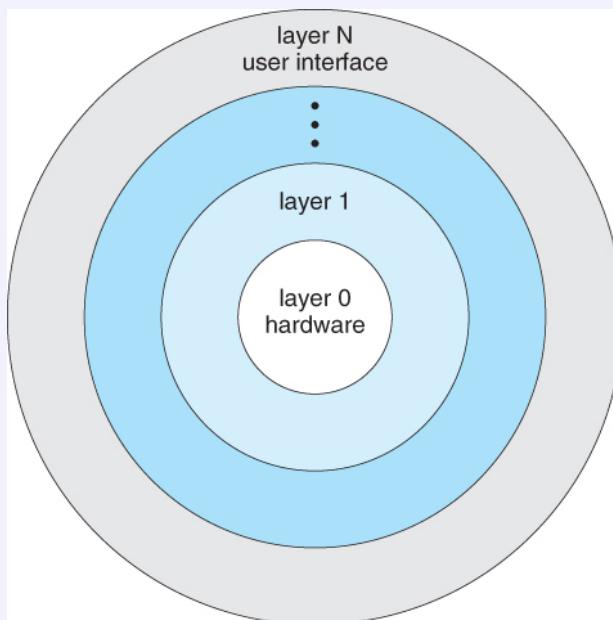
Microkernel

Minimize what goes into kernel, implement rest of OS as user-level processes

- + better reliability (isolation between components)
- + ease of extension and customization (easy to replace parts)
- poor performance (a lot of user/kernel switches)

Layered Kernel

Implement OS as a set of layers, each layer interacts only with layer below.



- + more reliable (separation of components)
- strict layering isn't flexible enough - in real life modules might need to communicate with not only nearby layers.
- poor performance, each layer crossing has overhead associated with it (due to API generalization)
- Disjunction between model and reality - system modelled as layers, but not really built that way

Dynamically loadable kernel modules

Core services in the kernel, others dynamically loaded.

Common in modern implementations:

- **Monolithic:** load the code in kernel space (Solaris, Linux, etc.)
- **Microkernel:** load the code in user space (any)
 - + Convenient: no need for rebooting for newly added modules
 - + Efficient: no need for message passing unlike microkernel
 - + Flexible: any module can call any other module unlike layered model
 - Memory fragmentation: fragments OS memory which is normally unfragmented when loaded initially

Hybrid OS Design

Many different approaches. Key idea: exploit the benefits of monolithic and microkernel designs. Extensibility via kernel modules.

IO

I/O

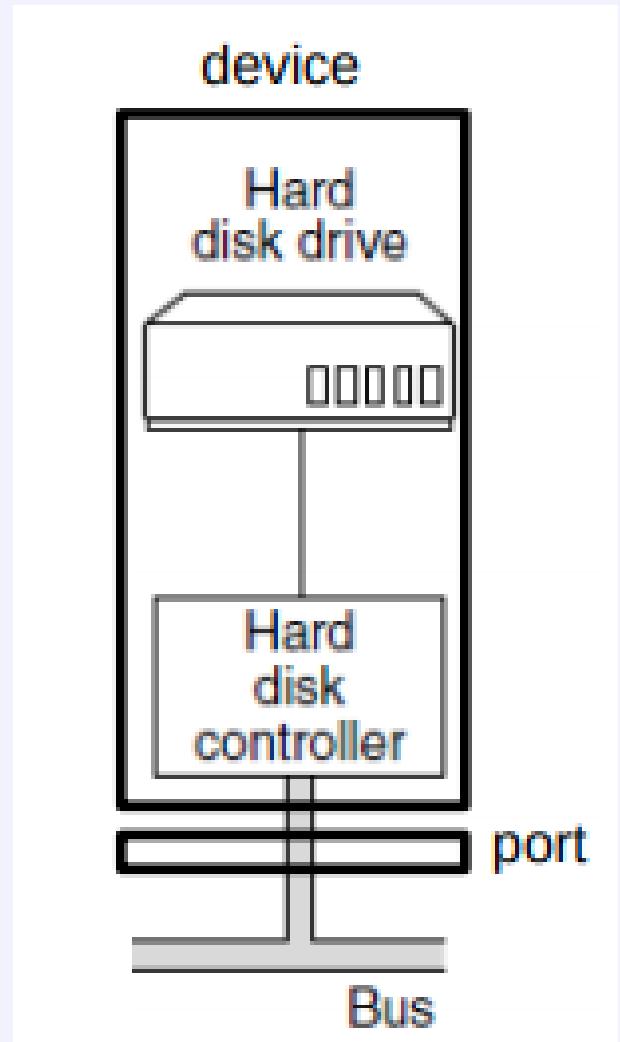
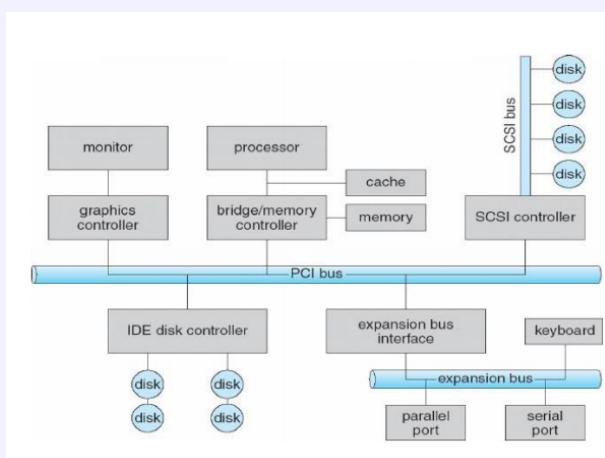
Variety of I/O Devices

Port : Connection point for a device (e.g., USB, parallel, serial, ethernet)

Bus : Peripheral buses (e.g. PCI/PCIe), Expansion bus connects relatively slow devices

Device

Controller(host adapter) : electronics that operate port, bus, device (sometimes integrated). Contains processor, microcode, private memory, bus controller etc.



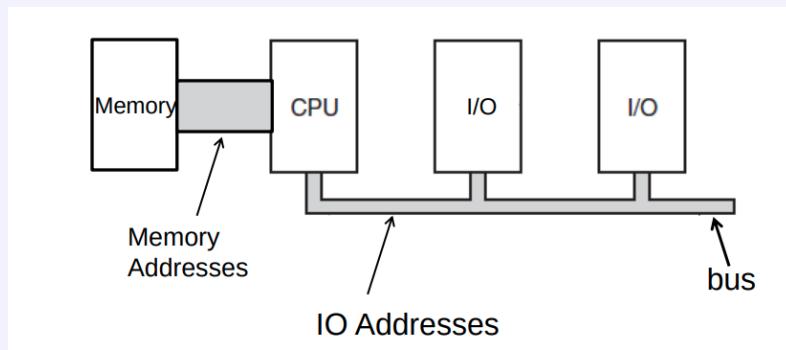
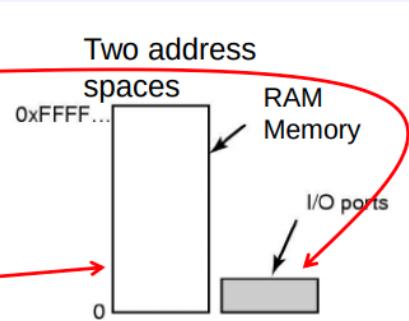
Controllers have **registers** for data and control as well as **buffers**, mostly for data. Communication Methods:

- **IO Ports**
- **Memory-mapped IO**
- **Hybrid**

I/O Ports

- Each control register has an I/O port number
- Special instructions exist to access the I/O port space
- CPU reads from device I/O PORT to CPU register (IN REG, PORT)
- CPU writes to device I/O PORT from CPU register (OUT PORT, REG)
- Instructions are privileged (OS kernel only)
- Separate I/O Port space and memory space:

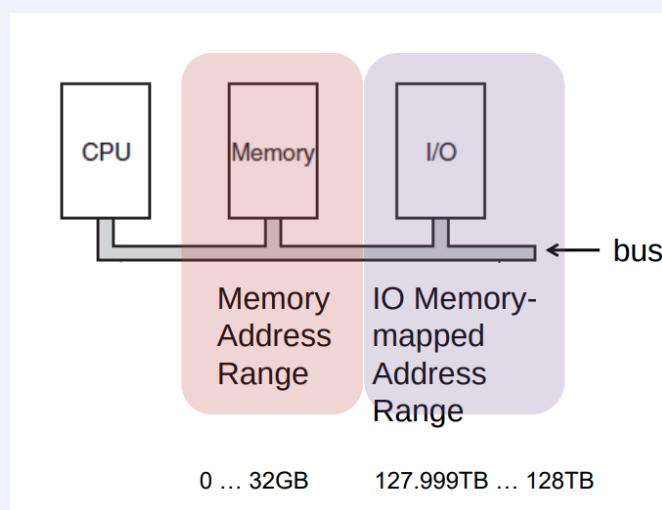
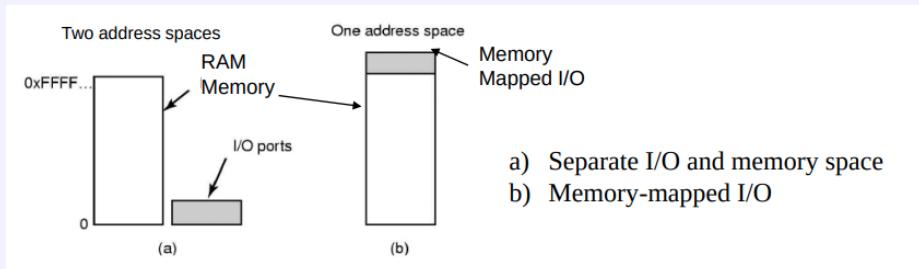
- I/O instructions
 - IN R0, 4
 - OUT 4, R0
- Similar memory access instruction
 - MOV R0, 4
 - MOV 4, R0



I/O address range (hexadecimal)	device
000–00F	DMA controller
020–021	interrupt controller
040–043	timer
200–20F	game controller
2F8–2FF	serial port (secondary)
320–32F	hard-disk controller

Memory Mapped I/O

- All control registers and buffers mapped into the memory space
- Each control register is assigned a unique memory address
- There is no actual RAM memory for that address
- Such addresses may be at the top of the physical address space



Hybrid I/O

Simply do both, use memory mapped I/O for the **data buffers**, and keep separate I/O ports for **control registers**.

Offloaded Communication

The CPU can request data from an I/O controller one byte at a time (Programmed IO). This wastes CPU time for large data transfers, small data transfers are ok.

CPU can instead offload data transfers using DMA:

DMA (Direct Memory Access) controller transfers data from the CPU, either from/to IO or between IO devices.

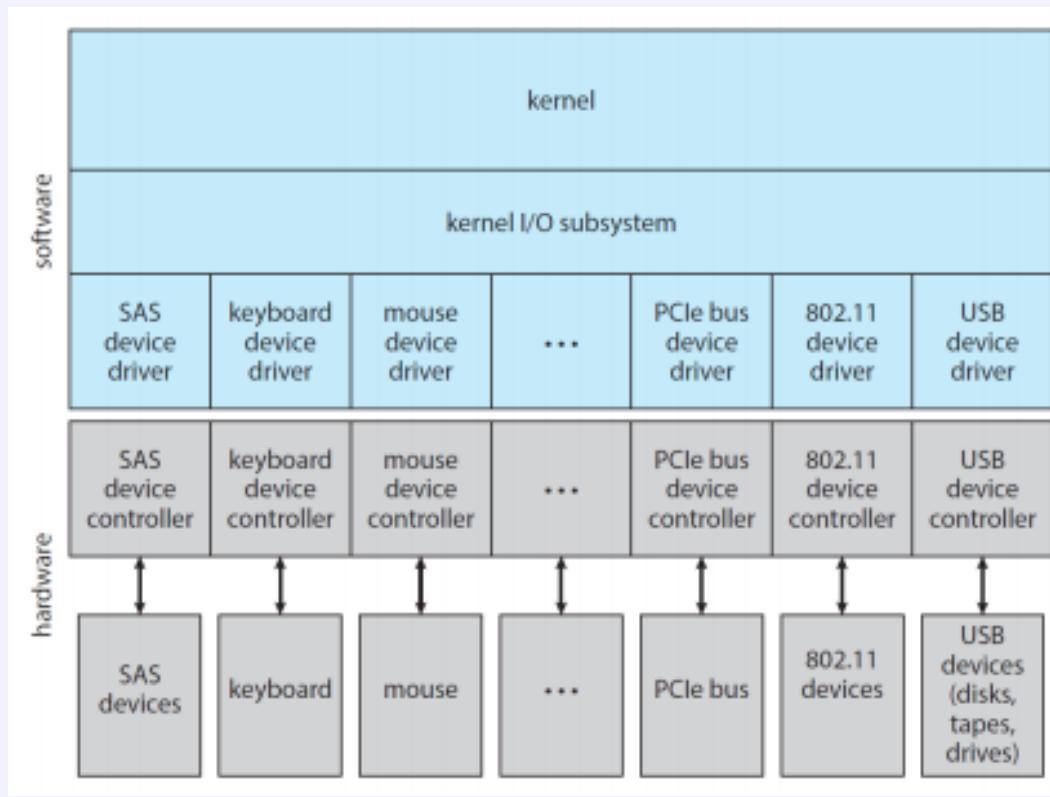
This requires a DMA controller either on the device's host controller, and the motherboard. This controller contains registers to be read/written by the software:

- Memory address register
- byte count register
- Control registers: direction, unit, byte burst size etc..

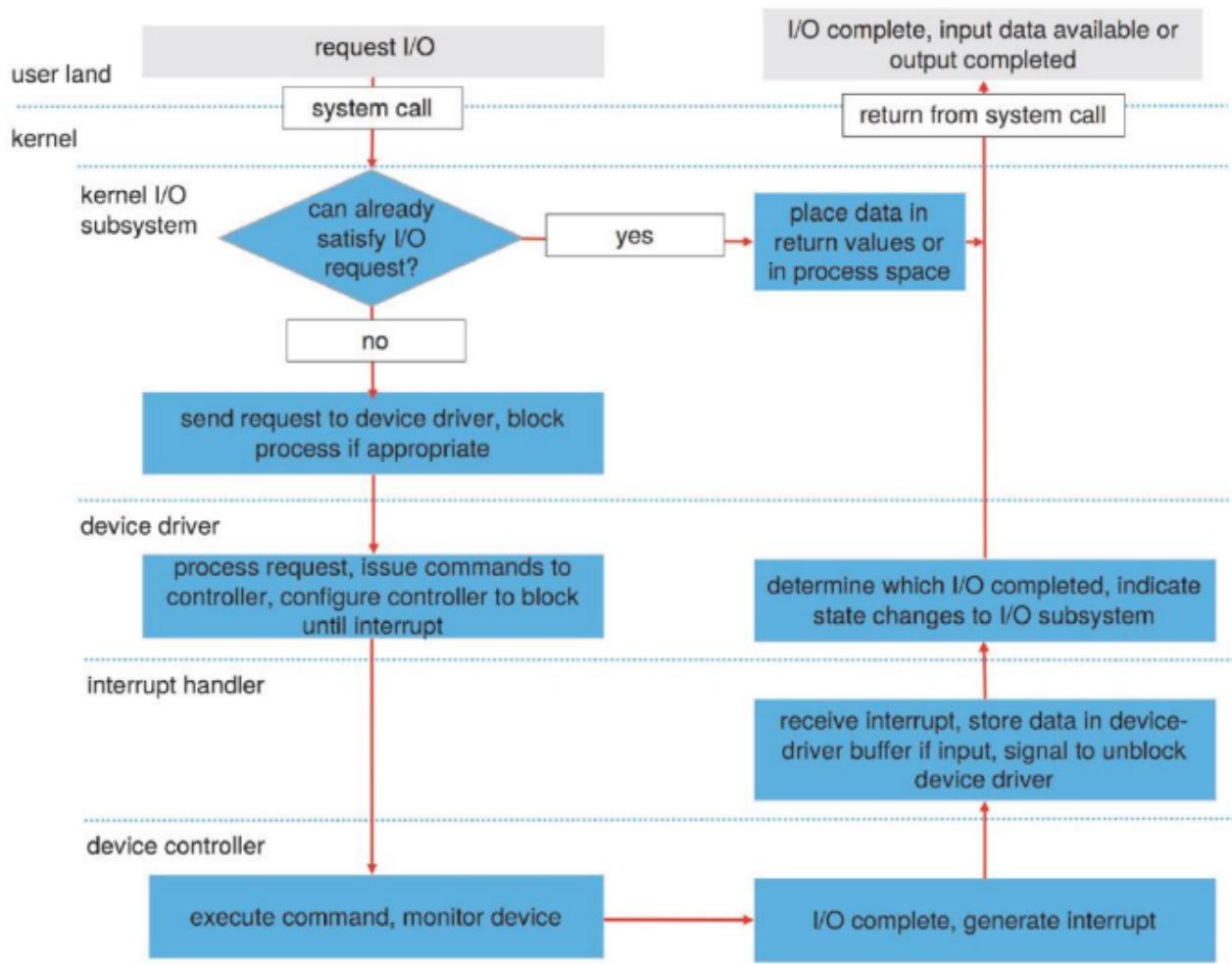
OS Device drivers

Great variety of devices, each one has very different specs.

OS Deals with IO devices in a standard and uniform way. Each type of driver is an interface which the vendor can implement as a class. Each OS has its own standard.



Life cycle of an IO request



Processes

Process

Process is the OS's abstraction for execution.

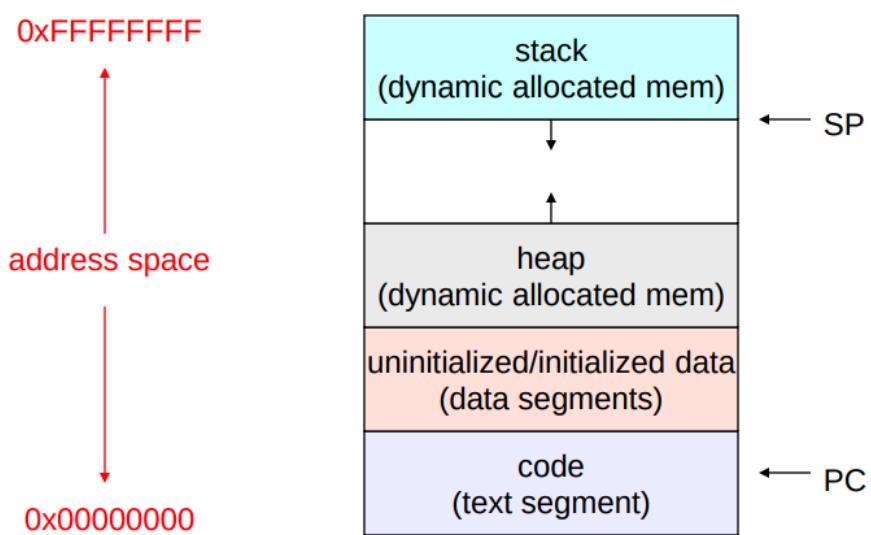
- Program is the list of instructions, initialized data, etc
- A process is a **program in execution**
- A single flow/sequence of instruction in execution
- An address space (an abstraction of the CPU)

Only one process can be running on a processor core at any instant

Contents:

- An address space, containing:
 - Code (instructions) for running program
 - Data for the running program (static data, heap data, stack)
- A CPU state, consisting of
 - Program counter, indicating the next instruction
 - Stack pointer, current stack position
 - Other general-purpose register values
- A set of OS resources
 - Open files
 - network connections
 - sound channels

I.e. everything needed to run the program



Each process is identified by a process ID (**PID**). PID's are unique and global. With certain exceptions (cgroups)

Operations that create processes return a PID, and those which operate on processes accept PID's as arguments

Process representation

Each process is represented internally by the OS with a **Process control block (PCB)** or process/task descriptor, identified by the PID.

OS keeps all of a process's execution state in (or linked from) the PCB when the process isn't running:

- PC, SP, registers etc.
- when a process execution is stopped, its state is transferred out of the hardware into the PCB

When the process is running its state is spread between the PCB and the hardware (CPU regs)

PCB's contain:

- Process ID (PID)
- Parent process ID
- Execution state
- PC, SP, registers
- Address space info
- UNIX user ID, group ID
- Scheduling priority
- Accounting info
- Pointers for state queues

and likely many more.

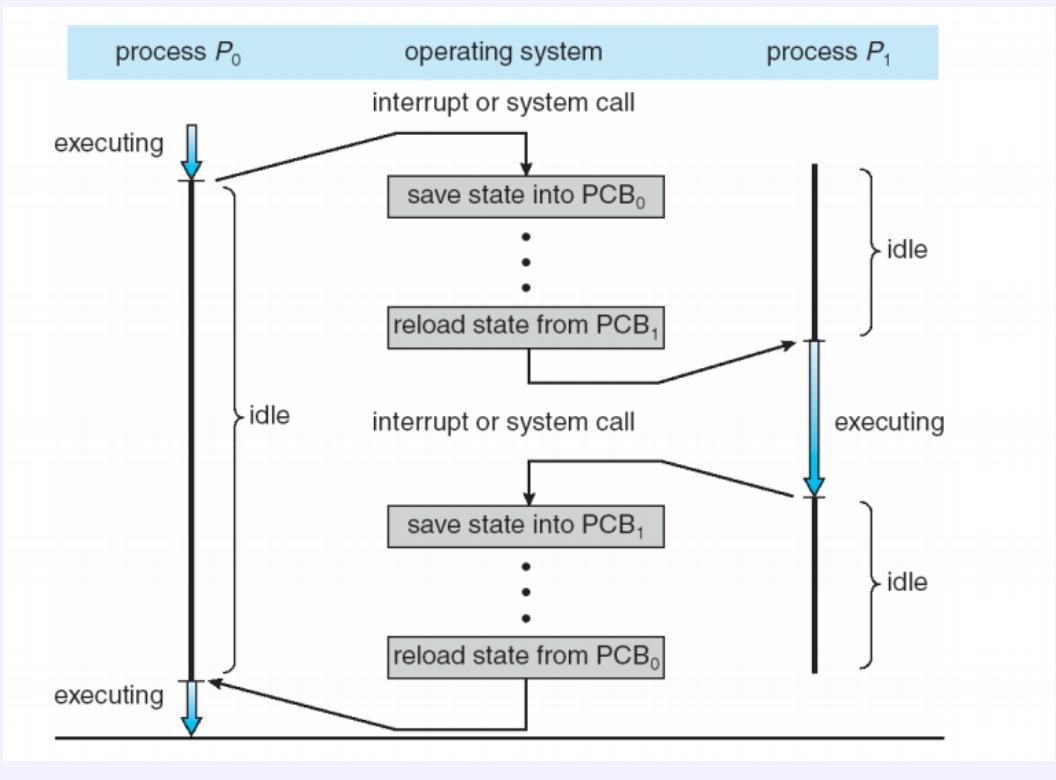
Whenever the OS gets control because of :

- Syscalls
- Exceptions
- Interrupts

The OS then saves the CPU state into the PCB. Whenever the process is resumed into execution again, its PCB is loaded onto the machine registers SP, PC etc.

This is called a **Context switch**

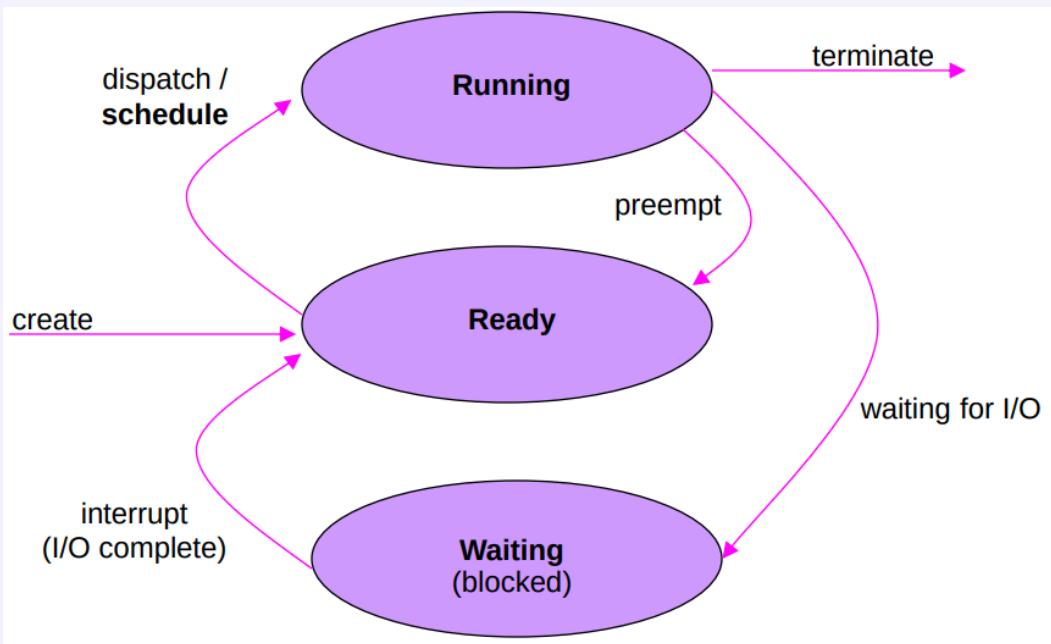
Context Switch



Execution states

Each process has an **Execution state**, which indicates what it's currently doing.

- **Ready:** waiting to be assigned to a CPU
- **Running:** executing on a CPU
- **Waiting:** Waiting for an event, e.g. IO completion, or a message from another process.



State queues

The OS maintains a collection of queues, that represent the state of all processes in the system. Typically one queue for each state (executing, waiting etc..) Each PCB is queued onto a state queue according to the current state of the process it represents. As a process changes state, its PCB is unlinked from one queue, and then linked onto another.

There may be many wait queues, one for each type of wait (specific device, timer, message) etc.

Process creation

New processes are created by existing processes (parent-child)

The first process is started by the OS, everything else stems from it (init in linux)

Depending on OS, child processes inherit certain attributes of parent, (i.e. open file table: implies stdin/stdout/stderr) Some systems divide resources of parent between children.

UNIX - fork()

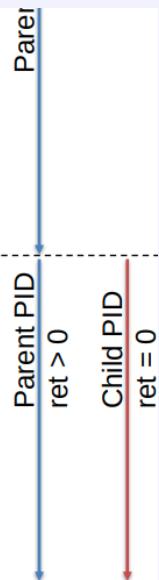
On UNIX systems, process creation is done through the fork() system call:

- Creates and initializes a new PCB
- Initializes kernel resources of new process with resources of parent (e.g. open files)
- Initializes PC,SP to be same as parent
- Creates a new address space, which is an identical copy of this of the parent's (by value)

The fork call returns "twice" once in the parent, and once in the child. In the child the PID returned is 0 and in the parent, the child's PID is returned.

```
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

int main(int argc, char **argv)
{
    char *name = argv[0];
    int ret = fork();
    if (ret < 0) { /* error */
        printf("Error\n");
        return 1;
    } else if (ret > 0) { /* parent */
        printf("Child of %s is %d\n", name, ret);
        return 0;
    } else { /* child */
        printf("My child is %d\n", ret);
        return 0;
    }
}
```

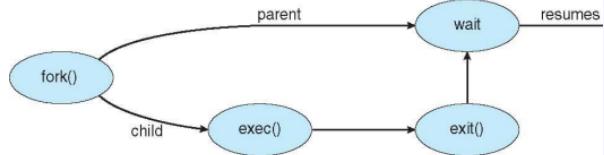


UNIX - exec()

In order to start a new program instead of just copying the old one, we must use exec(). Which is the call which stops the current process, loads a new program into the address space, initializes the hardware context and args for the new program and finally places the PCB onto the ready queue

```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int main() {
    pid_t pid;
    pid = fork(); /* fork a child process */
    if (pid < 0) { /* error occurred */
        fprintf(stderr, "Fork Failed");
        return 1;
    }
    else if (pid == 0) { /* child process */
        execvp("/bin/ls", "ls", NULL);
    }
    else { /* parent process */
        wait(NULL); /* parent waits for the child to complete */
        printf("Child Complete");
    }
    return 0;
}
```



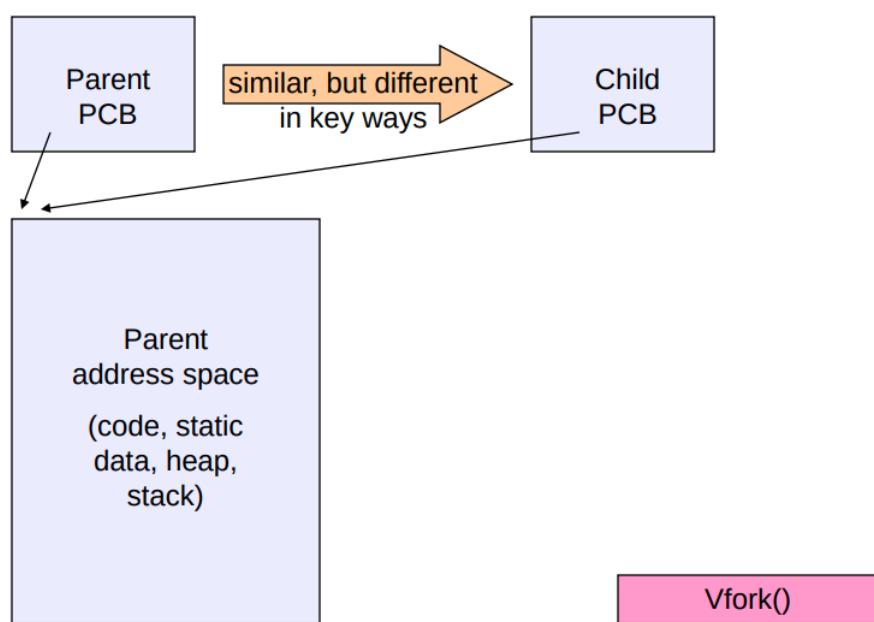
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Alternatively use vfork() which is faster but less safe

UNIX - vfork()

Same as fork, but the child's address space **IS** by address the same space as the parents.

Usage relies on the child not modifying the address space before doing an execve() call, otherwise bad things can happen.



Copy-on-write (COW) fork()

Retains original semantics, but copies "only what is necessary" rather than the entire address space.
On fork():

- create a new address space
- initialize page tables with same mappings as parents (identical)
- Set both parent and child page tables to make all pages read-only
- if either parent or child writes to memory, an exception occurs
- On exception, OS copies the page, adjusts page tables, etc..

Interprocess communication

Shared memory

Allow processes to communicate and synchronize:

- Sharing part of address space
- OS doesn't mediate communication (no overhead)
- Usually OS prevents processes from accessing each other's memory
- Processes should agree to void this restriction

Data:

- Format decided by application
- Direct access (not mediated by the OS) - very fast
- Application programmer fully manages the data transfer - not trivial

Possible use cases:

- Passing of large (single) objects (image)
- Notification variable

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <fcntl.h>
#include <sys/shm.h>
#include <sys/stat.h>
#include <sys/mman.h>

int main() {
    const int SIZE = 4096; /* the size (bytes) of shared memory object */
    const char *name = "OS"; /* name of the shared memory object */
    const char *message 0 = "Hello"; /* written to shared memory */
    const char *message 1 = "World!"; /* written to shared memory */
    int fd; /* shared memory file descriptor */
    char *ptr; /* pointer to shared memory object */

    /* create the shared memory object */
    fd = shm_open(name,O_CREAT | O_RDWR,0666);
    /* configure the size of the shared memory object */
    ftruncate(fd,SIZE);
    /* memory map the shared memory object */
    ptr = (char *)
        mmap(0,SIZE,PROT_READ | PROT_WRITE,MAP_SHARED,fd,0);
    /* write to the shared memory object */
    sprintf(ptr,"%s",message 0);
    ptr += strlen(message 0);
    sprintf(ptr,"%s",message 1);
    ptr += strlen(message 1);

    return 0;
}

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    int fd; /* shared memory file descriptor */
    char *ptr; /* pointer to shared memory object */

    /* open the shared memory object */
    fd = shm_open(name,O_RDONLY,0666);
    /* memory map the shared memory object */
    ptr = (char *)
        mmap(0,SIZE,PROT_READ | PROT_WRITE,MAP_SHARED,fd,0);
    /* read from the shared memory object */
    printf("%s",(char *)ptr);
    /* remove the shared memory object */
    shm_unlink(name);

    return 0;
}
```

Message Passing

Allow processes to communicate and synchronize:

- Without sharing part of address space
- OS mediates communication (overhead likely)

Works with processes on the same machine and also those on different inter-networked machines! This is not possible with shared memory.

Message passing facility provides at least two operations:

- Send(message)
- Receive(message)

Communication link:

- Several implementation tradeoffs, .e.g. messages size
- Fixed
- Variable

Communicating processes must refer to each other:

- Direct communication:
 - Symmetric: explicit name of sender and receiver
 - * send(P, message) - send message to P
 - * receive(P, message) - receive message from P
 - Assymmetric: Explicit at least on one end:
 - * send(P, message) - send to p
 - * receive(id, message) - receive from any process, sender saved in id
- Indirect communication:
 - No need to know/explicitly in advance sender and/or receiver
 - Mailboxes (e.g., POSIX mailbox)
 - * send(A, message) - send message to mailbox A
 - * receive(A, message) - receive message from mailbox A
 - A mailbox can be accessed by more than two processes
 - Multiple mailboxes might exist between processes

send() and receive() calls might be implemented as **blocking** or **synchronous** as well as **nonblocking** or **asynchronous**. different combinations of these might be offered:

- Blocking send
- Nonblocking send
- Blocking receive
- Nonblocking receive

Rendezvous - When both send and receive are blocking

Buffering

Messages exchanged reside in temporary buffers/queues with either:

- Zero capacity (no buffering) - no message waiting, sender must block until recipient receives message
- Bounded capacity - n messages may reside. If the queue is not full, then nonblocking, otherwise blocking
- Unbounded - never blocks

Example implementation: Pipes

A pipe acts as a conduit allowing two processes to communicate **one-way** only and either **Anonymously** or **Named**.

```
#include <sys/types.h>
#include <stdio.h>
#include <string.h>
#include <unistd.h>
#define READ_END 0
#define WRITE_END 1
int main(void) {
    char write msg[256] = "Greetings";
    char read msg[256];
    int fd[2];
    pid t pid;

    if (pipe(fd) == -1) {/* create the pipe */
        fprintf(stderr,"Pipe failed");
        return 1;
    }
    pid = fork(); /* fork a child process */
    if (pid < 0) { /* error occurred */
        fprintf(stderr, "Fork Failed");
        return 1;
    }
    if (pid > 0) { /* parent process */
        close(fd[READ_END]); /* close the unused end of the pipe */
        write(fd[WRITE_END], write msg, strlen(write msg)+1); /* write to the pipe */
        close(fd[WRITE_END]); /* close the write end of the pipe */
    }
    else { /* child process */
        close(fd[WRITE_END]); /* close the unused end of the pipe */
        read(fd[READ_END], read msg, 256); /* read from the pipe */
        printf("read %s",read msg);
        close(fd[READ_END]); /* close the read end of the pipe */
    }
    return 0;
}
```

Mechanically act like file descriptors (streams)

Client-Server communication

- Sockets abstraction
 - endpoint for communication
 - identified by an IP address concatenated with a port number
 - servers implementing specific services (SSH, FTP, HTTP) listen to well-known ports
 - an SSH server listens to port 22, an FTP server listens to port 21, a web or http server listens to port 80
- Remove procedure call (RPC)
 - Abstract the procedure-call mechanism
 - for use between systems with network connections
 - similar in many respects of the IPC
 - uses message-based communication to provide remote service

Signals

- OS mechanism to notify a process (one way)
- From the OS POV can be thought as a software-generated interruption/exception (synchronous or asynchronous)
- From other processes POV, it is only a notification, no data is transferred. A communication method for: management, synchronization etc.

UNIX: signal handlers must be registered, and provide code for handling the signal.

```
#include <unistd.h>
#include <signal.h>
#include <stdio.h>
#include <sys/types.h>
#include <sys/wait.h>
#define SIG_STOP_CHILD SIGUSR1

main() {
    pid_t pid;
    sigset(SIGSTOP, catchit);

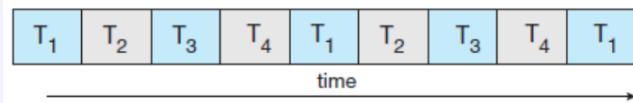
    if ((pid = fork()) == 0) { /* Child */
        struct sigaction action;
        void catchit();
        sigemptyset(SIGSTOP);
        sigadd(SIGSTOP, SIG_STOP_CHILD);
        sigprocmask(SIG_BLOCK, SIGSTOP, &oldmask);
        action.sa_flags = 0;
        action.sa_handler = catchit;
        if (sigaction(SIG_STOP_CHILD, &action, NULL) == -1) {
            perror("sigusr: sigaction");
            _exit(1);
        }
        if (sigsuspend(SIGSTOP, &oldmask) != -1)
            _exit(0);
    } else { /* Parent */
        int stat;
        sleep(10);
        kill(pid, SIG_STOP_CHILD);
        pid = wait(&stat);
        printf("Child exit status = %d\n", WEXITSTATUS(stat));
        _exit(0);
    }
}

void catchit(int signo) { /* Signal Handler */
    printf("Signal %d received from parent\n", signo);
    _exit(0);
}
```

Threads

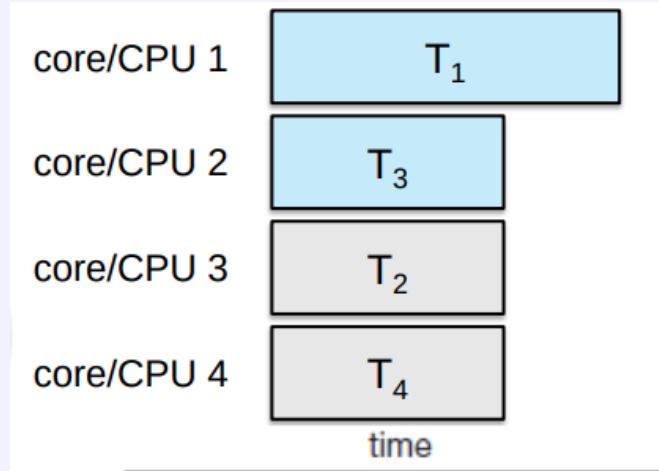
Concurrency

Concurrency is carrying out multiple tasks in parallel but only one at the same time instance:



Parallelism

Parallelism is carrying out multiple tasks in parallel at the same time instance:



Communication problems

Multiple processes are required for both concurrency and parallelism, this requires communication. But the methods discussed thus far have limited usability.

Message passing:

- slow, OS mediates

Shared Memory:

- limited shareability, not all pointers work (both processes have different virtual memory layouts)
- OS resources not shared by default - cumbersome

Possible solution:

1. Fork several processes
2. cause each of them to map to the same shared memory (shmget())
3. make them open the same OS resources

Couple problems:

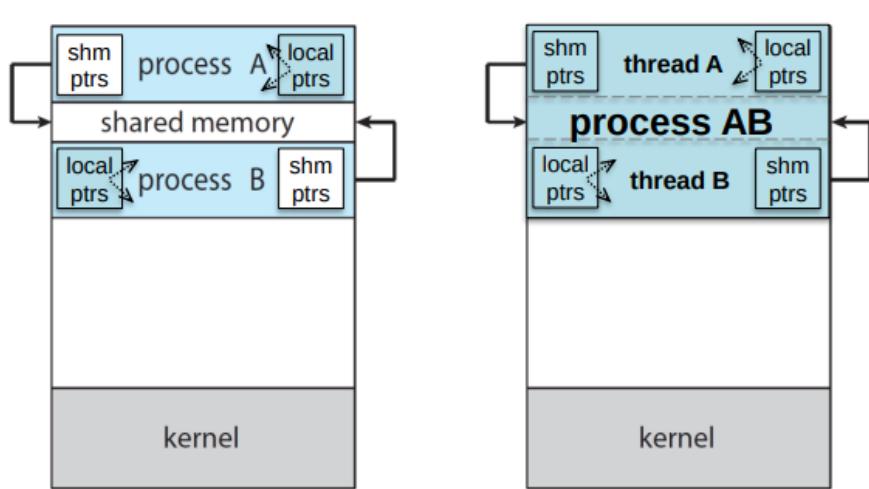
- cumbersome
- has limited shareability again
- inefficient - takes a long time to create all this, requires a PCB per process etc..

Threads

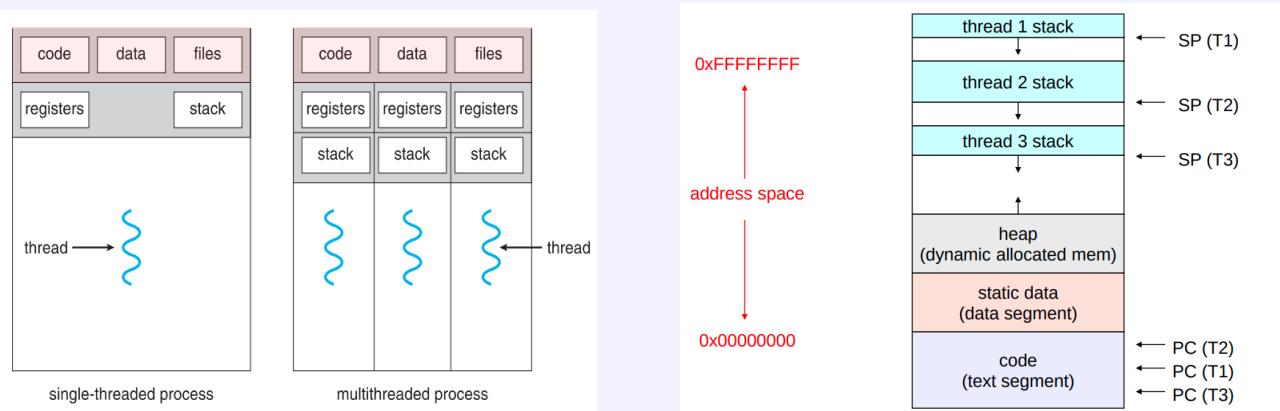
Threads are a great solution to the communication problem: Instead of spawning a new process per task, use **threads**.

Each thread is part of the same spawning process, shares **address space & OS resources**.

Threads only differ in their **execution state (instruction flow)** i.e. private stack, and CPU state



A thread abstracts the execution state away from a process, and now a process represents the static parts of a task (address space, OS resources etc)



Threads become the **unit of scheduling** (depending on implementation of course).
Think processes are boxes for threads in which they execute.

Thread Control Block - TCB

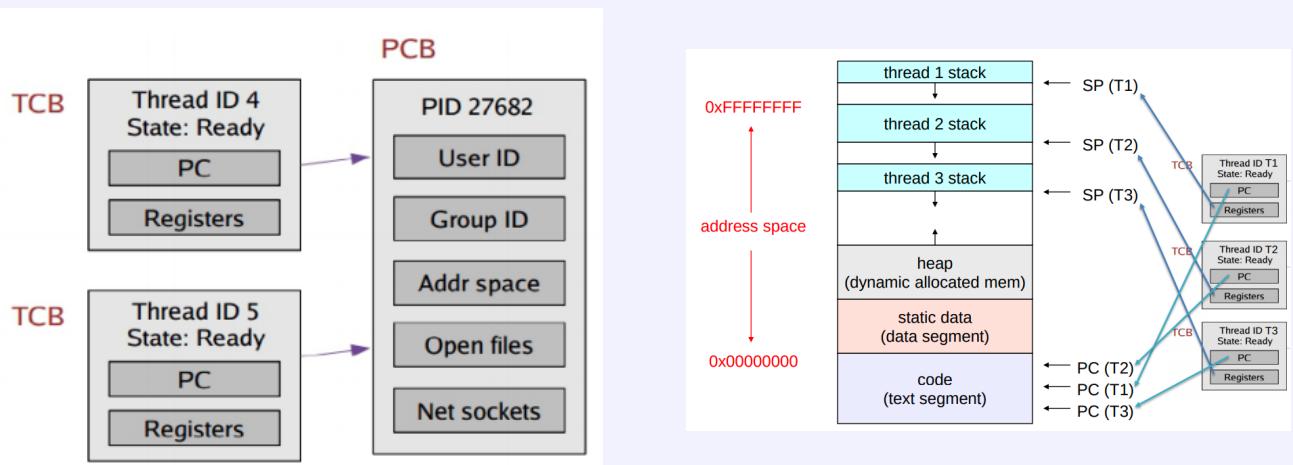
On the OS side, the PCB need to be adjusted to accomodate threads, easiest way is to create sub blocks for each thread representing execution state:

TCB contains:

- Program counter
- CPU registers
- Scheduling information
- Pending I/O information

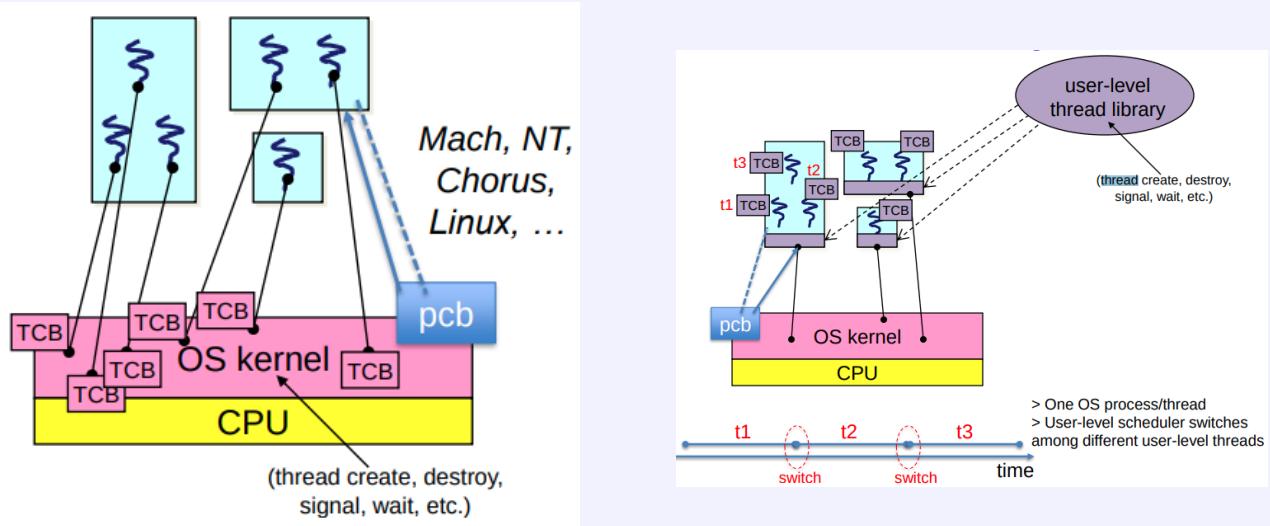
PCB stores:

- Memory management information
- Accounting information



User vs Kernel level threading

Threading can be either implemented as part of the OS, or as a library in the user space



Kernel level threading 1:1

- OS allocates and manages threads
- TID's are used to identify threads
 - + if one thread blocks, the OS can run other threads within the same process
 - + possibility to efficiently overlap IO and CPU time within a process
 - + Threads are cheaper than processes - less state to manage
 - pretty expensive for fine-grained use
 - Orders of magnitude more expensive than procedure calls
 - thread operations are syscalls (context switches + argument checks)
 - Must maintain kernel state for each thread

User Level threading 1:N

- Threads managed at the user level, within the process
- A library in the program manages the threads
- the thread manager doesn't need to manipulate address spaces (Only OS can)
- Threads differ only in hardware contexts (PC,SP,registers), which can be manipulated by user-level code
- The thread package multiplexes user-level threads in a process
- TID's are now unique per process not globally
- No context switching between thread operations, these are done via procedure calls now (10-100x times faster than kernel threads)
 - if one thread tries to do IO, the whole process is blocked!

N:M Threading

Best of both worlds, can start OS level threads for threads which will use IO.

Scheduling

Dispatcher

Mechanism used to switch between tasks (save and restore state)

Scheduler

Decides on policy (implemented by scheduling algorithms) for ordering execution of tasks (threads/processes)

CPU Bursts

Bursts of CPU processing done by a task. **Application dependent**

IO Bursts

Similar to CPU Burst but for IO operations

Performance goals

- CPU Utilization
- Throughput (processes completed per unit time)
- Turnaround time (time from submission of task to completion)
- Waiting time (all periods spent waiting in the ready queue from submission)
- Response time (time from submission of request to when response produced)
- Energy (joules per instruction) subject to some constraint (fps)

In most cases we optimize the **average metric**. Goals may be conflicting

Fairness

No single compelling definition of fair for process resource allocation.

Sometimes goal is to be unfair and prioritize some classes of requests higher.

We want to avoid starvation - everyone needs at least some service

Classes of schedulers

- Batch - throughput / utilization oriented
- Interactive - response time oriented
- Real time - deadline driven

Preemptive scheduling

Non-preemptive scheduling:

- Processes/threads execute until completion or until they want
- The scheduler gets involved only at exit or on request

Preemptive scheduling:

- While a process/thread executes, its execution may be paused, and another process/thread resumes its execution
- Involuntary process switch

Scheduling algorithms

First-come First-served (FCFS)

Processes/tasks served in the order they arrive:

Process	CPU time	Turnaround time
P1	24	24
P2	3	$24 + 3 = 27$
P3	3	$24 + 3 + 3 = 30$

Execution order: P1,P2,P3

$$\text{Avg. Turnaround time: } \frac{24 + 27 + 30}{3} = 27$$

- Non pre-emptive
- Poor average response time
- poor utilisation of **other resources** - a CPU-intensive job prevents I/O- intensive job from tiny bit of computation on the CPU before returning to IO and keeping disk busy

Shortest Job First (SJF)

Associate with each process the length of its CPU time Sort jobs, shortest CPU time goes first Can be preemptive (simply re-sort including the current process - Shortest Remaining Time Next, SRTN)

Non-Preemptive

Process	Arrival time	CPU time	Turnaround time
P1	0	7	7
P2	2	4	$12 - 2 = 10$
P3	4	1	$8 - 4 = 4$
P4	5	4	$16 - 5 = 11$

Execution order: P1,P3,P2,P4

$$\text{Avg. Turnaround time: } \frac{7 + 10 + 4 + 11}{4} = 8$$

Preemptive

Process	Arrival time	CPU time	Turnaround time
P1	0	7	16
P2	2	4	$7 - 2 = 5$
P3	4	1	$5 - 4 = 1$
P4	5	4	$11 - 5 = 6$

Execution order: P1 (2s),P2 (2s),P3(1s),P2(2s),P4(4s),P1(5s)

$$\text{Avg. Turnaround time: } \frac{16 + 5 + 1 + 6}{4} = 7$$

- + Preemptive is optimal
- Too complex, to be implemented in practice
- not always possible to determine the CPU/IO burst lengths

Round-robin (RR)

Processes run in discrete time slots, after each time slot a new process/task is chosen to be run

Time quantum = 20	Process	CPU time	Turnaround time
	P1	53	125 - 0 = 125
	P2	8	28 - 0 = 28
	P3	68	153 - 0 = 153
	P4	24	112 - 0 = 112

Execution order: P1(20s),P2(8s),P3(20s),P4(20s),P1(20s),P3(20s),P4(4s),P1(13s),P3(20s),P3(8s)

$$\text{Avg. Turnaround time: } \frac{125 + 28 + 153 + 112}{4} = 104.5$$

Long time quanta cause poor response times with a lot of processes, a too low time quanta, causes a lot of context switching loss.

- + Solves fairness and starvation
- + Fair allocation of CPU across jobs
- + Low average waiting time when job lengths vary
- + Good for responsiveness (interactivity) if small number of jobs
- Context switching time may add up for long jobs

Priority (PRIO)

Always execute highest-priority runnable jobs to completion

Process	CPU time	Priority	Turnaround time
P1	10	3	16
P2	1	1	1
P3	2	4	18
P4	1	5	19
P5	5	2	6

Execution order: P2,P5,P1,P3,P4

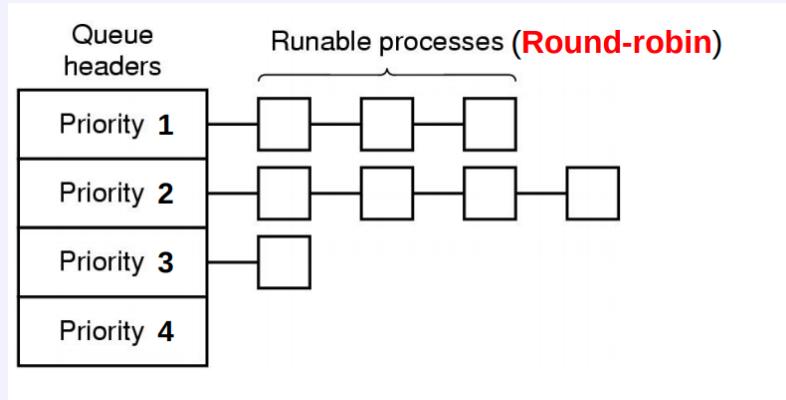
$$\text{Avg. Turnaround time: } \frac{16 + 1 + 18 + 19 + 6}{5} = 12$$

How to assign priorities ? Based on process type, User, price paid etc. or dynamically, based on how long the process ran etc..

- Starvation - lower priority jobs dont get to run because higher priority always running
- deadlock - priority inversion - happens when a low priority task has lock needed by high priority task (busy waiting)

Multiple Queues(MQ)

Multiple round-robin scheduled queues, with queues of higher priority always scheduled first



Process	CPU time	Priority	Turnaround time
P1	10	3	19
P2	1	1	1
P3	2	3	10
P4	1	3	11
P5	5	2	6

Execution order: P2(1s),P5(5s),P1(2s),P3(2s),P4(1s),P1(8s)

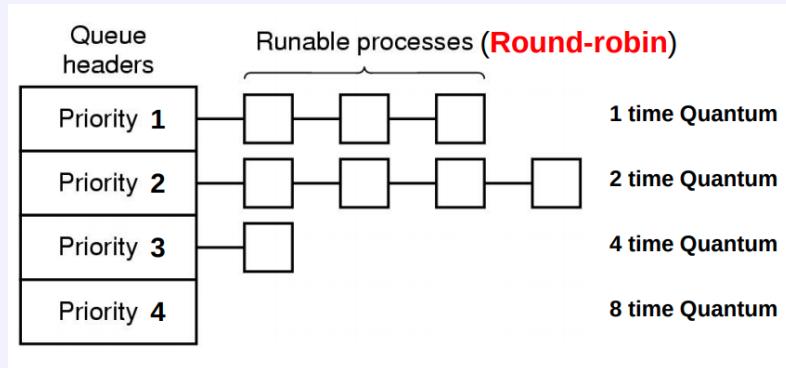
$$\text{Avg. Turnaround time: } \frac{19 + 1 + 10 + 11 + 6}{5} = 9.4$$

How to assign priorities ? Based on process type, User, price paid etc. or dynamically, based on how long the process ran etc..

- Starvation - lower priority jobs don't get to run because higher priority always running
- deadlock - priority inversion - happens when a low priority task has lock needed by high priority task (busy waiting)

Multilevel Feedback Queue(MLFQ)

Same as MQ but each queue has a different time quanta. Time quanta are increasing inversely with priority of queue (higher priority lower time quanta). Each process starts in queue 1 - but when it exceeds its quanta it's pushed lower in the queues. When a process becomes inactive it is moved to a higher priority. This can be gamed by making a process interactive.



Process	CPU time	Turnaround time
P1	100	102
P2	2	3

Execution order: P1(1s),P2(1s),P1(2s),P2(1s),P1(4s),P1(16s),P1(37s)

$$\text{Avg. Turnaround time: } \frac{102 + 3}{2} = 52.5$$

8 context switches vs 101 with fixed quanta

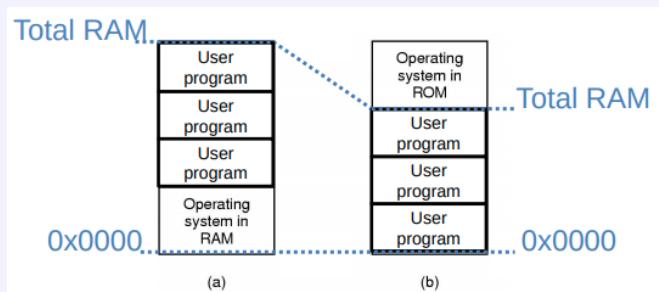
- Starvation - lower priority jobs don't get to run because higher priority always running
- deadlock - priority inversion - happens when a low priority task has lock needed by high priority task (busy waiting)

Memory

Why use abstraction

In the case that a program sees the physical memory directly, the program can mess with the OS and BIOS code, whether intentionally or unintentionally. There is a need for a protection system.

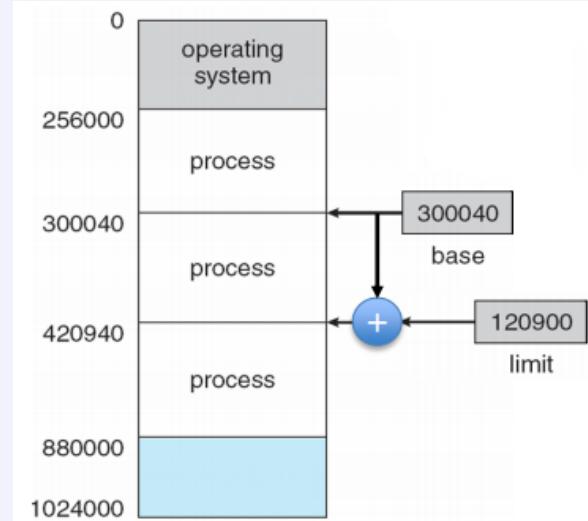
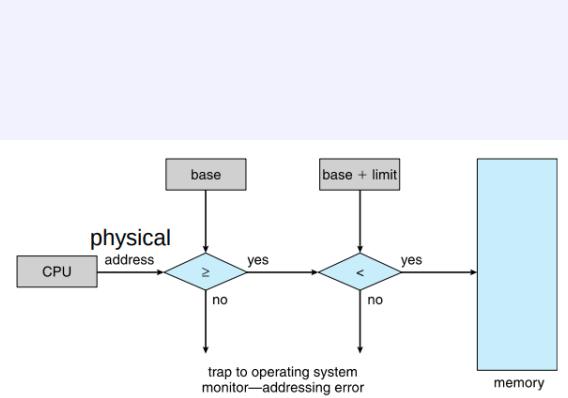
The situation gets worse when multiple programs are running with access to direct physical memory. In which case each program can alter all the other running programs. The total number of programs that can be run is then limited by the memory size!



Protection - Base and Limit registers

A simple solution to prevent bad memory accesses, is to use base and limit registers.

This requires hardware support, but is enough to allow multiple **relocatable** programs to be run on the same physical address space.

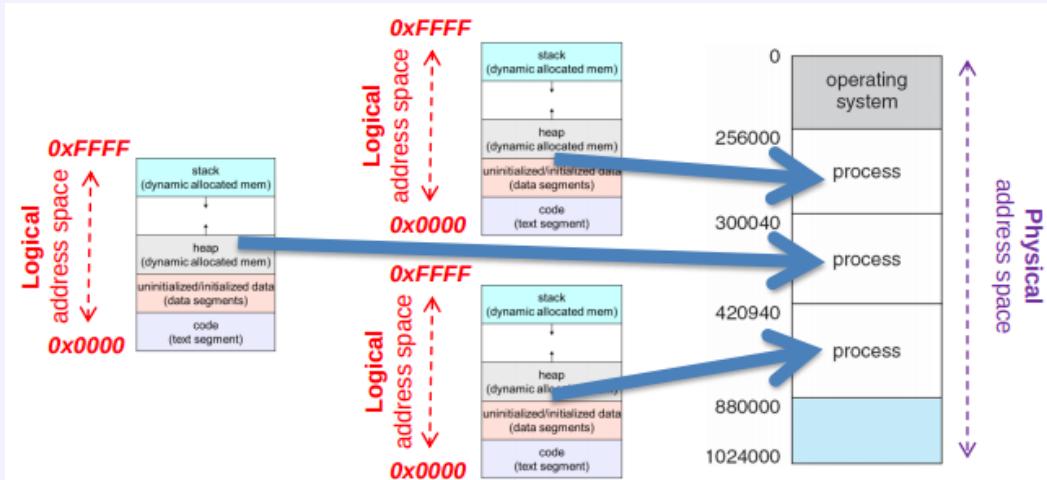


Address Space

Abstraction from physical memory space. Defines the set of memory addresses that a process can use independently from other processes.

To make it easier to manage memory of multiple processes, we can make processes use **logical addresses** instead of physical ones!

These logical addresses are independent of physical addresses, yet the data lives in physical memory, so the OS manages the data location in the physical memory. Logical addresses are **translated by hardware** with the OS' aid.

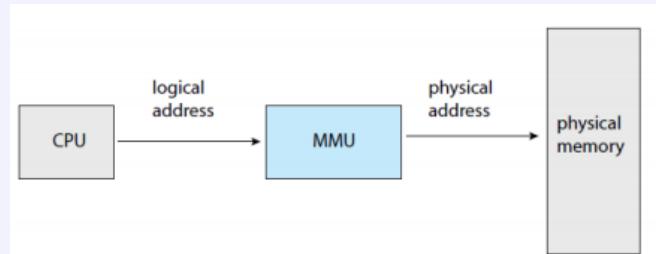


Memory-Management Unit (MMU)

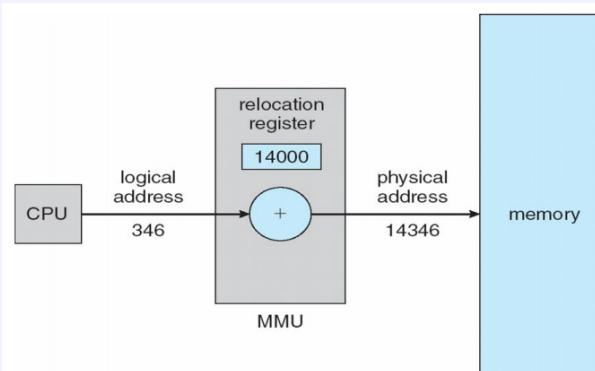
A hardware component which translates CPU generated addresses to physical addresses.

Programs deal with logical addresses and never see the physical ones.

Can be implemented in many ways (paging, relocation+limit registers, segmentation etc.)

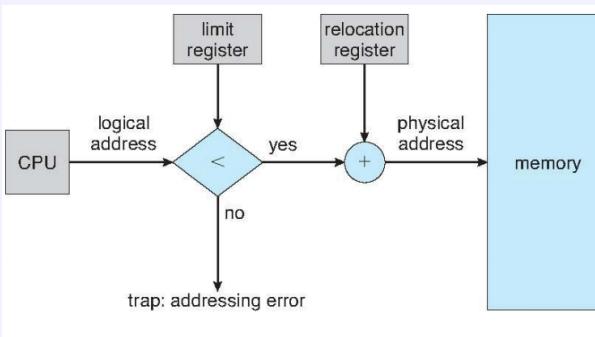


Relocation register



- no protection, nothing checks if address is outside of range

Relocation + limit registers



- + program doesn't have to be relocatable (it operates on "fake" physical memory) = simpler loader and faster load time
- + protection - each program has its own private address space
- + each program can have a different partition size (amount of physical memory allocated)

Memory allocation

The process of allocating physical memory to programs requiring it.

We want efficient and fast allocation with smallest memory waste. Allocation is done with hardware support (MMU)

Contiguous Allocation

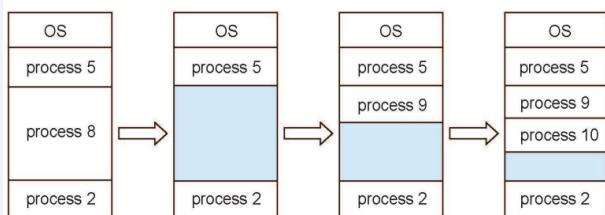
All techniques above allocate memory in contiguous chunks.

Multiple-partition allocation

Allocation of contiguous block of physical memory of various sizes (to minimize loss)

Hole: a block of available memory; holes have various sizes. When a process arrives, OS allocates memory from a hole large enough to accommodate it. On process exiting, the partition is returned to OS, and adjacent holes are merged. OS keeps information about allocated partitions and free partitions.

- degree of multiprogramming limited by number of partitions used



Many possible policies:

First-fit

Allocate the **first** hole that is big enough

Best-fit

Allocate the **smallest** hole that is big enough; must search entire list, unless ordered by size - produces the smallest leftover hole

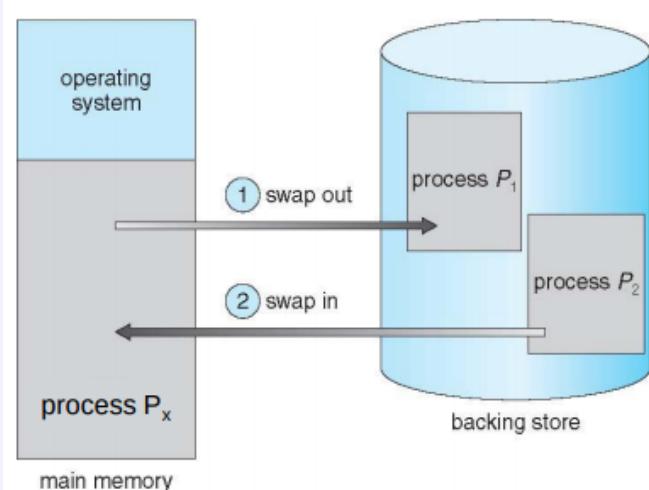
Worst-fit

Allocate the **largest** hole; must also search entire list - produces the largest leftover hole

First and best fit better than worst fit in terms of speed and storage utilization.

Swapping

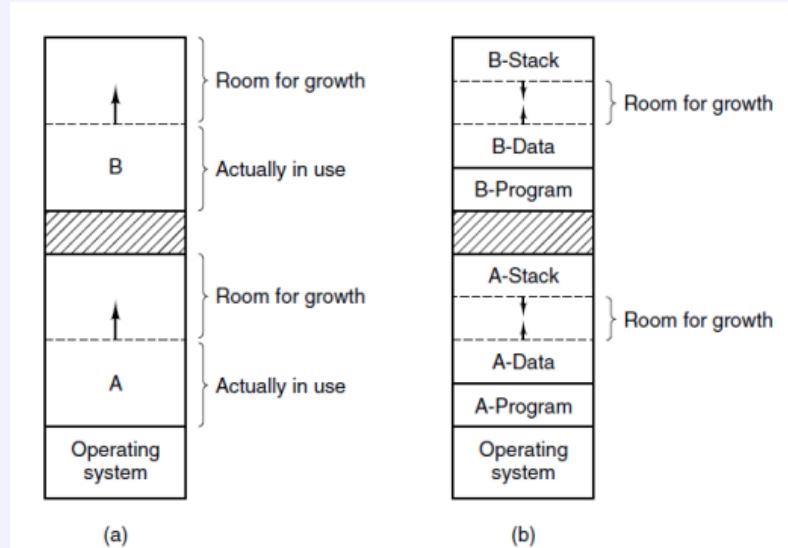
What to do when we run out of memory? We have to keep some programs in the backing storage. To do this we need to be able to swap in and out programs from memory.



Growing programs problem

Programs are not actually static! They can allocate memory dynamically, and hence grow in memory.
Two solutions possible:

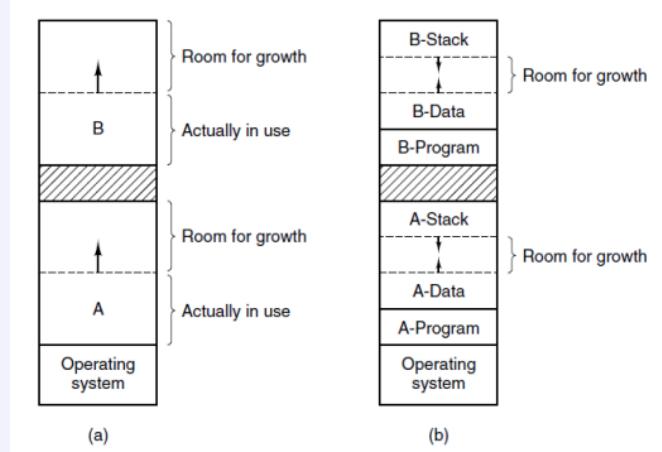
- Allocate more space than needed, if more needed, relocate
- Allocate space for growing program in its address space



Both of these aren't ideal

Memory fragmentation

Processes create memory holes, which might not be conveniently sized for other programs to occupy:



External fragmentation - you allocate the exact amount of memory requested, total memory space exists to satisfy a request, but it is not contiguous.

Internal fragmentation - you allocate more than what required, allocated memory may be slightly larger than requested memory

First fit analysis - N blocks allocated = $0.5 N$ blocks lost to fragmentation, $1/3$ may be unusable

Paging

Non-Contiguous Allocation

Issues with Contiguous allocation:

- loads the entire program at once into memory when needed
- external fragmentation
- long swap times
- long **compaction** times (tight reallocation)

Presenting Non-contiguous allocation:

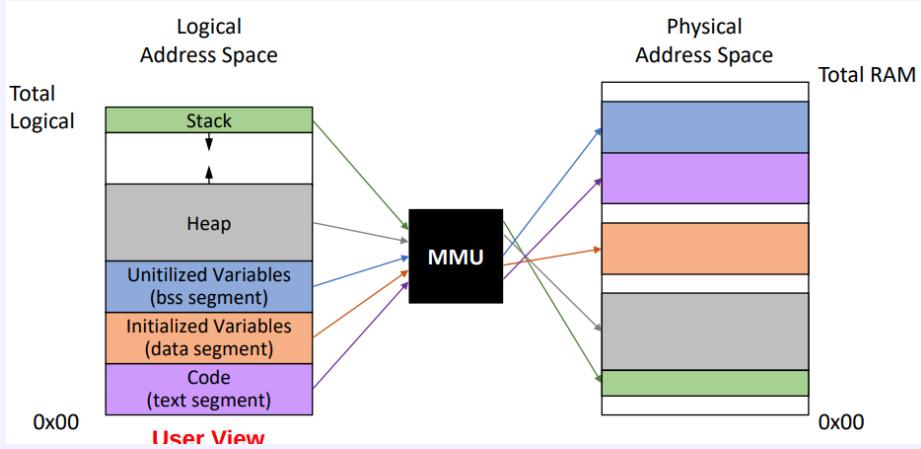
- request physical space for each program's chunk when required
- split logical address space in chunks
- contiguous in logical memory, non-contiguous on physical memory
- segmentation + paging

Segmentation

Partition an address space into **variable size** chunks/units. **Logical units** = stack,heap,data,code,subroutines ..

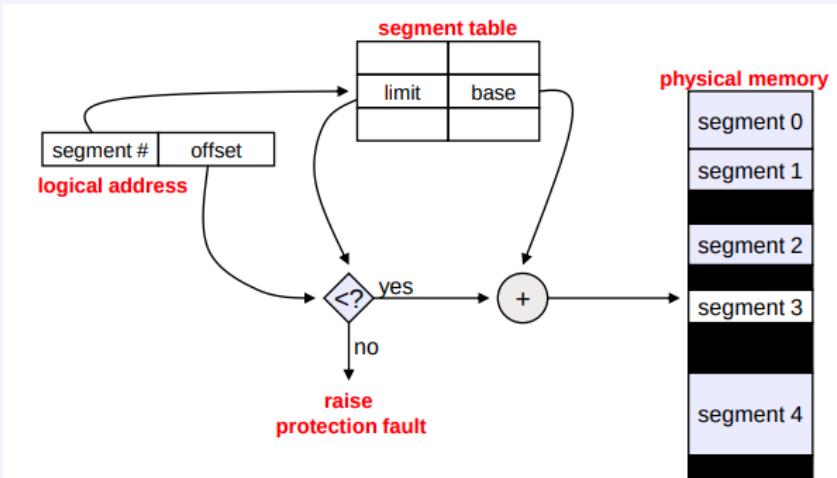
A logical address is split into (segment#, offset)

The logical address space is divided in **variable size** chunks



Hardware support

Segment table:



Multiple base/limit pairs, one for each part of the program (segment) the segment number is used as the index into the segment table

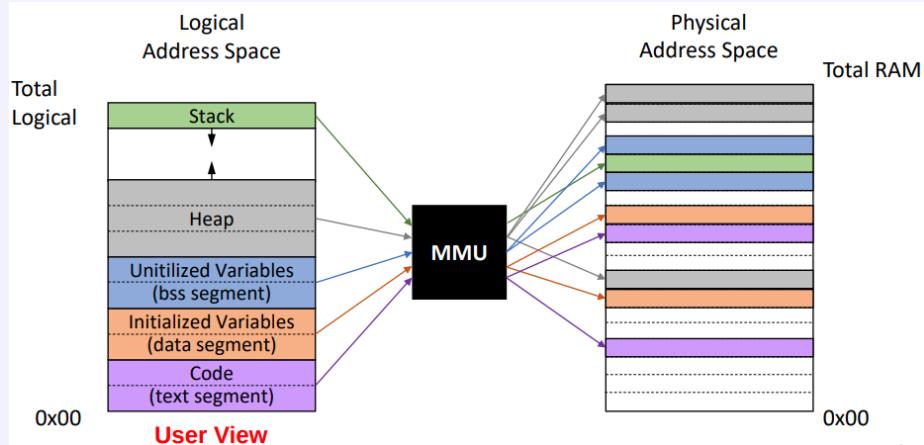
The segments can roughly be associated with addresses based on conventions.

- + allows non-contiguous physical addresses
- + reduces fragmentation by exploiting varying sized holes
- + allocated chunks are smaller than the entire program address space
- + enables sharing (same segment can be shared across processes, think threads)
- process view and physical memory are extremely different
- + protection, process can only access its own memory
- external fragmentation still occurs

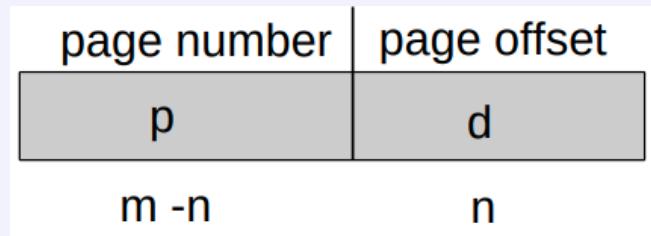
Paging

Similar to segmentation, but logical address space divided in **fixed size** chunks. Here we **combine** base address with offset instead of adding to entire address by single offset, this establishes a mapping. Each process might have its own page table, or a single one can be used.

Pages mapped to **frames**, page size = frame size

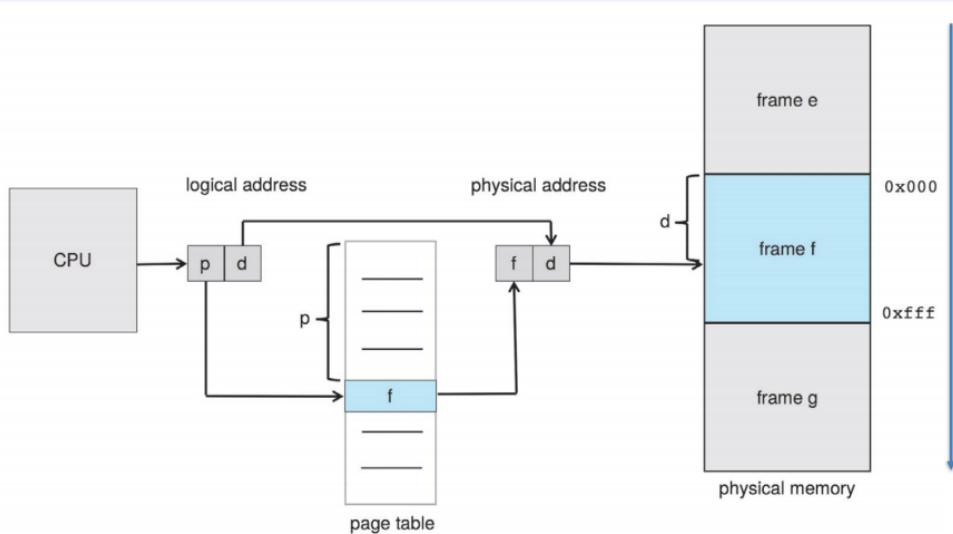


Logical address is (page #, page offset). page # is used as index into **page table** which again contains base addresses, page offset is **combined** with base address to create physical memory address.



logical address space size = 2^m bytes. Page and frame size = 2^n bytes

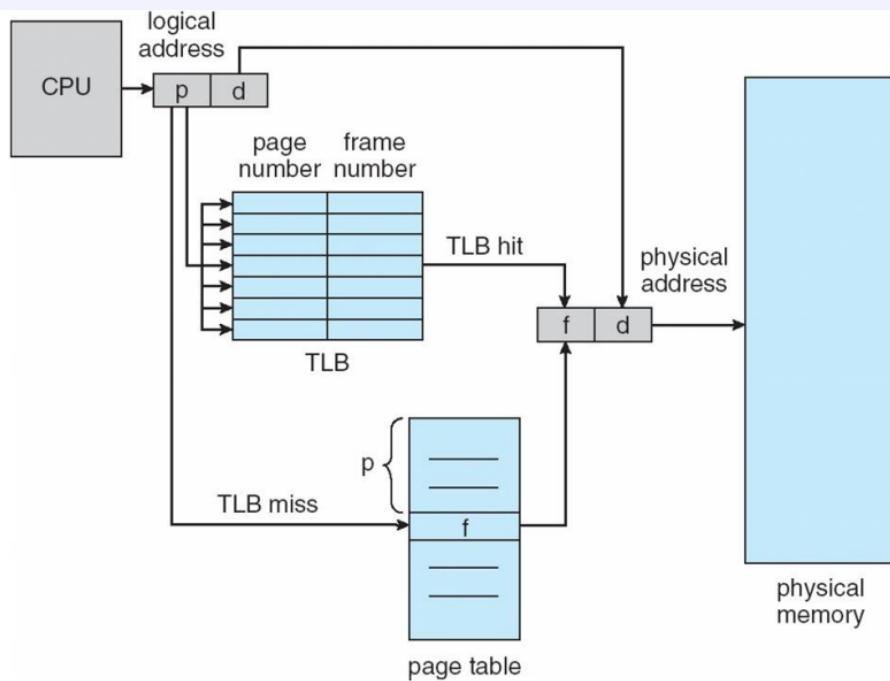
Hardware Support



- + no external fragmentation!
- internal fragmentation depends on page size, if program "overflows" when dividing by page size.
- translations may require memory accesses (costly)
- different page sizes available on every system
- *average fragmentation = .5 frame size, worst case = frame size - 1 byte*
- page tables get huge, require more complex arrangements to cut size down

Translation look-aside buffers (TLB)

In order to avoid wasteful memory lookups, a TLB cache is used when paging.
If translation exists in TLB, use it (free), otherwise fetch translation from memory (expensive)



Memory access time - time the CPU waits to access main memory directly

Hit ratio (α) - percentage of times taht a page number is found in TLB

Miss ratio - $1 - \text{Hit ratio}$

Effective access time (EAT) - the average experienced access time:

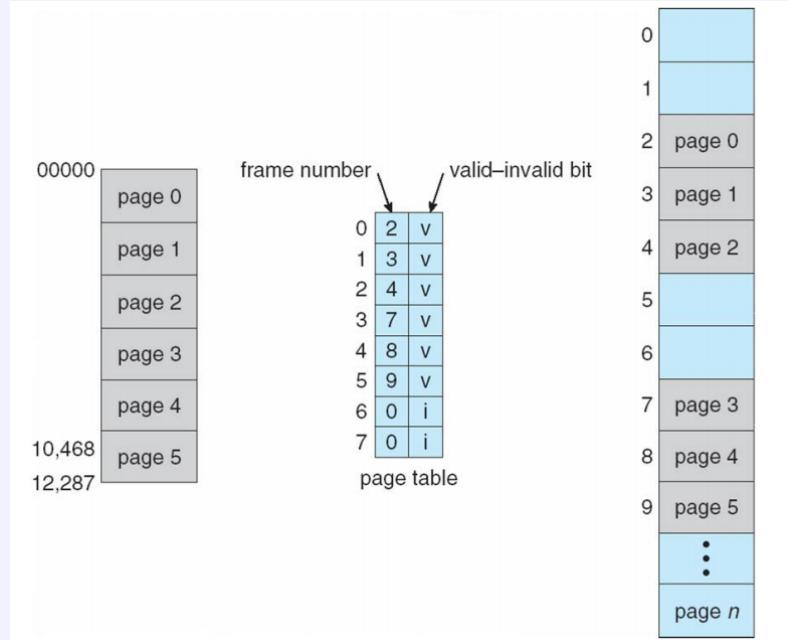
with $\alpha = 80\%$, 100ns access times = $0.8 * 100 + 0.2 * 200 = 120\text{ns}$

with $\alpha = 99\%$, 100ns access times = $0.00 * 100 + 0.01 * 200 = 101\text{ns}$

Memory protection

Page table entries (PTEs) can contain more information:

- protection bits - read-only, read-write, execute-only
- valid bits - valid = translation exists and is in the logical address space of process otherwise not in process' space (when more frames than logical pages)
- violations result in traps

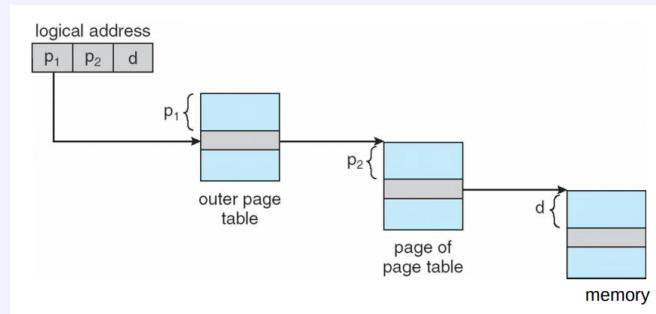


Multi level TLBs

Consider 32-bit logical address space, with page size of 4kB (2^{12}). The entire address space is divided into 1 million frames ($2^{32}/2^{12}$). Each entry is 32 bits and so we need 4MB in total for the page table.

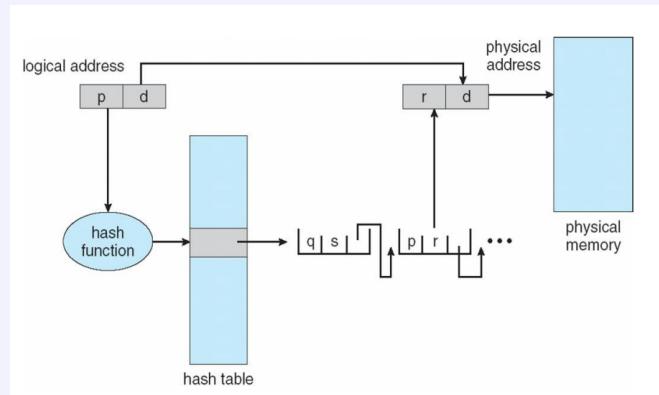
We can create a table for the page table itself, to reduce the amount of "page translations" held in memory, we would only need to store the outer table entries:

So the first half of the address gets split according to the hierarchy, i.e. 22 bit page number can be divided into 12 bits for the outer and 10 for the inner tables. this means we only have to store the 2^{12} entries of the page table



Hashed page tables

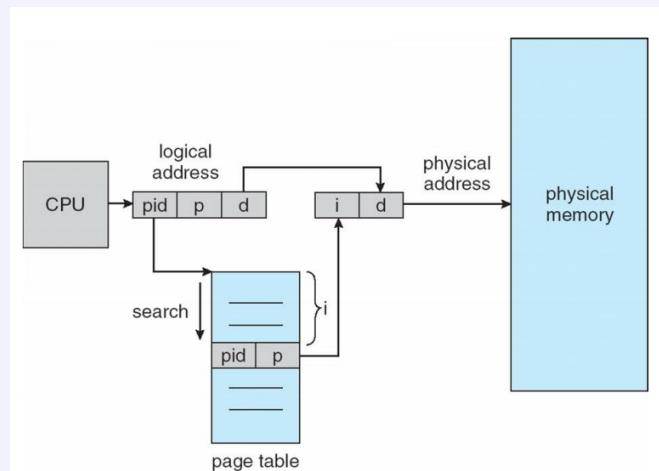
The logical page number can be hashed to generate the page table index, then the elements at that index need to be searched against (each entry would have the logical page number, the page frame, and the pointer to the next element)



Advantages: speed, fast access times

Inverted Page table

Instead of each process having a page table and keeping track of all possible logical pages, track all physical pages
each physical page = one entry
each entry has the virtual address owning that memory location along with the pid of the process whose virtual memory that is
this requires less memory for translations, but much more time is needed to search through the table, we can use hash tables to limit the search to one/few page-table entries
Shared memory requires OS intervention



Advantages of paging

- inter-process memory protection
- prevents code being rewritten (protection bits)
- detects null pointer dereferencing at runtime
- reduce memory usage (shared libraries) - one copy of a library only necessary, not one per process
- generalizes use of "shared memory"
- can implement **copy-on-write(CoW)** mechanics easily with read only pages and page faults
- memory-mapped files - can load a file on demand into logical addresses

Virtual Memory

Overlays

What if the logical address space is greater than the available physical memory ? Can a program correctly execute even if it is not all in memory at all times?

One solution is to simply divide the program into **overlays**, which are smaller than the physical memory, then load and unload them as needed via some root overlay manager (user program) which determines when a new overlay needs to be loaded.

This is something you'd need to use when really constrained on physical memory. However there are better solutions

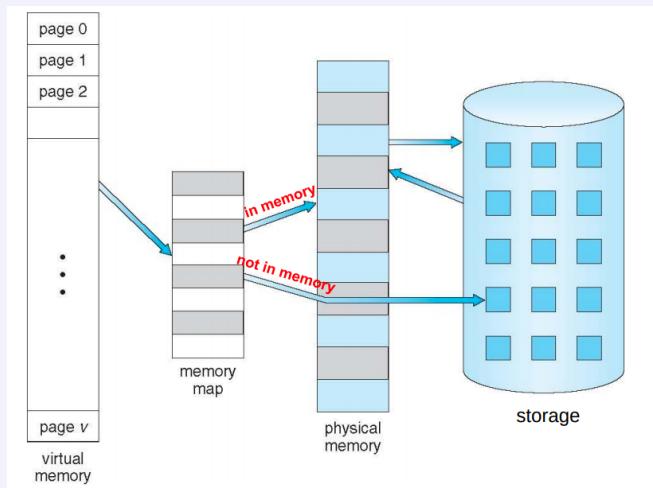
Virtual memory

fully decouples address space from physical memory, allows larger logical address space than physical memory.

We've already seen an example: **Paged virtual memory!**

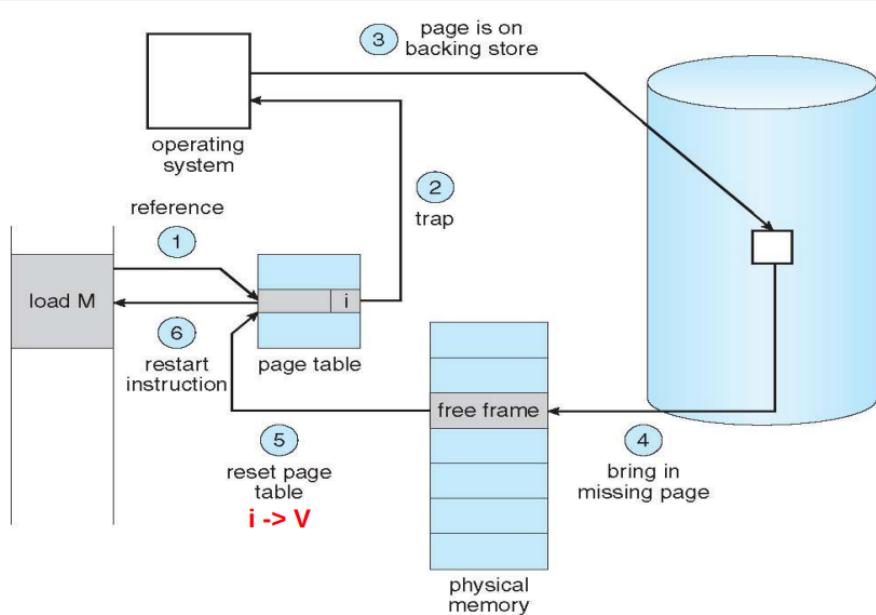
We can simply keep some of the pages out of the main memory and on the disk, and swap pages into memory when needed. This requires the **eviction** of older pages.

Main memory becomes a **cache** for pages!



Page Fault

1. Software accesses a page that is not in memory
2. Hardware triggers a **page fault**
3. Operating system checks internal data structures:
 - If invalid reference, abort the original program
 - If not in main memory currently, continue
4. Operating system finds a free frame - swaps page into frame via disk operation
5. Operating system sets internal data structures to indicate page now in memory + set valid bit in page table
6. Operating system restarts the instruction that caused the page fault



Demand paging

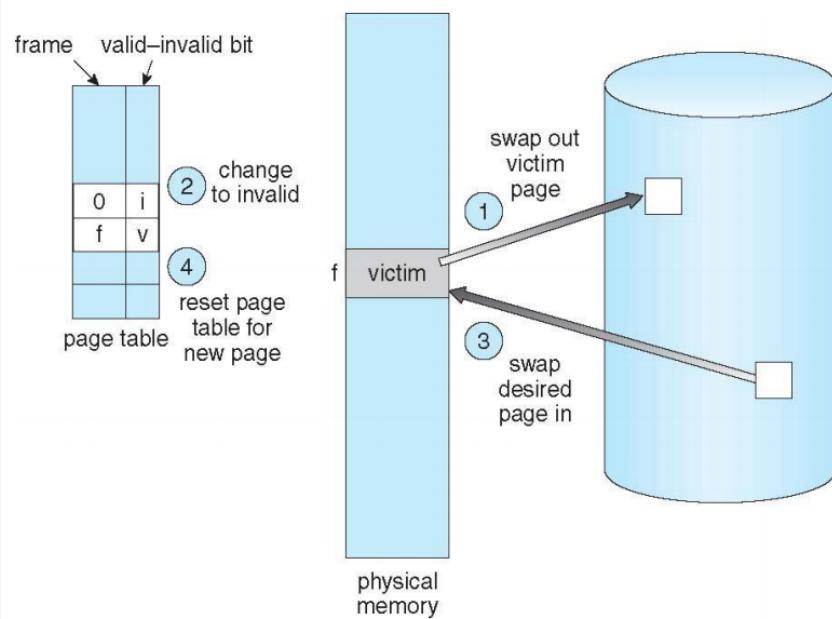
Pages brought into memory **when accessed first**

Few systems try to anticipate future needs, pages may be clustered - OS can anticipate which pages usually get used together and bring them all in when one is accessed

- expensive heavily depends on storage latency

Page allocation and replacement

When there are no more free frames, we must **evict** unfortunate pages in memory.



Page replacement policies

What page to evict ?

Reduce page-fault rate by selecting **best victim page** - one that we will never touch again or in the near future.

Belady's Theorem - evicting the page that won't be used for the longest period of time minimizes page fault rate

evict **unmodified** pages first - since don't have to write them back to disk

First-in-First-Out (FIFO)

replace page that has been inserted the longest time ago

- + simple, just a linked list or queue
- Belady's anomaly, more page frames do not guarantee less page faults!



Least Recently Used (LRU)

Replace page that has not been used in the most amount of time

- + uses past knowledge rather than predictions
- + does not suffer from Belady's anomaly (stack algorithm)
- requires substantial **hardware assistance** - keeping track of last usage of each page

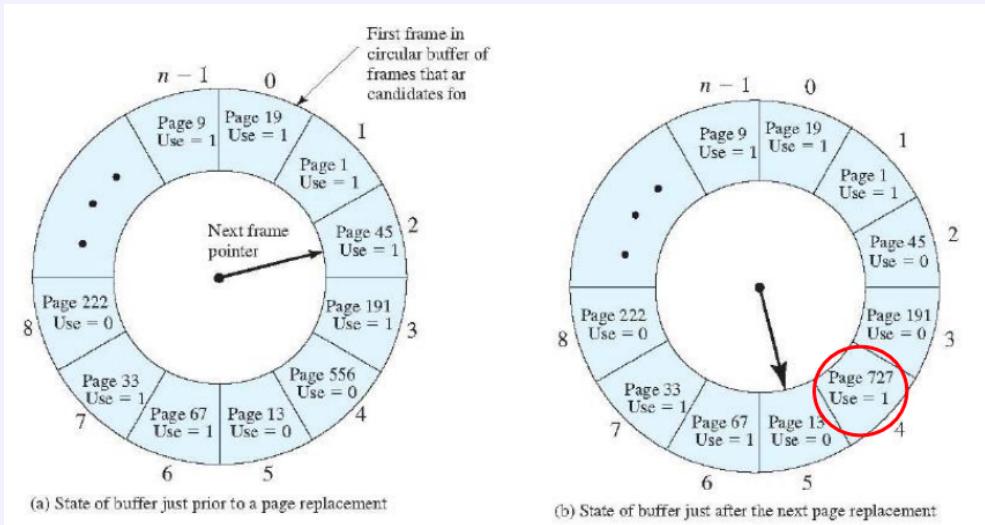
Need the following page table entry bits (**hardware**):

- Page referenced (if accessed or not)
- Page modified (if access was in write)

and need to keep track of a history for each page in the kernel.

Second chance

Variant of FIFO, makes use of page usage data. use circular queue and **reference bits**, keep "victim" pointer, if the victim was referenced, set reference bit to 0, and move pointer along by one, if not replace that page with new one, and move pointer along.



Frames as resources

We can decide to limit the number of physical frames available for certain processes. Frame Allocation can be:

- Equal: an equal share for all processes
- Proportional: a share based on the program size or other factors

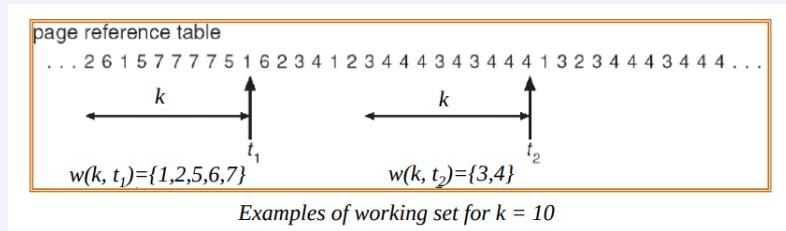
Frame Replacement can be:

- Local: each process is given a limit of pages it can use (pages against itself, i.e. evicts its own pages):
 - + doesn't affect other processes
 - poor overall utilization of frames, and long access times
- Global: the "victim" is chosen from all available frames regardless of owner
 - risk of global **thrashing**
 - + processes' page frame allocation can vary dynamically

Working set

let t be the time, k the working set **window** (measured in page refs) then
 $WS(k,t) = \text{Working set}$ in time interval $t,t-k$.

Then a page is in the WS, iff it was referenced in the last k references by the process.



The size of the working set changes with program locality - when program has poor locality, more pages are referenced and the working set grows

The working set must be wholly in memory, otherwise heavy faulting - **thrashing**

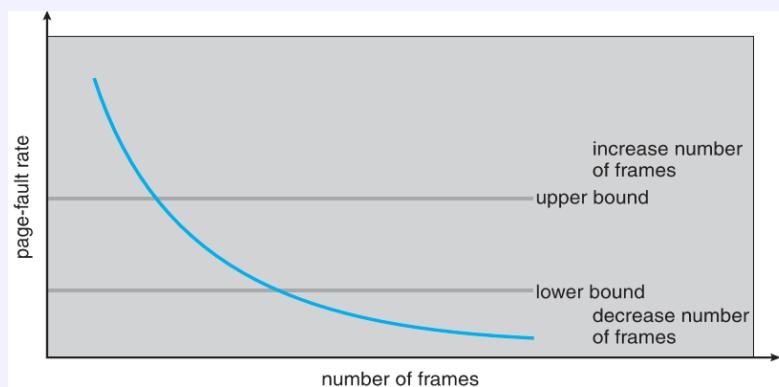
Page-Fault Frequency Allocation

We can make use of the working set to come up with a great allocation algorithm.

Notice: there is a relationship between the size of the working set and the page-fault rate of a process.

Use a local replacement algorithm (i.e. process pages against itself, with limited number of pages)

The higher the page fault frequency (PFF), the more the process is struggling to keep its working set in memory.
set an acceptable PFF range (lower and upper bound), if actual frequency higher than upper bound, increase the number of frames allocated to the process, if frequency lower than lower bound, remove one of the process' frames.

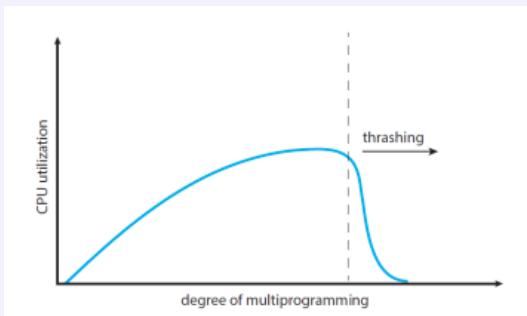


Thrashing

When system spends most of its time servicing page faults, little time spent doing useful work.

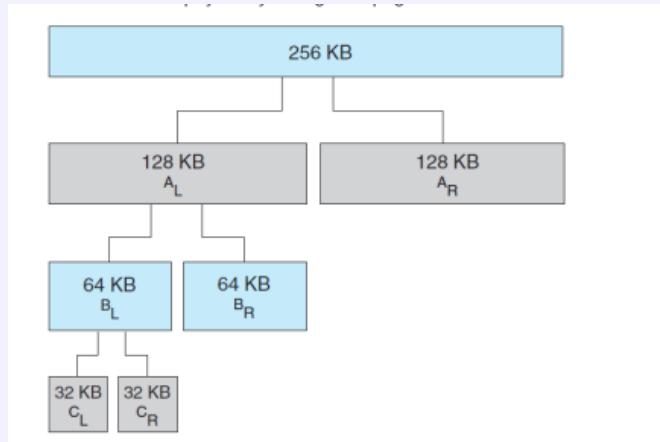
Reasons:

- Could be that there is enough memory but replacement algorithm is not working well - it's incompatible with the program behaviour
- Could be that memory is over-committed - OS sees CPU poorly utilized and adds more processes



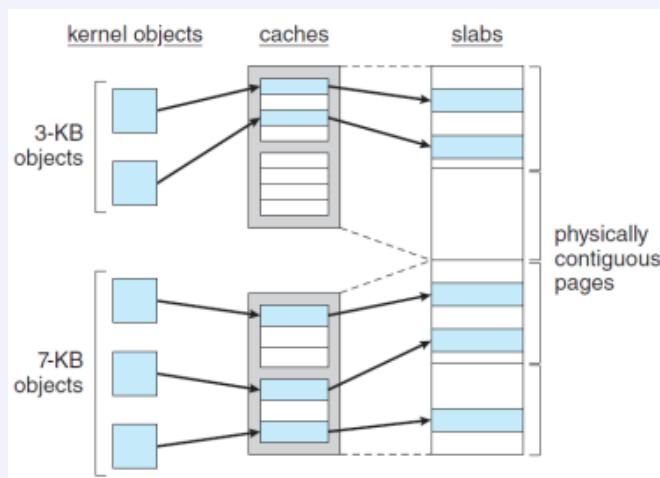
Buddy system

A contiguous power of 2 memory allocator for kernel structures. Satisfies request in units sized in powers of 2. all requests are rounded up to nearest power of 2.



Slab allocation

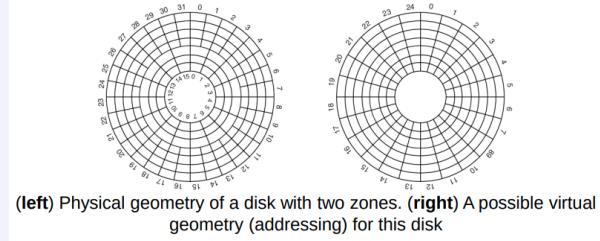
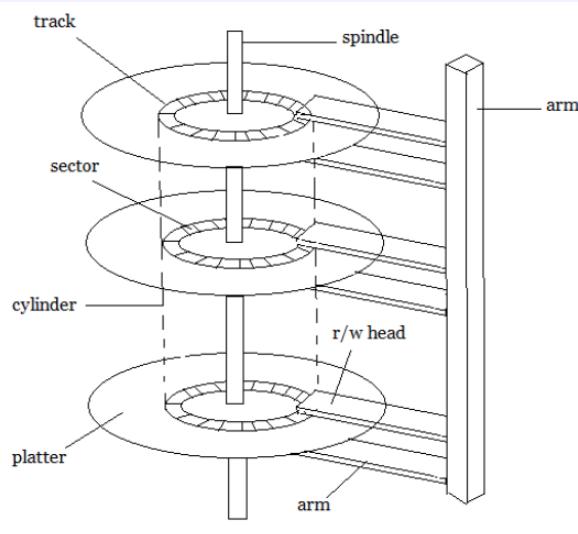
Contiguous memory allocator for kernel structures. Slabs are made up of one or more physically contiguous pages. A cache consists of one or more slabs. There is a cache for each **unique kernel data structure**. Each cache populated with objects If there are any **free slabs**, the allocation is immediate (no search for memory space)



Secondary Storage

Magnetic Disk

Traditional cheap HDD storage. Addressed either geometrically (Cylinder, head, sector) or more recently using **Logical block addresses (LBA)**



Performance depends on:

- **Seek time** - moving the disk arm to the correct cylinder. Depends on arm speed, does not diminish quickly due to physics
- **Rotation (latency)** - waiting for the sector to rotate under head. Depends on RPM of disk, rates are slowly increasing
- **Transfer time** - transferring data from surface to disk controller. Depends on density of bytes on disk, increasing relatively quickly

OS tries to minimise disk usage, mostly the seeking and rotation time.

OS can inflate file block size , or co-locate "related items" to reduce seeking (blocks of the same file, data and metadata for a file)

OS may keep data or metadata in memory to reduce physical disk access.

OS may fetch blocks into memory before requested (to hide slow disk accesses)

Block scheduling

Applications request data accesses to the OS, OS maintains **request queues** and generates **transfer commands** to/from the disk(s) (seeks,waits for rotations, data transfers, all the low level commands)

App waiting time can be reduced by modifying the order of blocks requested: This of course brings up a number of factors that need to be considered as with any scheduling:

- fairness
- efficiency
- speed

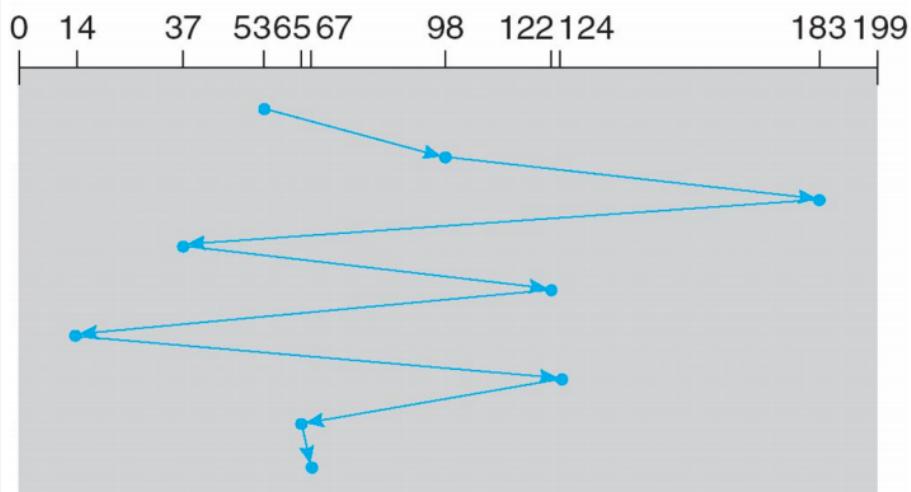
Many block scheduling algorithms exist.

First come first served (FCFS)

Simply keep a queue.

queue = 98, 183, 37, 122, 14, 124, 65, 67

head starts at 53



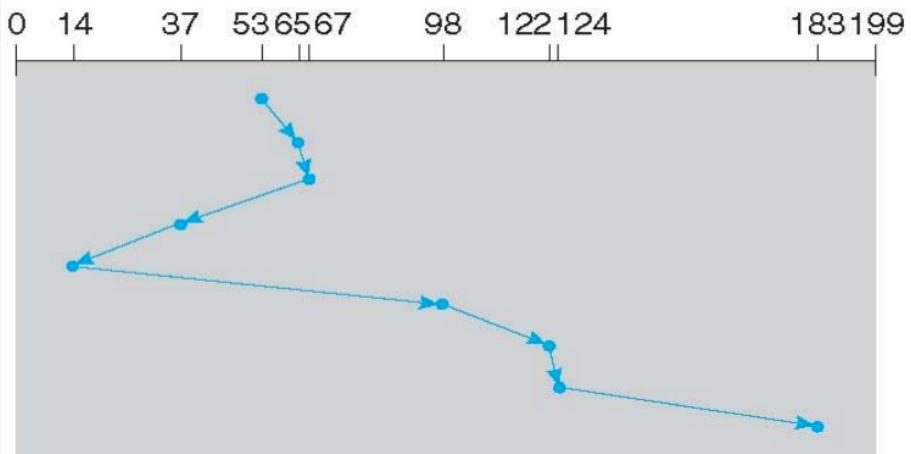
- + reasonable when load is low
- long waiting time for long request queues

Shortest seek time first (SSTF)

Order requests according to seek time, and serve them in that order

queue = 98, 183, 37, 122, 14, 124, 65, 67

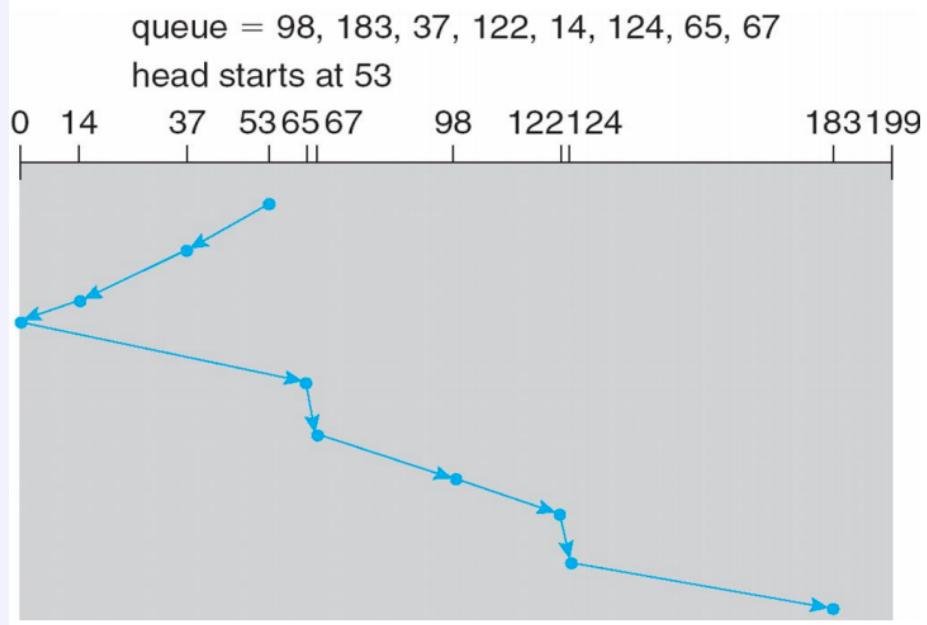
head starts at 53



- + minimizes seek time, and therefore maximizes request rate
- unfairly favors middle (clustered) blocks

SCAN

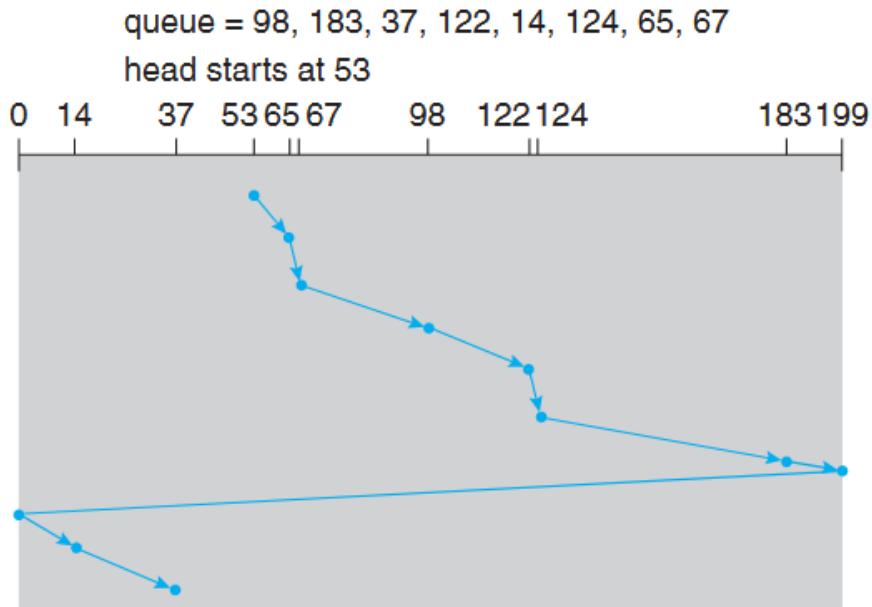
Disk arm starts at one end of the disk, then moves toward the other end, at which the direction is reversed and this repeated



- + simple, easy to understand
- + no starvation
- + better than FCFS
- + good under heavy load
- not fair - long waiting time for cylinders just visited by the head
- bad when all requests are uniformly spaced out ()
- skews wait times non-uniformly

C-SCAN

Same as SCAN, but once other side is reached, it returns to start position and repeats.



- + more uniform wait times than SCAN
- + good under heavy load

Selecting an algorithm

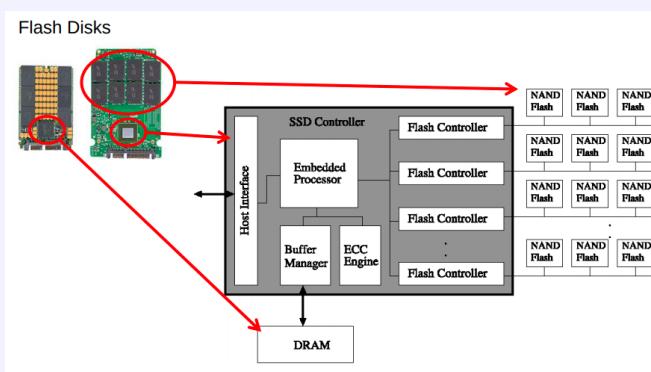
All algorithms behave like FCFS with one request.

Performance usually depends on number and type of requests

Requests for disk service can be influenced by file-allocation methods and the metadata layout.

Solid state drives (SSD)

A version of storage with no moving parts. More expensive, more robust.



Read access time is mostly independent of the device geometry - block scheduler is not needed.

Unit of read/write is a page (typically 4kB).

Usually lower write vs read speed. Higher write lag than read lag. Write usually lower throughput than read.
Flash media must be **erased before you can write to them**

Unit of erase is typically 64-256 pages. Limited number of times before unusable (10,000 - 1,000,000 times)

- higher cost per GB
- + more energy efficient than HDD
- + much more physically robust

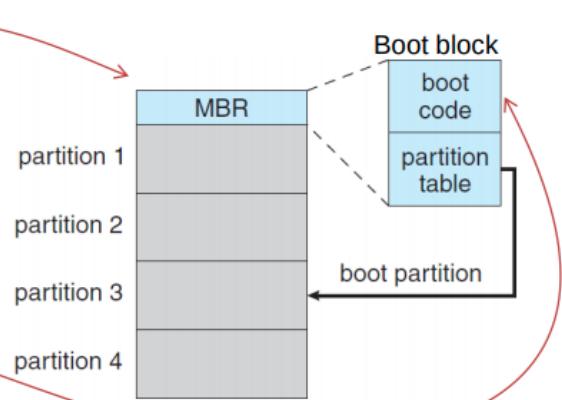
Storage device management

Storing data is not enough - need metadata
Before storing data, device needs to be initialized

- Low-level formatting
- For each partition
 - Volume creation (lvm2)
 - Logical formatting (file system)

• Booting

1. Firmware, or BIOS
2. Reads code in MBR
3. MBR also contain partition table
4. Code in MBR reads boot sector of the selected partition
5. Pass control to code in selected partition



File System

File System

Abstracts away secondary storage. **Files** are unit of abstraction, organized into **directories**.
Enables **sharing** of data between:

- Processes
- People
- Machines
- etc.

Provides additional:

- Access control
- Consistency
- Reliability
- etc.

File

A **named collection of related information** with some properties:

- Content
- Size
- Owner
- Protection
- Last read/write time

File **types** are understood by **file system**:

- Directories, symbolic links, **devices**
- Programs, Data

Types need to be encoded into file name on windows, not on linux (.com,.exe etc..)

File access methods

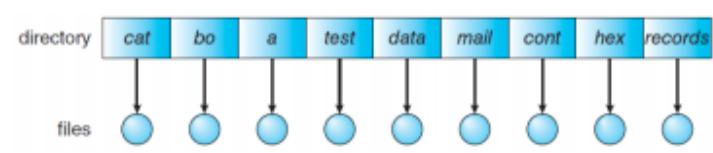
File systems provide different **access methods**

- **Sequential** - read/write bytes one at a time, in order
- **Direct** - random access given by a byte #
- **Record** - file is an array of fixed- or variable-sized records
- **Indexed** - One file contains an index to a record in another file

Directory structures

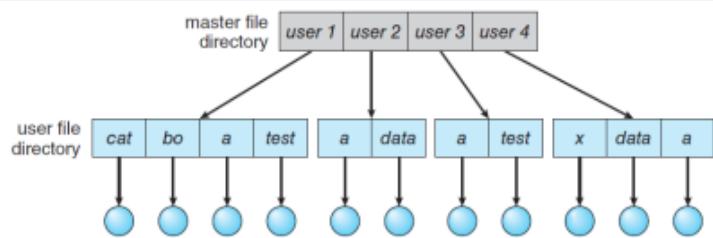
Single-level

Files must have unique names



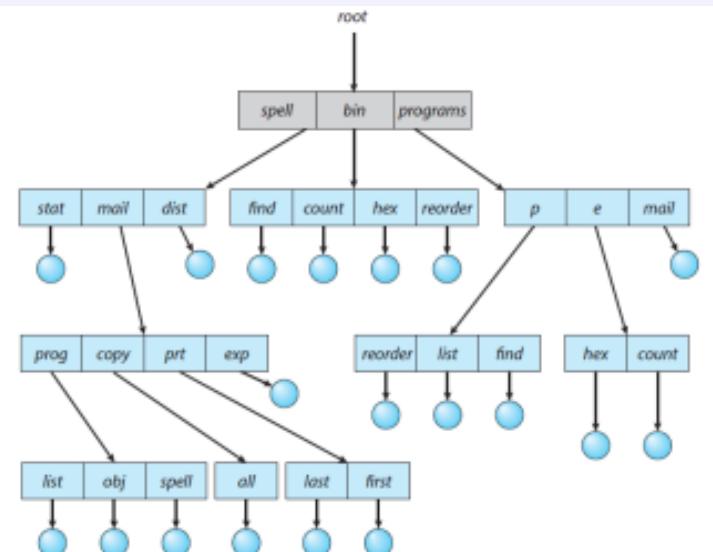
Two-level

Sharing requires path abstraction



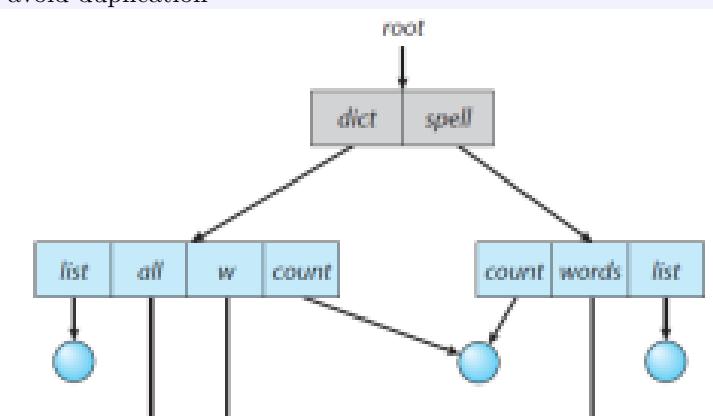
Tree structured

Eventual replication of files



Acyclic graph

Links as a solution to avoid duplication



Directories

Directories provide way for users to **organize their files** under convenient **file name spaces** for user and FS
Most file systems support **multi-level directories** (/,,/usr,/usr/local,/usr/local/bin)
Most file systems also support notion of **current directory**

Absolute names - fully-qualified starting from root of FS

Relative names - specified with respect to current directory

Internals

Usually just a **file** with special metadata.

Organized as a **symbol table** - list/hash table of name & file references

Contains **attributes** such as:

- Size
- Protection
- Location on disk
- Creation time
- Access time

Usually unordered ('ls' sorts the results)

File protection

File system implements protection system:

- Control **who**(user/group) can access **what** (file/directory)
- Control **how** the file can be accessed (read/write/exec)

Objects - the **what**

Principals - the **who**

Actions - the **how**

Protection system dictates whether a given action performed by a given principal on a given object should be allowed.

Protection models

Two different models:

- Access Control Lists (ACLs) - for each **object** keep list of **principal's** allowed actions
- Capabilities - for each **principal**, keep list of **objects** and **principal's** allowed actions

		objects		
		/etc/passwd	/home/gibble	/home/guest
principals	root	rw	rw	rw
	gibble	r	rw	r
	guest			r

ACL

capability

Principals usually summarised as groups:

- Owner
- Group (customized lists of users)
- Other

Data Structures

Some metadata is needed for a file system:

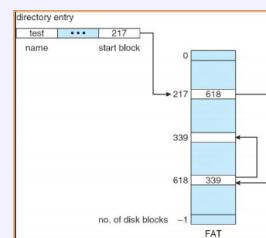
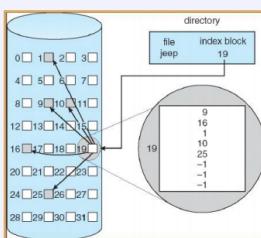
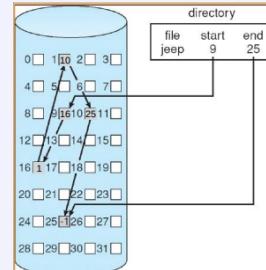
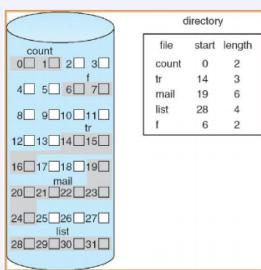
In backing storage

- Boot control block - information needed to boot an OS
- A per file File Control Block (FCB) - details about each file, unique ID
- Volume control block - volume details, number of blocks, size of blocks, free-block count and pointers, free-FCB count and pointers
- Directory structure - used to organise files

In memory

- Mount table - information about each currently mounted volume
- Directory-structure cache - information about most recently accessed directories (for speeding up queries)
- The system-wide open-file table - contains copies of FCB's for each open file with other information
- The per-process open-file table - contains pointers to the appropriate entries in the system-wide open-file table for all files that the process has opened
- Buffers - hold file-system blocks when they are being read/written to a FS

Disk allocation strategies



Contiguous Allocation

Each file is required to occupy a contiguous part of the disk. A file entry contains **Address of starting block** and **length of file in blocks**

- External fragmentation, holes that cannot be occupied due to size
- + reading file is quick
- + most resilient to file damage (know when there is memory errors)

Linked Allocation

Each file entry contains pointer to the next block, each directory entry contains the first and last block of a file.

- + no external fragmentation
- + files can grow as long as there is space
- + only really good for sequential access
- no random access, need to traverse all of previous blocks - $O(N)$

Indexed Allocation

Each file has a corresponding index block, which contains the indices of all the blocks which make up the file in order. Directory entries tie files to their index blocks.

- wastes a lot of space if files are made up of few blocks (internal fragmentation)
- + no external fragmentation, files can grow as long as there is space
- + fast random access unlike linked allocation

File allocation table (FAT)

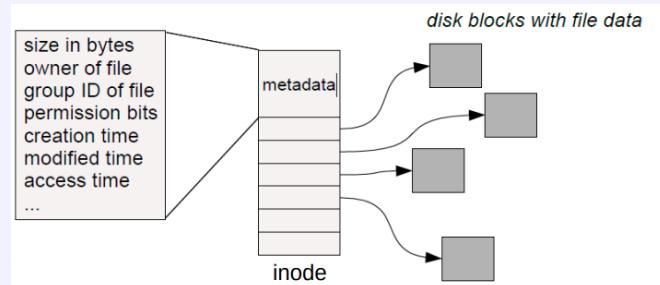
FAT table directly correlates entries to sectors, with each entry pointing to next sector of owning file. Directories contain sector numbers of start of each file.

- + more resistant to damage than linked allocation, can store multiple FAT tables easily
- + allows random access, but not too fast still need to traverse FAT table (but this is more localized and smaller)
- + only FAT needs to be traversed for each file operation (not various parts of disk)
- FAT might be spacious and depends on number of entries
- internal fragmentation depending on block size

INodes - Indexed allocation

Every file and directory is represented by an inode with a unique id (**index node**)
every inode contains:

- Metadata - file owner, access rights etc.
- Location - of file blocks on disk



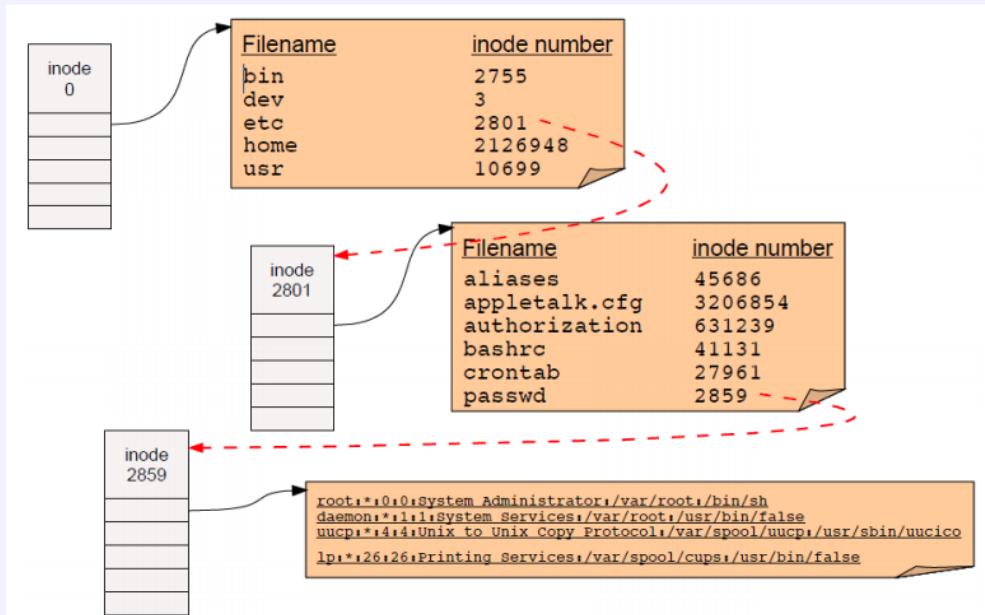
Directories

A directory is a flat file of fixed-size entries. Each entry links filename to inode ID

The diagram shows a 'metadata' block connected to a table of directory entries. The table has two columns: 'Filename' and 'inode number'. The entries are:

Filename	inode number
aliases	45686
appletalk.cfg	3206854
authorization	631239
bashrc	41131
crontab	27961
passwd	2859

To resolve a pathname, e.g. "/etc/passwd", start at root and walk down chain of nodes:



Multiple directories can contain the same file! (hard link in unix)

Inode file systems - data layout

The data on the disk contains different areas:

- Superblock - specifies boundaries of other areas, contains head of freelists of inodes and file blocks
- Inode area - contains inodes for each file on the disk (each the same size)
- File contents area - fixed-size blocks referenced by inodes



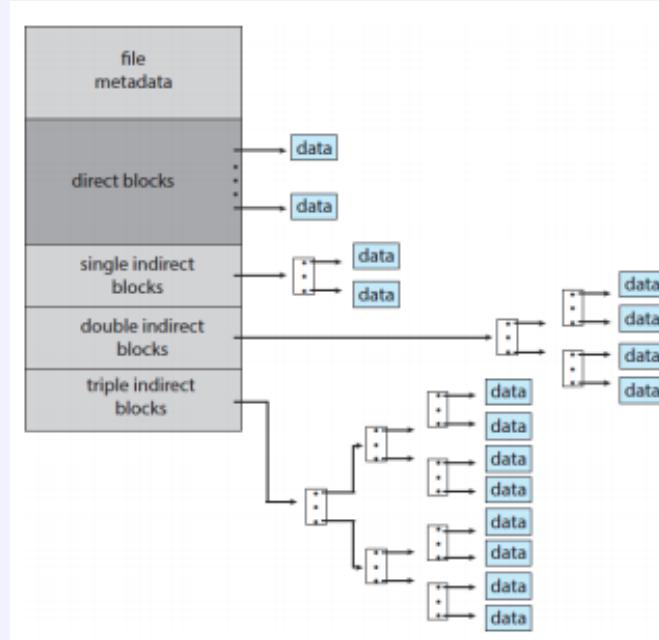
To find any inode, simply use their ID as index to the inode area! Can do this since they are fixed size.

- filesystem has fixed number of potential inodes - set when FS is created

Inode file system - block list

Each inode contains metadata and the **block list**.

To be able to store very small and very large files, the block pointers contain a number of direct pointer slots (i.e. ones that point directly to data blocks) and a number of single, double and triple indirect pointers which point to blocks containing more pointers!



Example

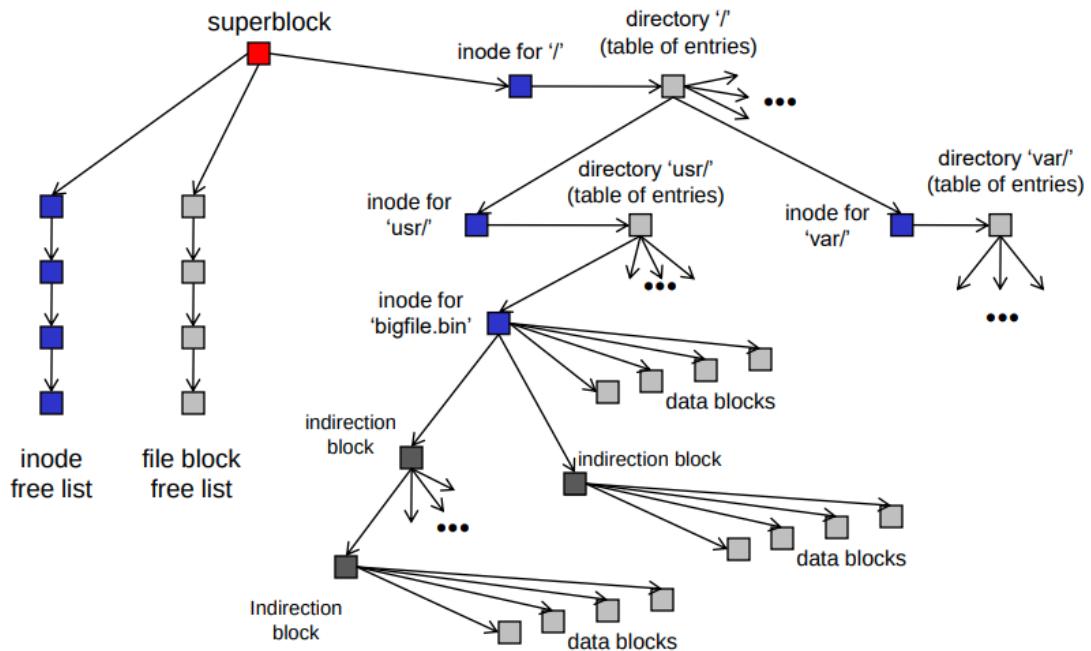
ters and if each inode contains 10 direct pointers, one single, double and triple indirect pointers (13 in total), then: With 512B data block sizes, 32b(4B) pointers

- Can access files as large as $10 \cdot 512B = 5120B$ with direct pointers
- The single indirect pointer, can link to a block containing $512B/4B = 128$ direct pointers, each pointing to a block: this lets us access $128 \cdot 512B = 64kB$
- The double pointer points to 128 single pointers which point to 128 blocks of data each, this lets us access $128 \cdot 128 \cdot 512B = 8MB$
- Similarly, we can access $128^3 \cdot 512B = 1GB$ with a triple indirect pointer
- In total: $5120B + 64kB + 8MB + 1GB \approx 1GB$

Inode file system - overview

The file system is simply just a huge data structure:

- The file system is just a huge data structure



An important part of a file system is to lay all this data out on a disk efficiently, also keeping in mind the physical constraints of the disk, i.e. trying to keep locality within a directory, and allowing sequential access to many files for when seek times are expensive.

Synchronization

Synchronisation

Cooperating tasks access the same data:

- Two or more threads of the same process share **data** and code
- Two or more processes can share data with **shared memory**

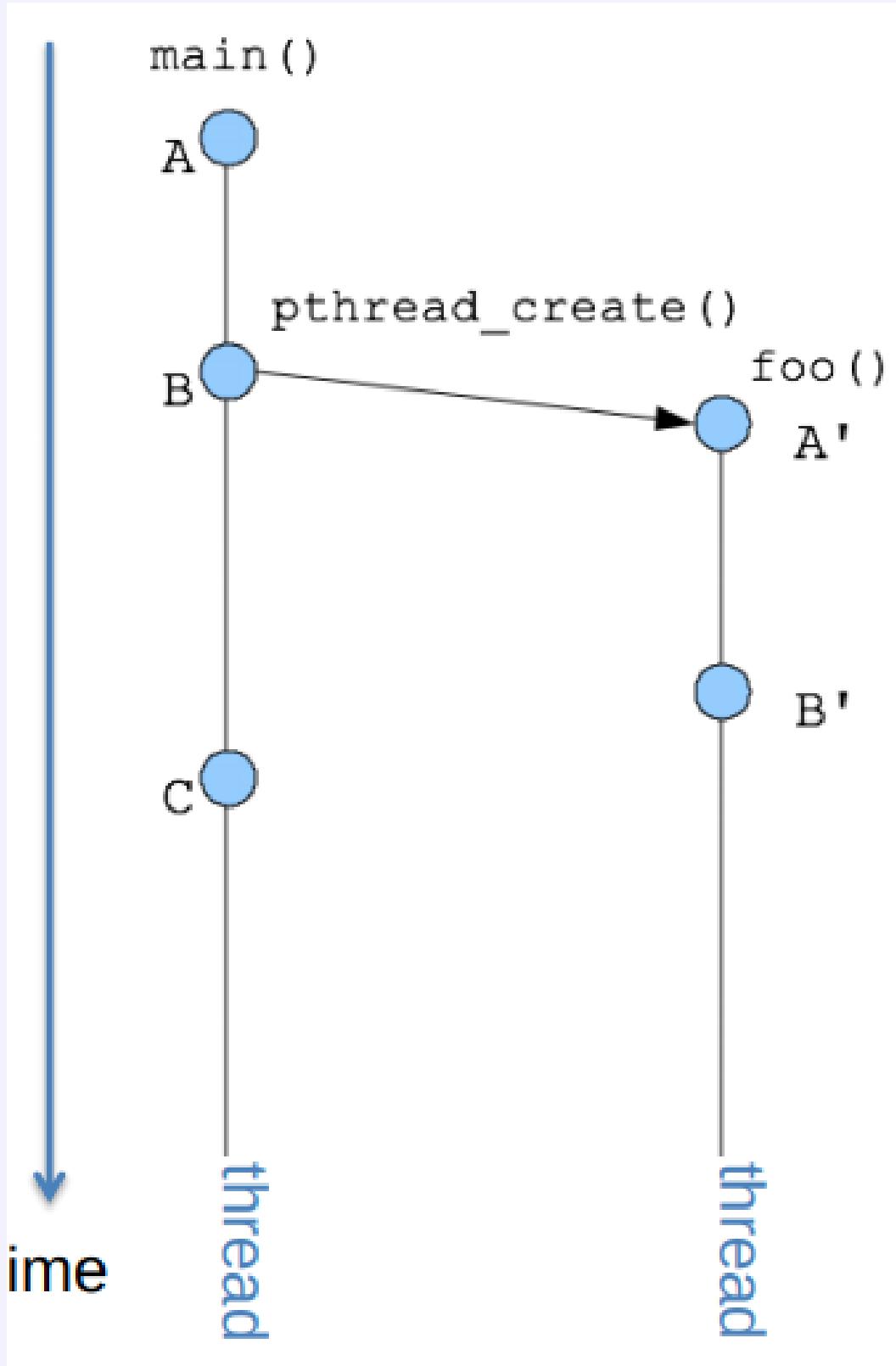
Concurrent or parallel access to shared data is either virtually done at the same time or actually at the same time for parallel access. This may result in **data inconsistency** (two processes may overwrite some data in a way which makes it invalid).

How to ensure **ordered** execution of cooperating tasks?

Ordered execution

Instructions executed by a single thread/process are **totally ordered**: $A < B < C$. i.e. A happens before B and C etc..

Without synchronization, instructions executed by a distinct thread/process must be considered **unordered/simultaneous**: cannot guarantee any of: $X < X'$ or $X' < X$ or $C == A'$ or $C == B'$
Creation relations always hold: $A < B < A' < B'$

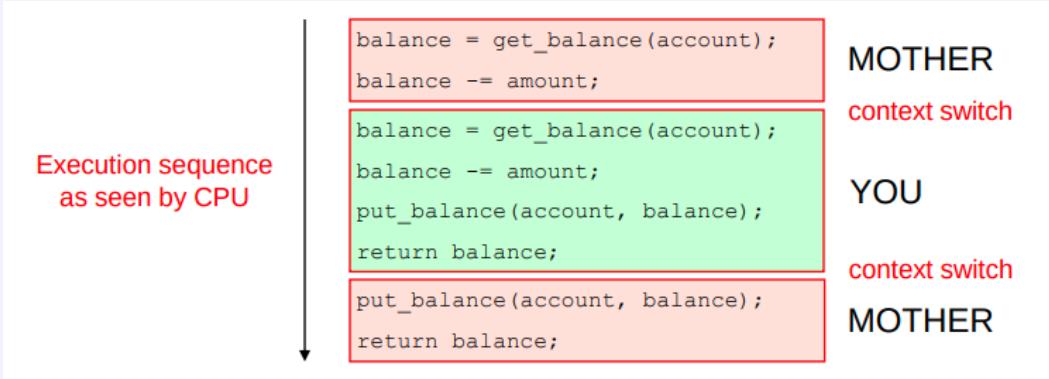


Race condition

When the result of concurrent or parallel execution is non-deterministic and depends on which thread runs precisely when.

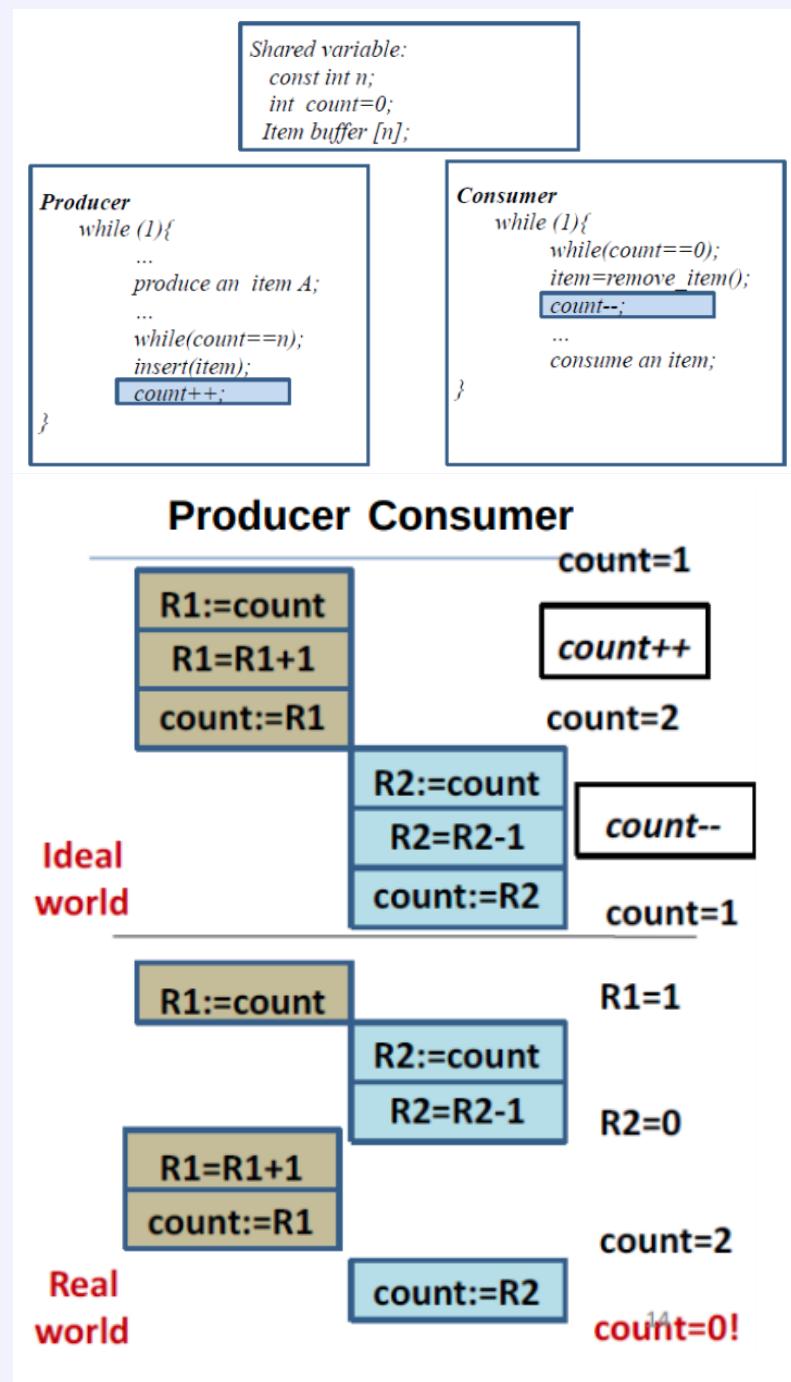
Example Race condition

Race conditions happen when two **interleaved** sections of the same code, execute in a harmful way.
The below code shows a case where the bank account does not register one of the transactions!



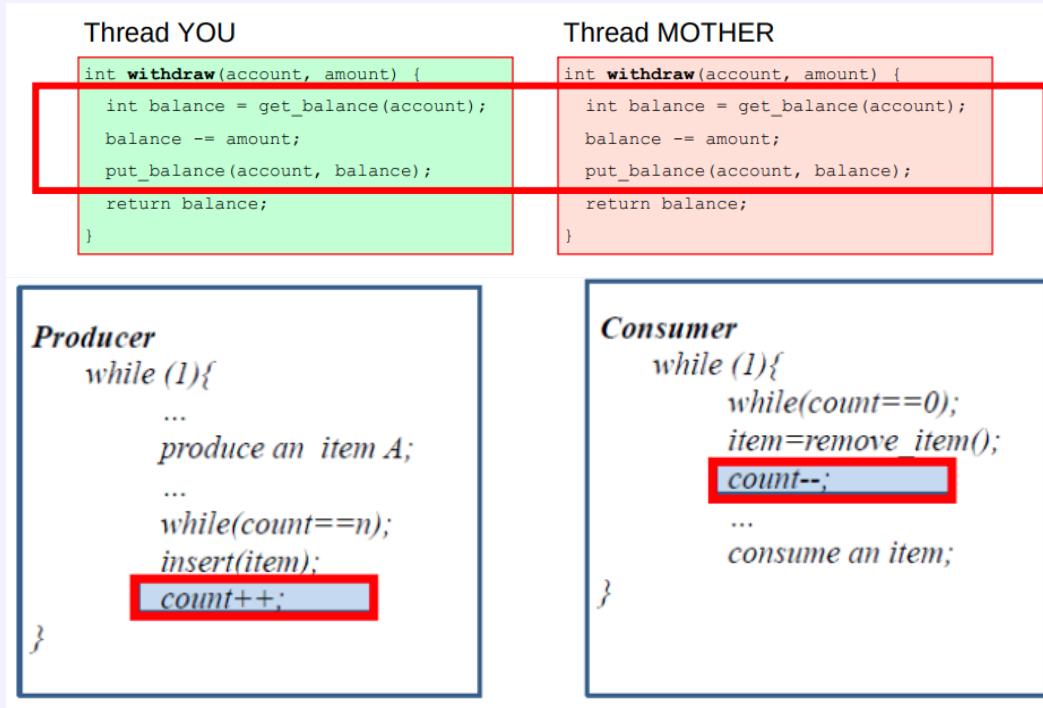
Example Race condition # 2

Race conditions can also happen between **seemingly** atomic instructions, in reality `count ++` would be executed as multiple assembly instructions:



Critical region

Critical regions are the areas of code which write/read to shared state, and can cause non-determinism:



Avoiding race conditions

Many factors need to ideally be taken under consideration:

- **Mutual exclusion** - at most one thread/process is in one critical region
- **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
- **Performance** - Overhead of entering and exiting critical section should be small wrt to work done inside it

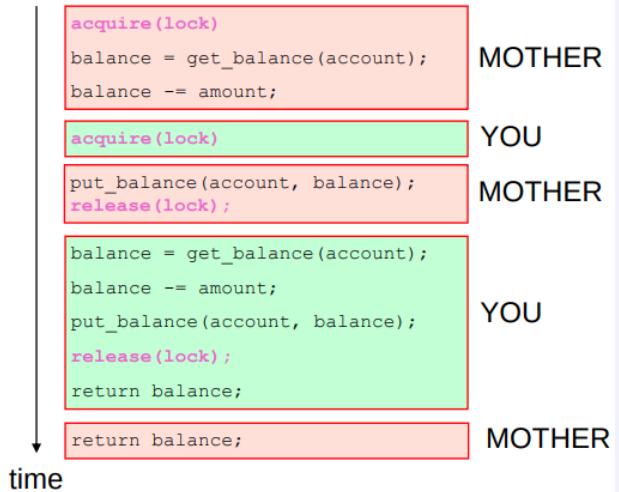
Locks

Locks are ways of ensuring mutual exclusion in critical parts of the code.
When one thread holds a lock, other threads wait until this lock is released.

Example

```
int withdraw(account, amount) {
    acquire(lock);
    balance = get_balance(account);
    balance -= amount;
    put_balance(account, balance);
    release(lock);
    return balance;
}
```

critical section



Bad implementation

Still has critical region itself!

```
1 while (TRUE) {
2 (1)while (lock->held != 0);(2)* loop */
3   lock->held = 1; (4)
4 (5)critical_region(); /* work */
5   lock->held = 0;
6   noncritical_region();
7 }
```

```
1 while (TRUE) {
2 (1)while (lock->held != 0);(2)* loop */
3   lock->held = 1; (3)
4 (5)critical_region();(4)* work */
5   lock->held = 0;
6   noncritical_region();
7 }
```

T1

T2

Good implementation

need **atomic** instruction ideally:

```
struct lock_t {
    int held = 0;
}
void acquire(lock_t* lock) {
    while(test_and_set(&lock->held)) { };
}
void release(lock_t* lock) {
    lock->held = 0;
}
```

- + simple easy to use and do the job effectively
- burn a lot of CPU cycles for no reason

Semaphores and Monitors

sleep() and wakeup()

sleep() - caller gives up CPU for some time, until a thread/process wakes it up

wakeup() - caller wakes up some sleeping thread/process

in practice sleep() might just be calling yield() (giving up CPU scheduling priority), signals might be used for waking up etc..

Semaphore

A sleep/wakeup version of a lock, which prevents the burning of CPU cycles!

Implementation

```
typedef struct {
    int value;
    struct thread *list;
} semaphore;

wait(semaphore *S) {
    S->value--;
    if (S->value < 0) {
        add this thread to S->list;
        sleep();
    }
}

signal(semaphore *S) {
    S->value++;
    if (S->value <= 0) {
        remove a thread T from S->list;
        wakeup(T);
    }
}
```

note: the thread objects might be TCB's as either user or kernel level constructs. Each function must be executed atomically! (spinlocks)

- threads/processes are blocked at the level of program logic
 - + no busy-waiting (burning cpu)
 - + scheduler is aware about thread/process waiting, other tasks can execute
 - still use spinlocks so some cpu cycles are still burned
 - easy to make mistakes, more complex problems can be solved but require more complex control
 - no guarantee of proper usage, signal() call is not enforced

Binary semaphore

Value initialized to 1. Protects single resource

Counting semaphore

Value initialized to # of protected resources. Positive means resource available, negative or zero = number of waiting for resources or no resources available

Synchronisation semaphore

Value initialized to 0, 0 means no events pending, **positive** value means there are events pending (waiting in sleep).

*If you have a routine S1 which needs to happen before S2, you call **signal** after S1, and **wait** before S2. This means that any process wanting to execute S2, will have to wait (value = -1) until S1 is executed by some process which reduces value to 0.*

```

Shared variables
const int N=100;
semaphore full=N, empty=0;
semaphore mux=1;

Producer
while (1) {
    produce an item A;
    wait(full);
    wait(mux); // acquire(mux)
    insert item;
    signal(mux); // release(mux)
    signal(empty);
}

Consumer
while (1) {
    wait(empty);
    wait(mux); // acquire(mux)
    remove item;
    signal(mux); // release(mux)
    signal(full);
    consume an item;
}

```

note: semaphores here are used to limit burning of CPU when buffer is full or empty, but we still need another semaphore on the actual buffer operations

Semaphore example - reading

Sometimes we want to let multiple reading threads in, but only one writer:

```
var mutex: semaphore = 1      ; controls access to readcount  
wrt: semaphore = 1    ; control entry for a writer or first reader  
readcount: integer = 0     ; number of active readers
```

```
writer:  
P(wrt)          ; any writers or readers?  
    <perform write operation>  
V(wrt)          ; allow others
```

```
reader:  
P(mutex)          ; ensure exclusion  
readcount++       ; one more reader  
if readcount == 1 then P(wrt)    ; if we're the first, synch with writers  
V(mutex)  
    <perform read operation>  
P(mutex)          ; ensure exclusion  
readcount--       ; one fewer reader  
if readcount == 0 then V(wrt)    ; no more readers, allow a writer  
V(mutex)
```

*note: how the first reader blocks the write semaphore, and the last releases it, while every writer does the same.
We still need to lock the manipulation of the shared variables*

Semaphore example - forever blocked

Starts with full=N, empty=0, mux=1

Producer

```
while (1) { ④  
    produce an item A; ⑤  
    wait(full); ⑥  
    wait(mux); ⑦ Blocked!  
    insert item;  
    signal(mux);  
    signal(empty);  
}
```

Consumer

```
while (1) { ①  
    wait(mux); ②  
    wait(empty);  
    remove item;  
    signal(mux);  
    signal(full);  
    consume an item;  
}
```

note: order of locks is important! bug prone

Monitor

Address key usability issues with semaphores, a **programming language construct**. An **abstract data type/class** in which every method automatically acquires a lock on entry and releases it on exit. includes:

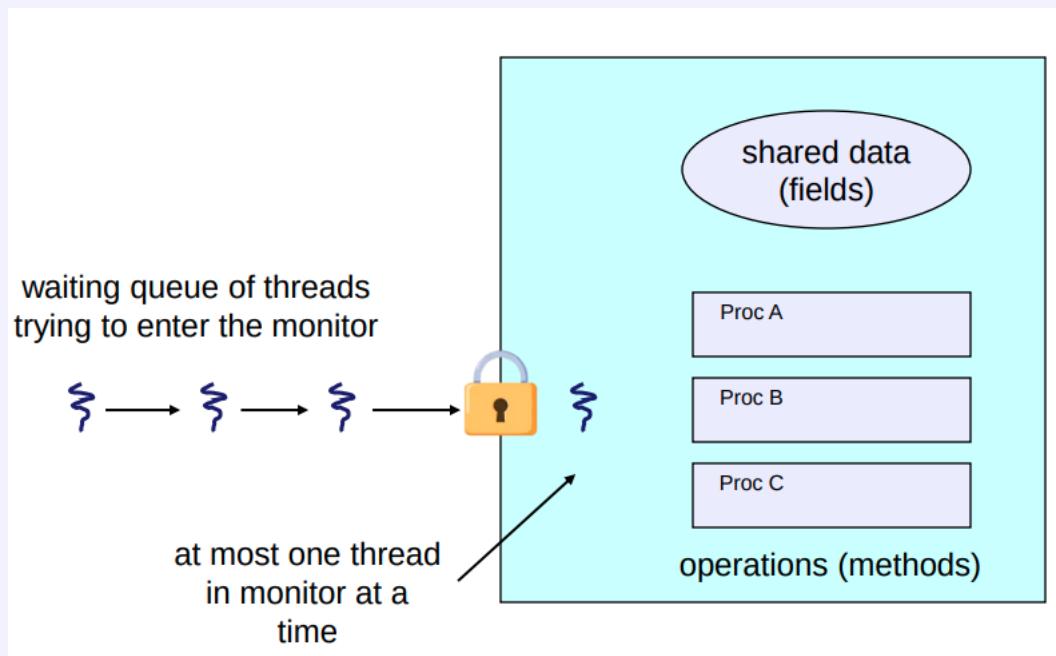
- **shared data** structures
- **procedures** that operate on the shared data
- **synchronisation** between concurrent execution flows that invoke those procedures

data is encapsulated from within:

- protects the data from unstructured access
- prevents ambiguity about synchronisation

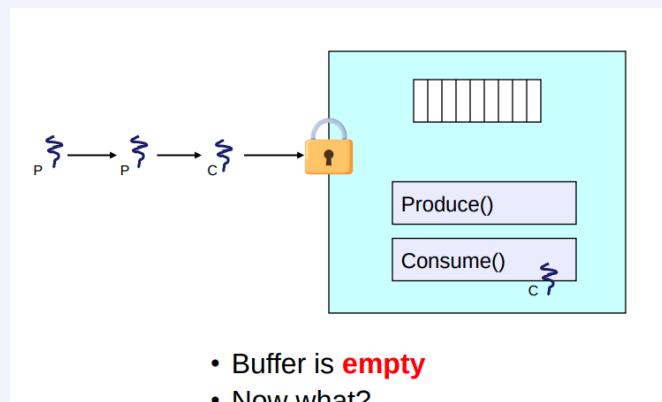
Automatic mutual exclusion

- Only **one thread** can be executing inside at any time
- Synchronization is implicitly associated with the monitor (free)
- If a second thread tries to execute a monitor procedure it **blocks** until the first has left the monitor
- more restrictive than semaphores but easier to use



Deadlock problems

Not as flexible, what to do in deadlocks ?



Condition variables

- **cond_wait(c)**
 - Release monitor lock, so somebody else can get in
 - Wait for someone else to call **cond_signal(c)**
 - Condition variables have associated wait queues
- **cond_signal(c)**
 - Wake up at most one waiting thread
 - Wake up immediately, signaller steps outside
 - If no waiting threads, signal is lost (difference from semaphores, no history)
- **cond_broadcast(c)**
 - Wake up all waiting threads (for c)

Monitor example

The compiler can be made to insert enter and exit monitor calls wheerever the programmer uses wait and signal calls:

```
Monitor producer_consumer {
    buffer resources[N];
    condition not_full, not_empty;

    produce(resource x) {
        if (array "resources" is full, determined maybe by a count) EnterMonitor(m)
            wait(not_full);
        insert "x" in array "resources"
        signal(not_empty);
    } ExitMonitor(m)

    consume(resource *x) {
        if (array "resources" is empty, determined maybe by a count) EnterMonitor(m)
            wait(not_empty);
        *x = get resource from array "resources"
        signal(not_full);
    } ExitMonitor(m)
}
```

Deadlocks

Deadlock

A situation in which every process/thread in a set of processes/threads is **waiting for an event** that can be caused only by another process/thread in the same set

```
Semaphore muxA = 1 /* protects resource A */  
Semaphore muxB = 1 /* protects resource B */
```

Process P:

```
{  
    /* initial compute */  
    down(muxA)  
    down(muxB)  
    /* use both resources */  
    up(muxA)  
    up(muxB)  
}
```

Process Q:

```
{  
    /* initial compute */  
    down(muxB)  
    down(muxA)  
    /* use both resources */  
    up(muxB)  
    up(muxA)  
}
```

Livelock

Similar to deadlock but occurs when a thread/process **continuously attempts** an action that fails

```
// thread 1  
getLocks12(lock1, lock2)  
{  
    lock1.lock();  
    while (lock2.locked())  
    {  
        // attempt to step aside for the other thread  
        lock1.unlock();  
        wait();  
        lock1.lock();  
    }  
    lock2.lock();  
}  
  
// thread 2  
getLocks21(lock1, lock2)  
{  
    lock2.lock();  
    while (lock1.locked())  
    {  
        // attempt to step aside for the other thread  
        lock2.unlock();  
        wait();  
        lock2.lock();  
    }  
    lock1.lock();  
}
```

Necessary conditions for deadlock

without any of the below conditions, a deadlock is not possible

- A) **Mutual exclusion** - each resource is either currently assigned to exactly **one** process/thread or is available
- B) **Hold and wait** - process/threads currently holding resources that were granted earlier can request new resources
- C) **No preemption** - Resources previously granted cannot be forcibly taken away from a process/thread
- D) **Circular wait** - there must be a circular list of two or more processes/threads each waiting for a resource held by the next member of the chain

System model

A system consists of a **finite number of resources**, partitioned into several types/classes, to be **distributed among a number of competing threads/processes**.

- Resource types/classes (**m**) - R_1, R_2, R_m
- Each resource type has E_i instances
- assume serially reusable resources (request - \downarrow ; use - \downarrow ; release)
- Processes/threads (**n**) - P_1, P_2, P_m

Let (V, E) be the directed graph representing the **current state** (snapshot) of resource usage.
Then

$$V = \{P \mid P \text{ is a process}\} \cup \{R \mid R \text{ is a resource type}\}$$

And

$$E = \{E \mid E \text{ is a directed request edge } (P_i, R_j)\} \cup \{E \mid E \text{ is an assignment edge } (R_i, P_i)\}$$

- Process node



- Resource node with 4 instances



- P_i requests instance of R_j



- P_i is holding an instance of R_j



Allocation graph - no deadlock

- Process node



- Resource node with 4 instances



- P_i requests instance of R_j

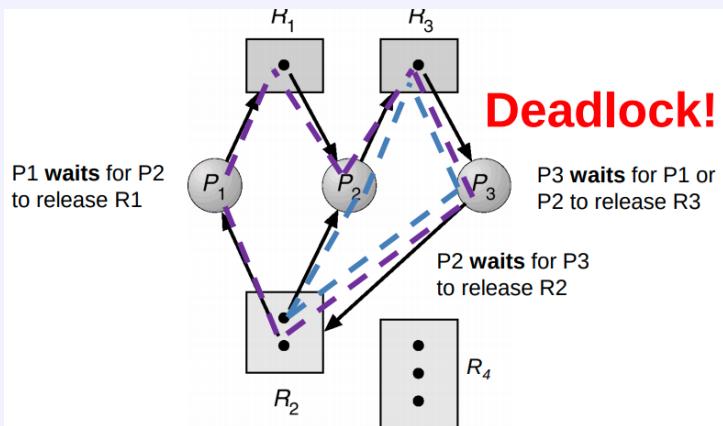


- P_i is holding an instance of R_j



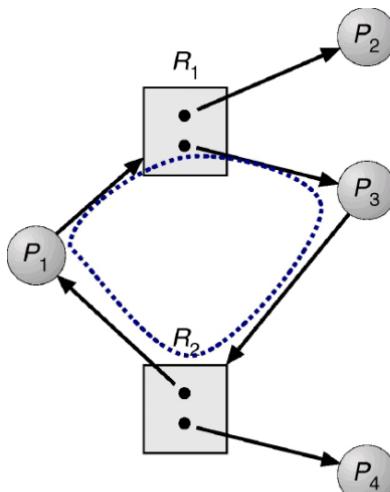
note: No cycles → thread/process is not deadlocked

Allocation graph - deadlock



note: cycles → thread/process may be deadlocked

Allocation graph - no deadlock cycle



A cycle **is not sufficient** to imply a deadlock

Only if each resource involved in a cycle has **exactly one instance**, then the processes are deadlocked iff they are a part of such a cycle.

note: cycle ≠ deadlock

Handling deadlocks

- **Prevention** - Negate one of the four necessary conditions
- **Avoidance** - Each resource request is analyzed and denied if it may deadlock
- **Detection and recovery** - detect deadlock after it happens, recover from it
- **Do nothing**(ye olde ostrich algorithm) - ignore the problem and pretend deadlocks never occur since they're so rare (actually done in some OS)

Attacking - Mutual exclusion

- Avoid assigning a resource unless absolutely unnecessary
- Try to make sure that as few processes as possible may actually claim the resource
- Practically - don't assign resources to a single processes for reads, and for writes use a mediator which serializes the write (spooler deamon in case of spooler)
- **Problem** - process may deadlock filling up the mediator

Attacking - Hold and wait

- Prevent processes that hold resources from waiting for more resources
- Require all processes to request all their resources before "executing"
- If everything is available, the process will be allocated whatever it needs and can run to completion
- If one or more resources are busy, nothing will be allocated and the process will just wait - then reallocate everything again
- **Problem** - processes don't always know all the resources they require

Attacking - No preemption

- If a process is holding some resources and requests another resource which is not available, then all resources the process is currently holding are preempted (released)
- Practically, can only be applied to resources whose state can be easily saved and restored (CPU registers, memory space, etc..)
- **Problem** - Not all resources can be virtualized

Attacking - Circular wait

- All requests of resources must be made in numerical order by process
- May be impossible to find an ordering to satisfy everyone

Process P:

```
{  
    /* initial compute */  
    down(muxA)  
    down(muxB)  
    /* use both resources */  
    up(muxB)  
    up(muxA)  
}
```

Process Q:

```
{  
    /* initial compute */  
    down(muxB)  
    down(muxA)  
    /* use both resources */  
    up(muxB)  
    up(muxA)  
}
```

Process Q:

```
{  
    /* initial compute */  
    down(muxA)  
    down(muxB)  
    /* use both resources */  
    up(muxB)  
    up(muxA)  
}
```

Deadlock avoidance

The OS/runtime needs to be given **additional information** in advance:

- What resources a thread/process will **request and use** during lifetime
- Complete **sequence of requests and releases** of each thread/process
- **Decide for each request** if a thread/process waits, considering the **resource-allocation state**
- Algorithm dynamically examines resource-allocation state for **circular-wait condition** existence

Safe state

When the system **can allocate all leftover resources** to each thread/process (up to maximum) **in some order** and still avoid **deadlocks**

A system is in a safe state iff there exists a **safe sequence**

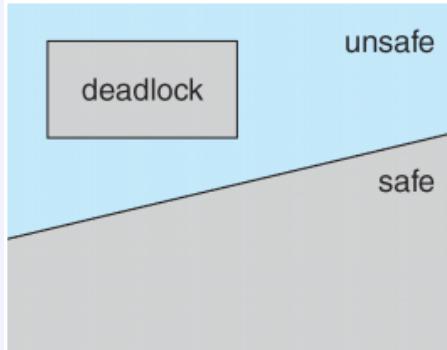
- A sequence $(p_1, p_2, p_3..p_n)$ of **all the processes in the systems**
- such that for each p_i , the resources that p_i can still request, can be satisfied by:
 - Currently **available resources** +
 - **Resources held** by all the p_j 's before it in the sequence
- In this situation if p_i needs some resource which is not immediately available:
 - p_i can wait until all p_j s.t. $j < i$ are done
 - Then p_i can obtain the needed resources, execute and return allocated resources then terminate
 - when p_i terminates p_{i+1} can obtain its needed resources and so on

Because of all the other necessary conditions:

safe state = non deadlocked state

deadlocked state \rightarrow unsafe state

unsafe state $\not\Rightarrow$ deadlock



- In a **safe state** - OS can avoid **unsafe states**
- In an **unsafe state** - OS cannot prevent resource allocations resulting in deadlocks

Banker's algorithm

Algorithm used to avoid deadlocks.

Requires:

- Set of **controlled resources**
- **Number of units** of each resource is known
- Each application declares **maximum possible requirement** of each resource type

Before approving any resource allocation request, check if it leads to a safe state, if not reject it.

Pseudocode:

Let n be the number of processes, and m the number of resources available, the below is done before any allocations are made

- Initialize n x m matrix **Max**, defined as $Max_{ij} = \text{maximum possible requirement of resource type } j \text{ to process } i$
- Initialize n x m matrix **Allocation**, defined as $Alloc_{ij} = \text{initial assignment count of resource type } j \text{ to process } i \text{ (the count of resources process } i \text{ owns of type } j)$
- Initialize n x m matrix **Need**, defined as $Need_{ij} = Max_{ij} - Allocation_{ij}$ i.e. the maximum possible leftover allocations of each resource type to each process
- Initialize m x 1 matrix **Available**, defined as $Available_i = \text{the number of leftover resources of type } i$
- The above structures form the **state** of the algorithm, we only allow **safe-states**

This state initially must be safe!

Next, given a request by process p for r the $mx1$ vector of resources for the next allocation cycle , which will mutate the state if allocated, we do the following:

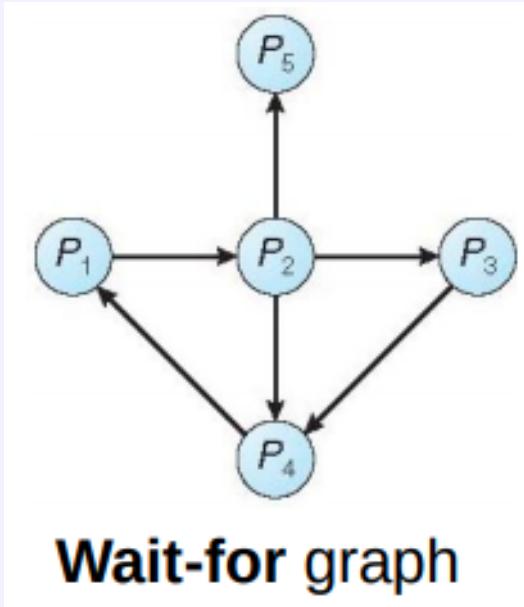
- a) If the request cannot physically be granted, i.e. if $Available - r$ or $Max_p - r^T$ have any negative entries - Reject the request
- b) Otherwise, assume the request is granted, and determine if the new state is safe by running the below algorithm, on a new instance of the state structure initialized to the hypothetical state, if r was approved. This new state is formed by:
 - i) Removing the allocated resources from the *Available* resources : $Available - r$
 - ii) Accounting for the new *Allocation* of resources: $Allocation_p + = r^T$
 - iii) Re-calculating the *Need* matrix : $Need_i - = r^T$
- c) if the state is safe, approve the request, otherwise decline it.

Given a hypothetical state, determine if it's safe with the following:

- a) Initialize the $mx1$ vector **Work**, to be: $Work = Available$. This will represent the mutation of Available resources over time as, requests are tried in order
- b) Initialize the $nx1$ boolean vector **Finish**, to: $\forall i. Finish_i = False$
- c) Now find a process p such that both:
 - i) $Finish_p = False$, i.e. a process which has not "had its turn yet"
 - ii) $\forall j. Need_{pj} \leq Work_j^T$, and one which can in the current state, "fully stock up" its resources to its maximum
- if none satisfy this condition, go to step g)
- d) "Free" the resources previously allocated to p : $Work+ = Allocation_p^T$
- e) Set p's status to finished: $Finish_p = True$
- f) repeat from c), and add p to the end of the "safe sequence" S
- g) if $\forall x. Finish_x = True$ holds, the system is in a safe state and the safe sequence is in S, otherwise the state is not safe

Deadlock detection

Maintain a different directed graph - the **wait-for** graph, where processes are nodes, and directed edges (P_1, P_2) imply P_1 is waiting for P_2 .
Periodically search for cycles in this graph, because **cycle \rightarrow deadlock!**
Search is $O(n^2)$.



note: does not work with multiple instances of each resource type

Recovery from deadlock

- Abort **all** deadlocked processes or just one at a time until deadlock is eliminated
- this may leave resources in an incorrect state
- Alternatively, preempt resources:
 - Select victim - resource and process to preempt
 - Rollback - return resource to safe state, restart process for that state
 - Starvation - avoid same process/thread as victim

Virtualization

Virtualisation

Process of creating a **virtual** version of a **physical** object

Hardware virtualisation - process of creating **virtual** version of real hardware. Virtual hardware can be used to run a complete OS

Virtual machine

A virtual representation of a physical machine

Virtual machine monitor/Hypervisor

A software application that monitors and manages running virtual machines

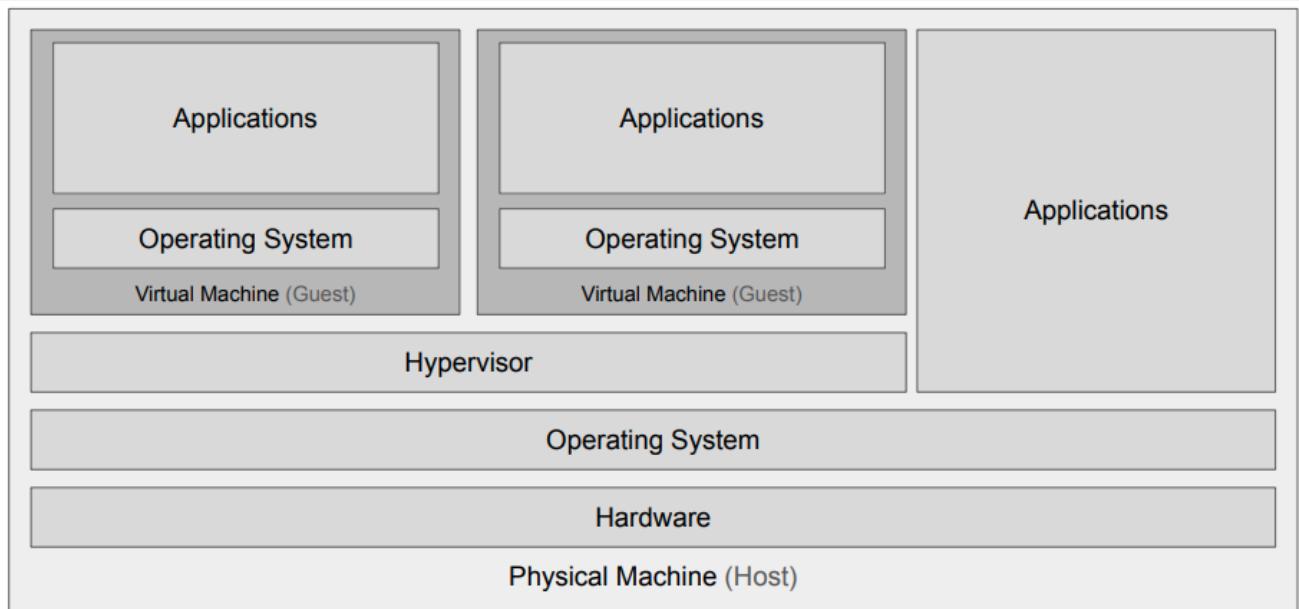
Host machine

The physical machine that a virtual machine is running on

Guest machine

The virtual machine running on the host machine

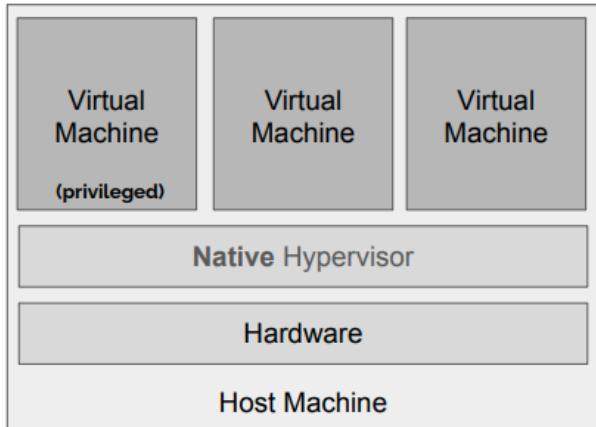
Virtualisation diagram



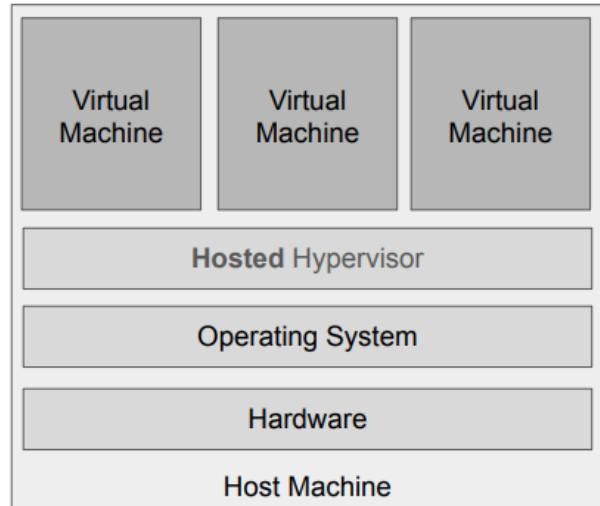
VMM/Hypervisor types

- **Native hypervisors (bare metal)** - run directly on the host machine, and share out resources (memory and devices) between guest machines (Oracle VM server)
- **Hosted hypervisors** - run as an application inside an operating system, and support virtual machines running as individual processes (QEMU, VBox)

Type 1 - Native



Type 2 - Hosted



Uses of virtualisation

- **Personal** - running multiple OS on one host, without rebooting. Running windows inside OS X
- **Technical** - OS/hardware design, kernel debugging/testing
- **Commercial** - Data centre server consolidation, high availability/migration

Types of virtualisation

- **Software emulation** - maximum flexibility, but very slow
- **Containers/namespaces** - isolate processes/ groups of processes within a single OS (Docker)
- **Full system/Hardware virtualisation** - isolate multiple OS from each other, within a single physical machine
- **Same-architecture virtualisation** - guest machine is the same architecture as host machine (ARM or x86)
- **Cross-architecture virtualisation** - Guest machine has different architecture (requires software emulation)

Popek and Goldberg requirements for virtualisation

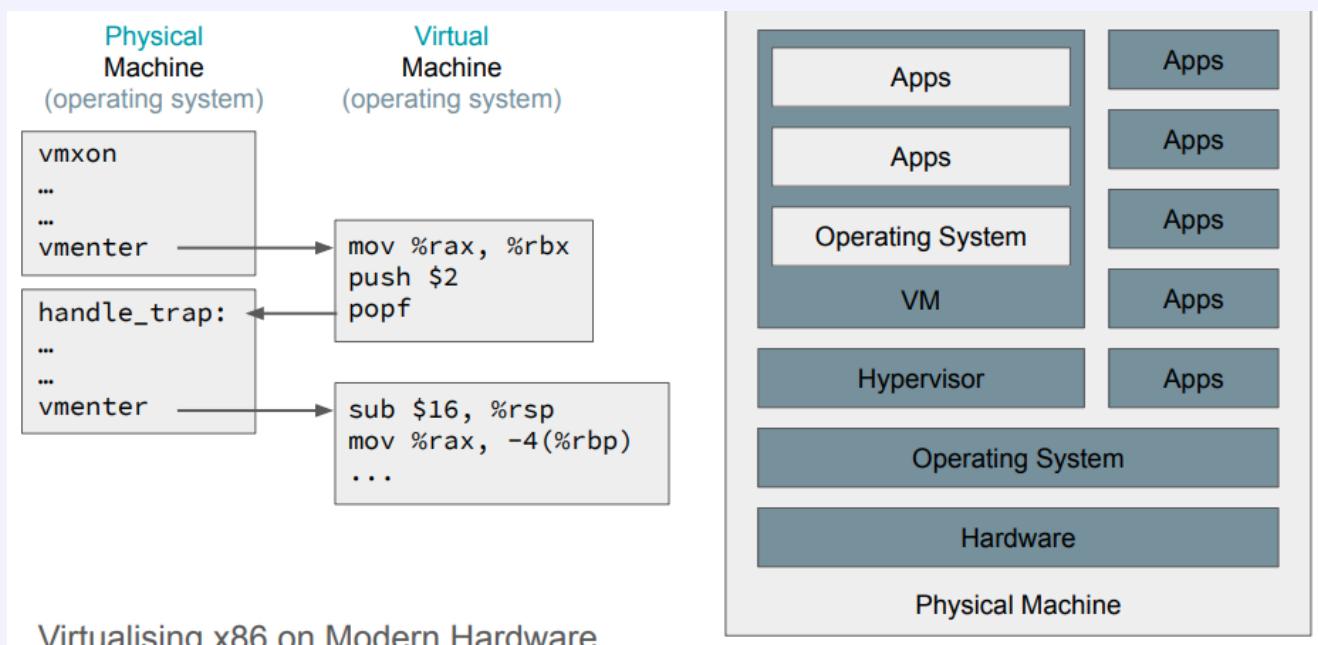
- **Efficiency** - the majority of guest instructions are executed directly on the host machine
 - Normal guest machine instructions should be execute directly on the processor.
 - System (kernel) instructions need to be emulated by the VMM
- **Resource control** - VMM must remain in control of all machine resources
 - VM cannot be able to arbitrary take control of any resources (security)
- **Equivalence** - the VM must behave in a way that is indistinguishable from if it was running as a physical machine
 - OS running inside VM, needs to believe it's running on physical machine (it shouldn't be able to detect it's on a VM)
 - exceptions include: **temporal latency** (some instruction sequences will take longer to run), and **resource availability** (less resources available due to sharing between VM's)

Methods of virtualisation

- **Full software emulation**
 - violates efficiency property, but this no longer holds due to advent of **efficient binary translation**
 - Required for cross-architecture virtualisation, as guest instructions cannot execute natively on the host
- **Trap-and-Emulate**
 - The guest OS system runs "de-privileged", all non-privileged instructions execute natively on the host.
 - All privileged instructions trap to the VMM
 - VMM emulates these privileged operations
 - Guest resumes execution after emulation

Virtualising x86

- Originally x86 was not "classically" virtualisable
- Some privileged instructions did not "trap", and so could not be emulated correctly
- **Interpretation** is too slow (violates efficiency)
- **Code patching** (editing code after to re-write privileged instructions) leaves traces of virtualisation (violates equivalency)
- **Binary translation** better but still incurs overhead
 - since 2005, x86 support virtualisation in hardware (intel-VT,AMD-V)
 - this enables trap-and-emulate style virtualisation at the hardware level
- Unmodified OS can run natively on host machines



Virtualising x86 on Modern Hardware

Hardware acceleration for Virtualisation

- Modern processes include hardware support for running VM's
- Hardware extensions allow all guest instructions (including system instructions) to run natively on the processor
- This works by providing an isolated view of the processor to virtual machines.
- OS can then run directly on the processor, believing they are running on real hardware
- Certain privileged instructions "trap" back to the hypervisor

Resource access

- VM's need:
 - Memory
 - Storage
 - Networking
 - Graphics
- VMM shares out these resources
- Access to physical memory is managed by the VMM
- For an unmodified OS, expecting a "real" storage device (such as HDD), the VMM must emulate its interface!
- Some devices may be passed straight through to the VM, e.g. dedicated network cards.

Paravirtualisation

- Guest operating systems are **aware** they are being virtualised
- They co-operate with the hypervisor to enable increased memory and device performance
- They no longer "trap-and-emulate", but instead request privileged operations from the hypervisor (API)
- They can co-operate with the hypervisor so that host memory can be more efficiently distributed
- Instead of providing an emulated storage device, the hypervisor can provide a paravirtualised implementation
- Typically used in **data centres** for large-scale virtualisation

Data-center technologies

fuq clooud