National University of Singapore

CS2106 Operating System

Midterm Summary Notes

Dong Shaocong A0148008J

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Contents

1 Basic Idea

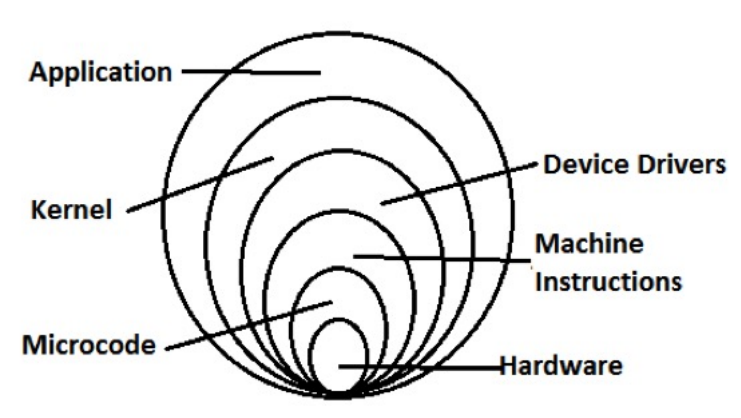
Definition 1.1. Operating System is a suite (i.e. a collection) of specialised software that:

- Gives you access to the hardware devices like disk drives, printers, keyboards and monitors.
- Controls and allocates system resources like memory and processor time.
- Gives you the tools to customise and tune your system.

Example 1.1. LINUX, OS X (or MAC OS, a variant of UNIX), Windows 8

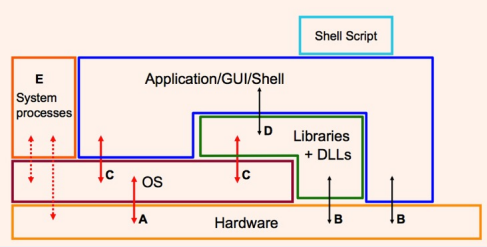
What are Operating System? It usually consists of several parts. (Onion Model)

- **Bootloader** First program run by the system on start-up. Loads remainder of the OS kernel.
  - On Wintel systems this is found in the Master Boot Record (MBR) on the hard disk.
- **Kernel** The part of the OS that runs almost continuously.
- **System Programs** Programs provided by the OS to allow:
  - Access to programs.
  - Configuration of the OS.
  - System maintenance, etc.



Definition 1.2. Micro-coding CPU designers implement a set of basic operations directly in hardware, then create a "microcode" a language that uses these operations to create complex machine instructions. (**Reason**: some instructions are too complex to do properly in hardware. Microcode on a CPU can let us write more compact code for the same equivalent program, than on a CPU without microcode. One assembly instruction can be made up of multiple micro instructions.)

Abstraction Layer & Opearating System Structure



- *A* : OS executing machine instructions, maybe *privileged*
- *B* : normal machine instructions executed (program/library code)
- *C* : calling OS using *system call interface*
- *D* : program calls library code
  - *statically linked:* contained in executable
  - *dynamic link libraries (DLL):* loaded at runtime
- *E* : system processes
  - usually special
  - sometimes part of the OS

OS takes control in *A* and *C*, maybe *E*.

Remark. System calls are provided by OS, and libraries calls are provided individual languages. Some library calls wrap around one or more system calls to provide the functionality to user program.

Definition 1.3. Boostrapping

- The **OS is not present in memory** when a system is cold started.
  - When a system is first started up, memory is completely empty.
- We start first with a **bootloader** to get an operating system into memory.
  - Tiny program in the first (few) sector(s) of the hard-disk.
  - The first sector is generally called the boot sector or master boot record for this reason.
  - Job is to load up the main part of the operating system and start it up.
- bootstrap routine in boot sector loads up core disk services, and use this to load up memory and process management routines, and use that to load up services like web servers, ssh servers, etc, and finally load up the shell.

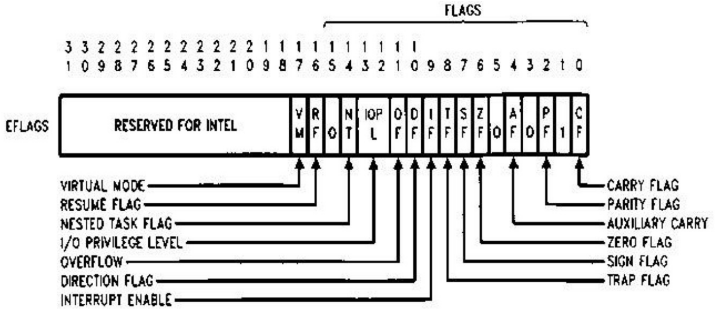
Definition 1.4. Core CPU units that can execute processes, because we have much more number of processes than the number of cores, we have to do **context switching** to share a core very quickly between different processes.

- Entire sharing must be transparent.
- Processes can be suspended and resumed arbitrarily.

Definition 1.5. Context switching

1. Save the context of the process to be suspended.
2. Restore the context of the process to be (re)started.
3. Issues of scheduling to decide which process to run.

Definition 1.6. special register Machine Status Word (MSW) or Status Register (SREG)



We can see that it contains flags that tell us the results of a previous arithmetic operation. E.g. Zero (ZF) tells us if a subtract resulted in a 0, Sign (SF) tells us if it resulted in a negative number. The Carry flag (CF) tells us if an addition resulted in a carry, the Overflow flag (OF) tells us if an overflow resulted (which means the results could be invalid), etc.

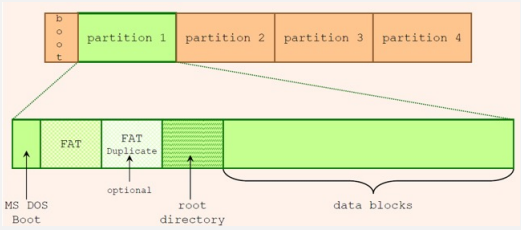
The ZF and SF are necessary for branch instructions. E.g. for a branch on less than (BLT), the ALU performs a subtraction, and the branch is taken if SF is set. Similarly for a BEQ, the branch is taken if ZF is set, etc.

The MSW also contains configuration flags, like the Interrupt Enable (IF) flag that enables or disables maskable interrupts (special signals that I/O hardware can use to get the CPU's attention essentially this flag tells the CPU whether to entertain or ignore such requests).

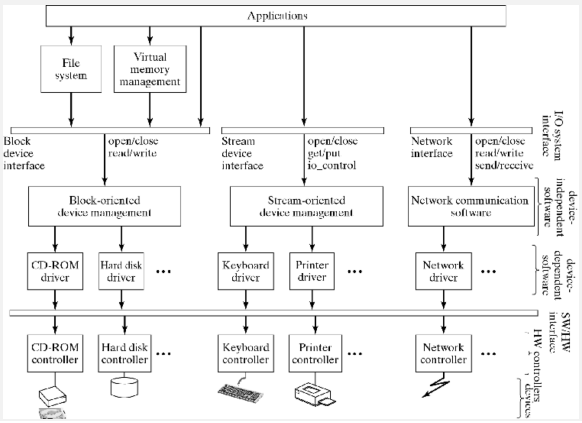
For correctness, MSW has to be stored during context save and restored during context restore.

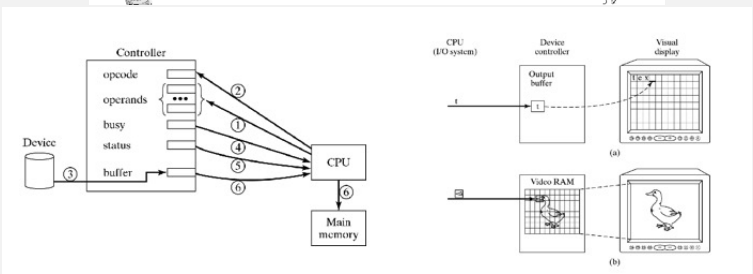
Definition 1.7. File system A set of data structures on disk and within the OS kernel memory to organise persistent data.

How OS file system works?



Hardware Interfaces



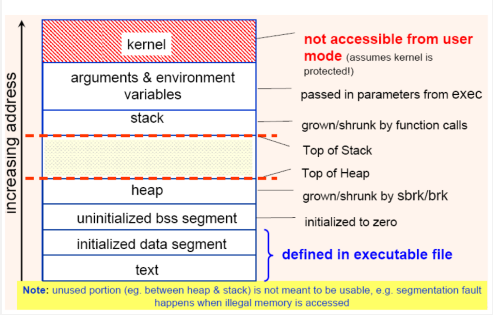


Remark. Comparison between device drivers

- **Block-oriented device management**: the **block devices** are usually storage devices that provide reading and writing operation of data in fixed-size blocks. Some **examples** of such devices are: hard drives, floppy disks, and optical drives such as DVD-ROM, and CD-ROM. **Advantage**: fewer pins to access data.
- **Stream-oriented device management**: **character (Stream) devices** are allowed to use **few bytes** in its operations. Also buffering is not required for such devices, and as such; the response time and the processing speed is faster than the block devices. **examples**: console, mouse, and all devices that are neither storage nor network devices. **Advantage**: I/O can be done directly between the device and the user and as such; the kernel is saved from copying operation and the overhead of buffering mechanisms.

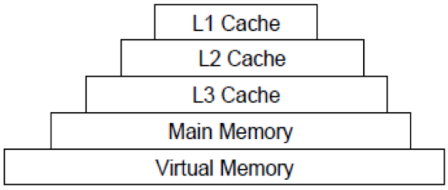
Definition 1.8. Memory static/dynamic (new, delete, malloc, free). Memory to store instructions Memory to store data.

Memory Management



Definition 1.9. Virtual Memory management

- For cost/speed reasons memory is organized in a hierarchy:

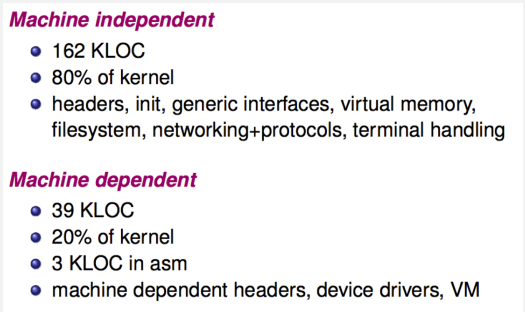


- The lowest level is called "virtual memory" and is the slowest but cheapest memory.
  - Actually made using hard-disk space!
  - Allows us to fit much more instructions and data than memory allows!

Definition 1.10. OS security

- Data (files): Encryption techniques, Access control lists
- Resources: Access to the hardware (biometric, passwords, etc), Memory access, File access, etc.

Writing an OS (BSD Unix)

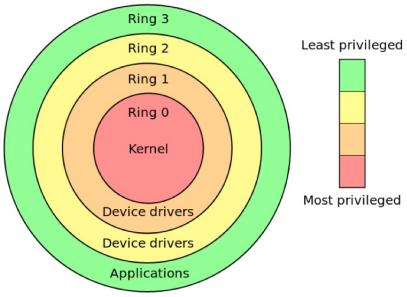


Example 1.2. Privilege Levels used in Intel CPUs

This diagram is useful to understand privilege rings:

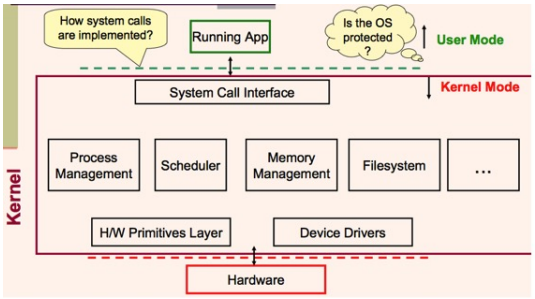
processes running in lower (outer) rings have more restrictive access to the machine than processes in the higher (inner) rings, to prevent a user, for example, from erasing the entire system drive.

why the highest priority task can still be interrupted by the lowest priority interrupt, and how this affects ISR design. (Hint: Interrupts are implemented in hardware in the CPU itself).
This is because task priorities are seen only by the OS. As far as the CPU is concern, it is just another program that is running, with instructions being fetched and executed. On the other hand interrupt lines are checked at the end of each instruction execution cycle, so interrupts are always serviced regardless of their priority level (and of the priority level of the running task).



Definition 1.11. Kernel

- Monolithic Kernel (Linux, MS Windows)
  - All major parts of the OS-devices drivers, file systems, IPC, etc, running in "kernel space" (an elevated execution mode where certain privileged operations are allowed).
  - Bits and pieces of the kernel can be loaded and unloaded at runtime (e.g. using "modprobe" in Linux)



- MicroKernel (Mac OS)
  - Only the "main" part of the kernel is in "kernel space" (Contains the important stuff like the scheduler, process management, memory management, etc.)
  - The other parts of the kernel operate in "user space" as system services: The file systems, USB device drivers, Other device drivers.

External View of an OS

- The kernel itself is not very useful. (Provides key functionality, but need a way to access all this functionality.)
- We need other components:
  - System libraries (e.g. stdio, unistd, etc.)
  - System services (creat, read, write, ioctl, sbrk, etc.)
  - OS Configuration (task manager, setup, etc.)
  - System programs (Xcode, vim, etc.)
  - Shells (bash, X-Win, Windows GUI, etc.)
  - Admin tools (User management, disk optimization, etc.)
  - User applications (Word, Chrome, etc).

Definition 1.12. System Calls are calls made to the Application Program Interface or API of the OS.

- UNIX and similar OS mostly follow the POSIX standard. (Based on C. Programs become more portable.) *POSIX: portable operating system interface for UNIX, minimal set of system calls for application portability between variants of UNIX.*
- Windows follows the WinAPI standard. (Windows 7 and earlier provide Win32/Win64, based on C. Windows 8 provide Win32/Win64 (based on C) and WinRT (based on C++).)

Example 1.3. User mode + Kernel mode

- Programs (process) run in user mode.
- During system calls, running kernel code in kernel mode.
- After system call, back to user mode.

How to switch mode? Use privilege mode to switching instructions:

- syscall instruction
- software interrupt - instruction which raises specific interrupt from software.

Remark. Comparison between User Thread and Kernel Thread

- **User threads** are implemented by users. OS doesnt recognised user level threads. Context switch time is less. Context switch requires no hardware support. If one user level thread perform blocking operation then entire process will be blocked. (e.g., Java thread, POSIX threads.)
- **kernel threads** are implemented and recognised by OS. Implementation of Kernel thread is complicated. Context switch time is more and hardware support is needed. If one kernel thread perform blocking operation then another thread can continue execution. it is the **number of kernel threads** that determine the CPU received. (visible and schedulable by the OS, e.g., events/n, pdflush)

Example 1.4. LINUX system call

1. User mode: (outside kernel)
   1.1. C function wrapper (eg. **getpid()**) for every system call in C library.
   1.2. assembler code to setup the system call no, arguments
   1.3. trap to kernel
2. Kernel mode: (inside kernel)
   2.1. dispatch to correct routine
   2.2. check arguments for errors (eg. invalid argument, invalid address, security violation)
   2.3. do requested service
   2.4. return from kernel trap to user mode
3. User mode: (Outside kernel)
   3.1. returns to C wrapper - check for error return values

Example 1.5. UNIX signal: SIGTERM or SIGKILL

- SIGTERM (triggered using kill <process id>):
  - The OS receives the SIGTERM request and passes it to the process.
  - The process receives this signal and can clean up and release resources it is using.
  - If the process has child processes, it will terminate the child processes also using a SIGTERM.

  - The process exits gracefully.
- SIGKILL (triggered using kill −9 <process id>):
  - Process is terminated immediately by init (the UNIX master process). SIGKILL is not passed to the process, and the process does not have any chance to do cleaning up.
  - SIGKILL can create zombie processes particularly if the killed process has children.

2 Process Management

Definition 2.1. Program consists of: Machine instructions (and possibly source code) and Data. A program exists as a file on the disk. (e.g. command.exe, MSword.exe)

Definition 2.2. Process consists of Machine instructions (and possibly source code), Data and Context. It exists as instructions and data in memory, **may** be executing on the CPU.

> Program vs. Process
> A single program can produce multiple processes. (e.g. chrome.exe is a single program, but every tab in Chrome is a new process!)

Remark. Comparison between foreground process and background process

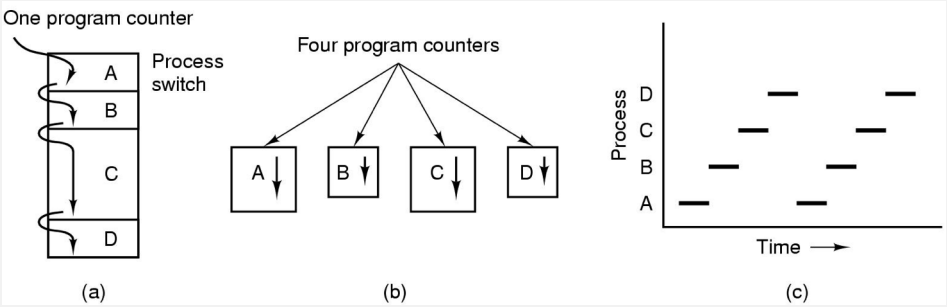
- **Foreground Process**: any command or task you run directly and wait for it to complete. Some foreground processes show some type of user interface that supports ongoing user interaction, whereas others execute a task and "freeze" the computer while it completes that task.
  Shell command: $ command1
- **Background Process**: the shell does not have to wait for a background process to end before it can run more processes. Within the limit of the amount of memory available, you can enter many background commands one after another. Background jobs are run at a lower priority to the foreground jobs. You will see a message on the screen when a background process is finished running.
  Shell command: $ command1 &

Definition 2.3. Execution Modes

- Programs usually run sequentially. (Each instruction is executed one after the other.)
- Having multiple cores or CPUs allow parallel ("concurrent") execution. (Streams of instructions with no dependencies are allowed to execute together.)
- A multitasking OS allows several programs to run "concurrently". (Interleaving, or time-slicing)

Remark. we mostly assume number of processes $\geq$ number of CPU otherwise can have idle CPU core. So each core must still switch between processes even for multi-cores, and we will assume a single processor with a single core.

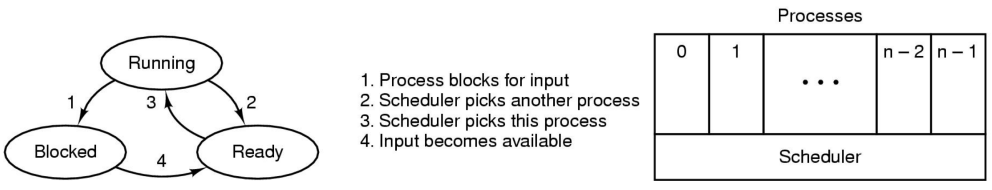
The Process Model



- Figure (b) shows what appears to be happening in a single processor system running multiple processes:
  - There are 4 processes each with its own program counter (PC) and registers.
  - All 4 processes run independently of each other at the same time.
- Figure (a) shows what actually happens.
  - There is only a single PC and a single set of registers.
  - When one process ends, there is a "context switch" or "process switch":
    - PC, all registers and other process data for Process A is copied to memory.
    - PC, register and process data for Process B is loaded and B starts executing, etc.
- Figure (c) illustrates how processes A to D share CPU time.

Definition 2.4. Process States there are three possible states for a process

- Running
  - The process is actually being executed on the CPU.
- Ready
  - The process is ready to run but not currently running.
  - A "scheduling algorithm" is used to pick the next process for running.
- Blocked.
  - The process is waiting for "something" to happen so it is not ready to run yet. e.g. include waiting for inputs from another process.



Definition 2.5. Process Context (values change as a process runs)

- CPU register values.
- Stack pointers.
- CPU Status Word Register
  - This maintains information about whether the previous instruction resulted in an overflow or a "zero", whether interrupts are enabled, etc.

– This is needed for branch instructions assembly equivalents of "if" statements.

– **Note**: The OS maintains information about CPU register contents, execution status, stack pointer information and program counter information but **doesn't include** contents of variables used by the process (kept in memory)

The AVR Status Register – SREG – is defined as:

Bit	7	6	5	4	3	2	1	0	
0x3F (0x5F)	I	T	H	S	V	N	Z	C	SREG
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

What other pieces of information does the OS need to save about a process?

- **File handles / Open File Table**: These are data structures that maintain information about files that are opened by the process, like the location that a process is inside the file, access rights to the file, file open modes, etc.
- **Pending signals**: A signal is an OS message to the process.
- **Process Running State**: Whether the process is suspending, ready, running, terminated, etc.
- **Accounting Information**: How much CPU time the process has used, how much disk space, network activity, etc.
- **Process ID**: Unique number identifying the process. Etc.

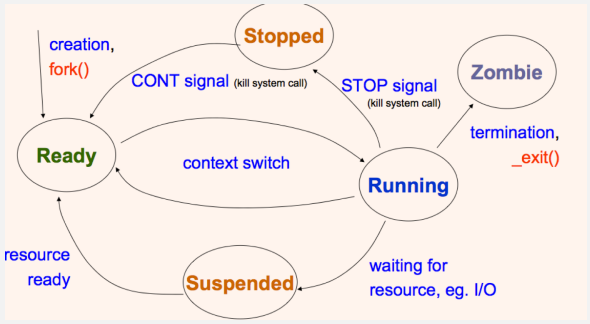
Example 2.1. Context Switching in FreeRTOS Atmega Port FreeRTOS relies on regular interrupts from Timer 0 to switch between tasks. When the interrupt triggers:

1. PC is placed onto Task A's stack.
2. The ISR calls portSAVECONTEXT, resulting in Task As context being pushed onto the stack.
3. pxCurrentTCB will also hold SPH/SPL after the context save.
   - This must be saved by the kernel.
   - The kernel stores a copy of the stack pointer for each task.
4. The kernel then selects Task B to run, and copies its SPH/SPL values into pxCurrentTCB and calls portRESTORE_CONTEXT.
5. The rest of portRESTORE_CONTEXT is executed, causing Task Bs data to be loaded into R31-R0 and SREG. Now Task B can resume like as though nothing happened
6. Only Task B's PC remains on the stack. Now the ISR exits, causing this value to be popped off onto the AVR's PC.
   - PC points to the next instruction to be executed.
   - End result: Task B resumes execution, with all its data and SREG intact!

How can context switching be triggered?
It can be triggered by a timer; currently running process waiting for input; currently running task blocking on a synchronisation mechanism; currently running task wants to sleep for a fixed period; higher priority task becoming READY; ...

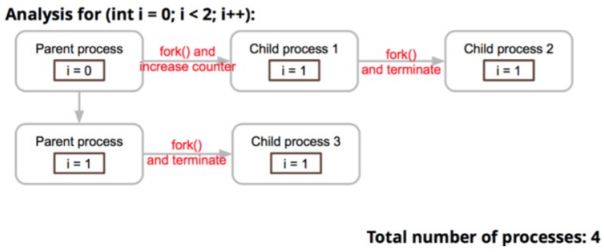
Definition 2.6. Process Control Block maintains information about that process: Process ID (PID), Stack Pointer, Open files, Pending signals, CPU usage, ...

Process Life Cycle



Definition 2.7. Creating a new process - fork()

- Fork system call creates a new process by duplicating the current image into a new process, *child process*
- same code (executable image) is executed
- Child differs only in process id (PID) and parent (PPID), fork return value
- Data in child is a COPY of the parent (i.e. not shared) → unique only to fork
- In PARENT process after fork:
  - PC is at return from fork system call
  - fork return value: new child PID
- In CHILD process after fork:
  - PC is at return from fork system call
  - fork return value: 0
  - Shares open file & signal handlers with parent, current working directory
  - Independent copy of: memory, arguments, environment variables (note: cloning example)
- fork return result is -1 if the fork failed.
- for(int i=0; i<10; i++) fork();, this for general case n, there are 2^n processes created including the original process.



- **Fork bomb**: is a denial-of-service attack wherein a process **continually replicates** itself to deplete available system resources, slowing down or crashing the system due to resource starvation.

Definition 2.8. Waiting for child process - pid_t wait(int *stat_loc)

- If any process has more than one child processes, then after calling wait(), parent process has to be in wait state if no child terminates.
- If only one child process is terminated, then wait() returns process ID of the terminated child process.

- If more than one child processes are terminated than wait() reap any **arbitrarily** child and return a process ID of that child process.
- When wait() returns they also define **exit status** (which tells our, a process why terminated) via pointer, If status are not **NULL**.
- If any process has no child process then wait() returns immediately "-1".
- Calling while(wait(NULL)>0); means wait until all child processes exit (or change state) and no more child processes are unwaited-for (or until an error occurs)
- Calling wait(NULL) will block parent process until any of its children has finished. If child terminates before parent process reaches wait(NULL) then the child process turns to a **zombie** process until its parent waits on it and its released from memory.

Definition 2.9. replaces the current process image with a new process image - execl()

Definition 2.10. The Master Process

- Every process has parent: where does it stop?
- Special initial process - init process created in kernel at the end UNIX boot process, traditionally having PID=1.
- Forking creates process tree, init is the root process.
- init watches for processes and response where needed, e.g. terminal login.
- init also manages system run levels (e.g. shutdown, power failure, single-user mode), etc. Example of a system-like process running in kernel mode.

Definition 2.11. The Zombie Process or **defunct process** is a process that has completed execution (via the exit system call) but still has an entry in the process table: it is a process in the **Terminated state**. This occurs for child processes, where the entry is still needed to allow the parent process to read its child's exit status: once the exit status is read via the wait system call, the zombie's entry is removed from the process table and it is said to be **"reaped"**.

A child process always first becomes a zombie before being removed from the resource table. In most cases, under normal system operation zombies are immediately waited on by their parent and then reaped by the system processes that stay zombies for a long time are generally an error and cause a resource leak.

Zombie process retains PID and stores termination status and result at its PCB table.

Definition 2.12. The Orphan Process is a computer process whose parent process has finished or terminated, though it remains running itself. (this means it's still in **Running state**)

Definition 2.13. Start/Stop a Process

- kill() system call sends signal to process
- Special process signals:
  - stopping process (SIGSTOP)
  - killing process (SIGKILL)
  - restart stopped process (SIGCONT)

Terminating a process

- system call: `void _exit(int status)`
- _exit system call used for immediate voluntary termination of process (never returns!).
- Closes all open file descriptors; children processes are inherited by init process;
- parent sent `SIGCHLD` signal (see later section on signals & IPC)
- status returned to parent using wait()
- Usually status is used to indicate errors, eg. convention is
  - _exit(0) for success, 0 means no error
  - _exit(1) for error, positive number for error number

- Process finished execution
- can release **most** system resources used by process

are released on exit

- **BUT** some basic process resources not releasable: PID & status needed when `wait()` is called. Also process accounting info, e.g. cpu time. Note: may mean that process table entry still being used

Notes: See `wait()`, zombies

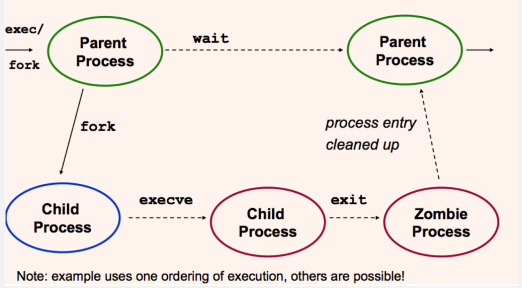
Definition 2.14. Normal Program Termination - void exit(int status) from standard C library function

- Usually don't use _exit() but exit(), which cleans up: open streams from C stdio library (e.g., fopen, printf) are flushed and closed
- calls some exit handlers
- finally calls _exit(status) after all standard C cleanup done.

Remark. returning from main() implicitly calls exit. exec didn't actually call main directly but a startup routine. Open files also get flushed automatically.

Waiting for Child Processes to Terminate - process interaction

- system call: `pid_t wait(int *status)`
- Parent can wait until some child processes terminates (calls `exit`)
- Note: also some other conditions
- `status` gives child exit status
- cleans up remainder of child system resources – ones not removed when exit!
- Other versions of wait: (some are non blocking!) `waitpid(), wait3(), wait4()`



Note: example uses one ordering of execution, others are possible!

Zombie Process

- process is "dead" / terminated
- Recall: `wait()` means that process termination is not complete when it exits
- process goes to **zombie state**: remainder of process data structure **cleaned up** when `wait()` happens (if it happens!)
- **can't delete** process since dont know if wait from parent needs exited process info! (so it's a consequence of having a wait() operation defined!)
- **cannot kill** zombie since already exited!

2 cases:

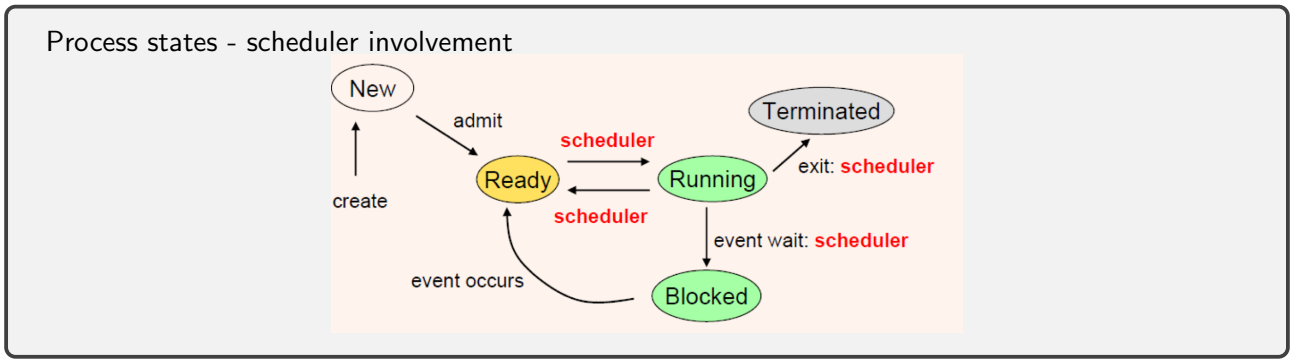
- Parent dies before child, the `init` process becomes "pseudo" parent of child processes. Child dying sends signal to `init` process, which organizes to call `wait()` to cleanup process
- Child dies before parent but parent didn't call `wait`. Becomes a zombie process. Can fillup process table requiring reboot. Unix SVR4 can specify no zombie creation on termination
- modern Unixes have mechanisms to avoid zombies

3 Process Scheduling

Definition 3.1. Computer jobs Computatings + reading/writing memory + input/output.

- CPU bound
  - Most of the time spent on processing on CPU
  - Graphics-intensive applications are considered to be "CPU" bound.
  - Multitasking opportunities come from having to wait for processing results.
- I/O bound

- Most of the time is spent on communicating with I/O devices
- Multitasking opportunities come from having to wait for data from I/O devices.



Definition 3.2. Types of Multitaskers

- **Batch Processing** (Not actually multitasking since only one process runs at a time to completion.)
- **Co-operative Multitasking** (Currently running processes cannot be suspended by the scheduler; Processes must volunteer to give up CPU time. Context switching is controlled entirely by processes themselves. Co-operative multitasking is simpler and less prone to concurrency issues, but should any process go into an infinite loop, it could potentially freeze up the system.)
- **Pre-emptive Multitasking** (Currently running processes can be forcefully suspended by the scheduler. Timer-triggered multitasking.)
- **Real-Time Multitasking** (Processes have fixed deadlines that must be met.)
  - **Hard** Real Time Systems: Disaster strikes! System fails, possibly catastrophically!
  - **Soft** Real Time Systems: Mostly just an inconvenience. Performance of system is degraded

Remark. Policies are determined by the kind of multitasking environment. Shorter time-quantum for timer interrupts → More responsive, scheduler runs more often → net loss of user CPU time.

Definition 3.3. responsiveness of a scheduling algorithm refers to how soon can a newly created task receives its first share of CPU time.

Method 3.1. Scheduling Policies - enforce a priority ordering over processes

- **Fixed Priority** for all kinds of multitaskers
  - Each task is assigned a priority by the programmer. (usually priority number 0 has the highest priority.)
  - Tasks are queued according to priority number.
  - Batch, Co-operative: Task with highest priority is picked to be run next.
  - Pre-emptive, Real-Time: When a higher priority task becomes ready, current task is suspended and higher priority task is run.
- Policies for **Batch Processing**
  - First-come First Served (FCFS)
    - Arriving jobs are stored in a queue.
    - Jobs are removed in turn and run.
    - Particularly suited for batch systems.
    - Extension for interactive systems: Jobs removed for running are put back into the back of the queue. This is also known as round-robin scheduling.

        * Starvation free as long as earlier jobs are bounded.
    - Shortest Job First (SJF)
        * Processes are ordered by total CPU time used.
        * Jobs that run for less time will run first.
        * Reduces average waiting time if number of processes is fixed.
        * Potential for starvation.
- Policies for **Co-operative Multitasking**
    - Round Robin with Voluntary Scheduling (VS)
    - **Voluntary Scheduling**: Processes call a special yield function. This invokes the scheduler. Causes the process to be suspended and another process started up.
- Policies for **Pre-emptive multitasking**
    - Round Robin with Timer (RR)
        * Each process is given a fixed time slot c_i.
        * After time c_i, scheduler is invoked and next task is selected on a round-robin basis.
        * Any process that has finished its run is blocked until the next time it is due to run again.
        * The process can be preempted in the middle of its run.
        * It simply cycles through the processes without caring about their deadlines, (unlike RMS and EDF which take into account deadlines), so we cannot guarantee that processes meet their deadlines in general.
    - Shortest Remaining Time (SRT)
        * Pre-emptive form of SJF.
        * Processes are ordered according to remaining CPU time left.
- Policies for **Real-Time Multitaskers**
    - Rate Monotonic Scheduling (RMS)
        * Processes are prioritized according to P_i, Shortest period = highest priority.
        * **Critical Instance Analysis** is used to test that all processes meet their deadlines
        * We can also write down the table to see and the pattern will repeat for every $LCM(P_1, \ldots, P_n)$.
    - Earliest Deadline First Scheduling (EDF)
        * Processes are prioritized according to who is closest to their respect deadlines.
        * All processes are guaranteed to meet their deadlines as long as: $U = \sum_{i=1}^{n} \frac{C_i}{T_i} \leq 1$
        * There is no context switching for processes, each process will run till the end if gets started.

Remark. Real Time Scheduling must guarantee that processes complete within time limits.

- Time limits are called deadlines
- Processes are assumed to be periodic with period P_i for process i.
- Processes are assumed to use a fixed amount of CPU time C_i each time.
- Deadline D_i is assumed to be the same as period P_i. (if a process runs at time T_i, it must finish running by $D_i = T_i + P_i$, If it doesnt, process has missed its deadline.) T_i is the process or task arriving time.

Method 3.2. Critical Instance Analysis for RMS

1. Sort T by period of each task, if T is not already sorted. (We will assume that T_1 has the shortest period, T_2 has the 2^{nd} shortest, etc.)
2. For each task $T_i \in T$, recursively compute $S_{i0}, S_{i1}, \ldots$ where:

$$S_{i,0} = \sum_{j=1}^{i} C_j; S_{i,(x+1)} = C_i + \sum_{j=1}^{i-1} C_j \times \lceil \frac{S_{i,x}}{P_j} \rceil = \text{CPU time} + \text{ALL possible preemptions}$$

3. Stop when $S_{i,(x+1)} = S_{i,x}$. Call this $S_{i,(x+1)}$ the final value $S_{i,F}$ (termination value).
4. If $S_{i,F} < D_i (= T_i + P_i)$, then the task i is schedulable and will not miss its deadlines.

Remark. Comparison between RMS and fixed priority policy on critical instance analysis In **critical instance analysis**, the only things that are important are:

1. The priority remains fixed in some way throughout the execution life of the processes. In RMS the priority remains fixed because we assume that P_i is fixed. Here the priority is fixed by definition.
2. The period P_i of each process is fixed so that each process is pre-empted by a higher priority processed in predictable ways.

If these two conditions are met, then it doesnt matter whether we are using a fixed priority policy or an RMS policy; If $S_{i,F} < D_i$ for all i, it means that for every process, the worst case execution time including all possible preemptions is still less than the deadline for each process, and thus all processes are guaranteed to meet their deadlines.

This is important because it means that CIA can also be used for fixed priority systems as long as the two conditions hold.

Remark. Check for starvation free is to check if a job can always get in front of another process.

Method 3.3. Managing Multiple Policies Multiple policies can be implemented on the same machine using multiple queues:

- Each queue can have its own policy.
- This scheme is used in Linux.

Example 3.1. Scheduling in Linux

- Processes in Linux are dynamic:
  - New processes can be created with fork()
  - Existing processes can exit.
- Priorities are also dynamic:
  - Users and superusers can change priorities using "nice" values.
  - nice n 19 tar cvzf archive.tgz * (Allows tar to run with a priority lowered by 19 to reduce CPU load. Normal users can only $0 \leq n \leq 19$. Superusers can specify $-20 \leq n \leq 19$. Negative nice increases priority.)
- Linux maintains **three types of processes**:
  - **Real-time FIFO**: RT-FIFO processes cannot be pre-empted except by a higher priority RT-FIFO process.
  - **Real-time Round-Robin**: Like RT-FIFO but processes are pre-empted after a time slice.
  - Linux only has "soft real-time" scheduling. (Priority levels 0 to 99) Cannot guarantee deadlines, unlike RMS and EDF.
  - Non-real time processes (Priority levels 100 to 139)

- Linux maintains 280 queues in two sets of 140: An active set, an expired set.
- The scheduler is called at a rate of 1000 Hz. (e.g. time tick is 1 ms, called a "jiffy".) RT-FIFO processes are **always** run if any are available. Otherwise:
  - Scheduler picks highest priority process in active set to run.
  - When its time quantum is expired, it is moved to the expired set. Next highest priority process is picked.
  - When active set is empty, active and expired pointers are swapped. Active set becomes expired set and vice versa.
  - Scheme ensures no starvation of lowest priority processes.
  - Without the expired set, only tasks in the highest priority queue will get to run: Tasks finish their time quanta have to be placed "somewhere" to be run again, and since theres no expired set, that "somewhere" is to the back of the queue. When these tasks reach the front again they will be run, starving all the other queues.

  What happens if a process becomes blocked? (e.g. on I/O)

  - CPU time used so far is recorded. Process is moved to a queue of blocked processes.
  - When process becomes runnable again, it continues running until its time quantum is expired.
  - It is then moved to the expired set.
  - When a process becomes blocked its priority is often upgraded and given MORE CPU time to catch up.

- Time quantums for RR processes: Varies by priority. For example: Priority level 100 - 800 ms, Priority level 139 - 5 ms, or System load.
- How process priorities are calculated: Priority = base + f(nice) + g(cpu usage estimate)
  - $f(.)$ = priority adjustment from nice value.
  - $g(.)$ = Decay function. Processes that have already consumed a lot of CPU time are downgraded.
  - Other heuristics are used: Age of process, More priority for processes waiting for I/O - I/O boost, Bias towards foreground tasks.
- **I/O Boost**
  - Tasks doing read() has been waiting for a long time. May need quick response when ready.
  - Blocked/waiting processes have not run much.
  - Applies also to interactive processes blocked on keyboard/mouse input.

  How long does this boost last?

  - Temporary boost for sporadic I/O
  - Permanent boost for the chronically I/O bound?
  - E.g. Linux gives -5 boost for interactive processes.
  - Implementation: We can boost time quantum, boost priority, do both.

4 Inter-Process Communication

Definition 4.1. Race Condition occur when two or more processes attempt to access shared storage. This causes the final outcome to depend on who runs first. "Shared storage" can mean:

- Global variables.
- Memory locations.
- Hardware registers.- This refers to configuration registers rather than CPU registers.
- Files.

Example 4.1. Race condition for two threads
There maybe four possible cases for tow threads running concurrently:

- Thread 1 runs to completion, $x = 6$, Thread 2 runs to completion, $x = 12$.
- Thread 2 runs to completion, $x = 10$, Thread 1 runs to completion, $x = 11$.
- Thread 1 loads x and is pre-empted, Thread 2 loads x and writes back $5 \times 2 = 10$, Thread 1 increments x to 6 and writes it back.
- Thread 2 loads x and is pre-empted, Thread 1 loads x, updates it to 6, writes back, Thread 2 gets $5 \times 2 = 10$

Definition 4.2. Correctness in multithreaded programs depends on the intended sequence of execution.

why we have wrong value?
It is either because the threads are executed in the wrong sequence, or because one thread gets pre-empted before it can save its results and the next thread gets a stale value. The first thread then overwrites the next threads results.

Definition 4.3. Critical Sections mutual exclusion - mutex
a RUNNING process is always in one of two possible "states":

- It is performing local computation. This does not involve global storage, hence to race condition is possible.
- It is reading/updating global variables. This can lead to race conditions. (it is within its "critical section")

Theorem 4.1. FOUR rules to prevent race conditions

1. No two processes can simultaneously be in their critical section.
2. No assumptions may be made about speeds or number of CPUs.
   - Note: We can relax this assumption for most embedded systems since they have single CPUs.
   - May apply to systems using multicore micro-controllers.
3. No process outside of its critical section can block other processes.
4. No process should wait forever to enter its critical section.

Can local variables created in C be affected by race condition?
Local variables are created on the processs stack when a function is called. Theyre popped off and lost when the function exits. They can never cause race conditions because only the thread or process calling that function can access to the variables. Since no other process or thread has access, race conditions are not possible.

What can cause Co-operative multitaskers produce incorrect results?

- The sequence of process execution might be wrong. The scheduler might choose to run process A before B, when A depends on a result in B.
- A process may inadvertently give up control of the CPU before completing calculations, causing a dependent process to run and get the wrong results. An example of this is when a process decides to call printf, which will trigger an OS call that might trigger a context switch without the programmers knowledge.

How mutual exclusion guarantees that the two processes produce only correct values of n?
Mutex guarantees that each process reads, updates and writes n before the other process runs. (Race condition for two not atomic operations)

Definition 4.4. Atomicity means that the steps taken in an instruction, or the steps taken in a group of instructions, are executed as one complete unit without possibility of interruption.

- Single-processor operating systems may disable interrupts to guarantee atomicity because task/process/thread switching does not happen without interrupts.
- User programs may not be as thoroughly tested, and allowing user programs to disable interrupts could lead to the entire system being crippled, as no further task switches would be possible.

Example 4.2. Mutual Exclusion Implementation

- **Disabling Interrupts** (which is the only way to preempt a process)
  - disabling interrupts will prevent other processes from starting up and entering their critical sections.
  - Carelessly disabling interrupts can cause the entire system to grind to a halt.
  - This only works on single-processor, single core systems. Violates Rule 2.
- Using **Lock Variables**
  - A single global variable lock is initially 1.
  - Process A reads this variable and sets it to 0, and enters its critical section.
  - Process B reads lock and sees its a 0. It doesnt enter critical section and waits until lock is 1.
  - Process A finishes and sets lock to 1, allowing B to enter
  - PROBLEM: Theres a race condition on lock itself.
  - NOTE: unlocking a mutex before it is locked can put it into an undefined state in POSIX systems.
  - **Test and Set Lock** (TSL)
    - CPU locks the address and data buses, and reads "lock" from memory. The locked address and data buses will block accesses from all other CPUs. ("atomic". This means that NOTHING can interrupt execution of this instruction. This is guaranteed in hardware.)
    - The current value is written into register "reg".
    - A "1" (or sometimes "0") value is written to "lock".
    - CPU unlocks the address and data buses.
    - ALTERNATIVE: the XCHG instruction, used on Intel machines. Swaps contents of "lock" and "reg" instead of just writing "1" to lock.

```
#define FALSE  0
#define TRUE   1
#define N      2                    /* number of processes */

int turn;                           /* whose turn is it? */
int interested[N];                  /* all values initially 0 (FALSE) */

void enter_region(int process);     /* process is 0 or 1 */
{
    int other;                      /* number of the other process */
    other = 1 – process;            /* the opposite of process */
    interested[process] = TRUE;     /* show that you are interested */
    turn = process;                 /* set flag */
    while (turn == process && interested[other] == TRUE) /* null statement */ ;
}

void leave_region(int process)      /* process: who is leaving */
{
    interested[process] = FALSE;    /* indicate departure from critical region */
}
```

  - **Peterson's solution**
    * It differs from the **single lock variable** implementation in that there are two different lock variables, one for each process
    * Each processes only WRITES to the lock variable, which is an atomic operation. The main weakness of the Lock Variable solution is that it involved read-update-write operations on a single shared variable, which does not happen in this case.
    * Before entering the critical section, both processes check to see whether THE OTHER process intends to enter. If so it waits.
    * Setting interested to TRUE takes place BEFORE this check, so in the worst case, both set interested to true at the same time, leading to deadlock.

> Busy-wait approaches like Peterson and TSL/XCHG have a problem called **deadlock**. Consider two processes H and L, and a scheduler rule that says that H is always run when it is READY. Suppose L is currently in the critical region.
>
> 1. H becomes ready, and L is pre-empted.
> 2. H tries to obtain a lock, but cannot because L is in the critical region.
> 3. H loops forever, and CPU control never gets handed to L.
> 4. As a result L never releases the lock.
>
> ****Rescue for Peterson**: by using turn, which can be either 0 or 1, we prevent both process stuck and busy waiting, one of them will execute the critical section and then leave and make interested = FALSE. (as shown in the above code)

- **Sleep/Wake**
  - When a process finds that a lock has been set (i.e. another process in the critical section), it calls "sleep" and is put into the blocked state.
  - When the other process exits the critical section and clears the lock, it can call "wake" which moves the blocked process into the READY queue for eventual execution.
  - producer-consumer problem: Deadlock occurs when:
    1. Consumer checks "count" and finds it is 0.
    2. Consumer gets pre-empted and producer starts up.
    3. Producer adds an item, increments count to "1", then sends a WAKE to the consumer. (Since consumer is not technically sleeping yet, the WAKE is lost.)
    4. Consumer starts up, and since count is 0, goes to SLEEP.
    5. Producer starts up, fills buffer until it is full and SLEEPs.
    6. Since consumer is also SLEEPing, no one wakes the producer. **Deadlock!**
- **Semaphores**, a special lock variable that counts the number of wake-ups saved for future use.
  - A value of 0 indicates that no wake-ups have been saved.

– Two ATOMIC operations on semaphores:
  * DOWN, TAKE, PEND or P: If the semaphore has a value of > 0, it is decremented and the DOWN operation returns. If the semaphore is 0, the DOWN operation blocks.
  * UP, POST, GIVE or V: If there are any processes blocking on a DOWN, one is selected and woken up. Otherwise UP increments the semaphore and returns.
– When a semaphores counting ability is not needed, we can use a simplified version called a mutex. (1 = Unlocked. 0 = Locked.)
– non_critical_section() → DOWN(sema) → critical_section() → UP(sema)
– We can also implement mutexes with TSL or XCHG. 0 = Unlocked, 1 = Locked

```
mutex_lock:
     TSL REGISTER,MUTEX          | copy mutex to register and set mutex to 1
     CMP REGISTER,#0             | was mutex zero?
     JZE ok                      | if it was zero, mutex was unlocked, so return
     CALL thread_yield           | mutex is busy; schedule another thread
     JMP mutex_lock              | try again later
ok:  RET | return to caller; critical region entered

mutex_unlock:
     MOVE MUTEX,#0               | store a 0 in mutex
     RET | return to caller
```

Problems with Semaphores: Deadlock (on the left is the correct version)

```
#define N 100                           /* number of slots in the buffer */
typedef int semaphore;                  /* semaphores are a special kind of int */
semaphore mutex = 1;                    /* controls access to critical region */
semaphore empty = N;                    /* counts empty buffer slots */
semaphore full = 0;                     /* counts full buffer slots */

void producer(void)
{
     int item;

     while (TRUE) {                     /* TRUE is the constant 1 */
          item = produce_item( );       /* generate something to put in buffer */
          down(&empty);                 /* decrement empty count */
          down(&mutex);                 /* enter critical region */
          insert_item(item);            /* put new item in buffer */
          up(&mutex);                   /* leave critical region */
          up(&full);                    /* increment count of full slots */
     }
}


void consumer(void)
{
     int item;

     while (TRUE) {                     /* infinite loop */
          down(&full);                  /* decrement full count */
          down(&mutex);                 /* enter critical region */
          item = remove_item( );        /* take item from buffer */
          up(&mutex);                   /* leave critical region */
          up(&empty);                   /* increment count of empty slots */
          consume_item(item);           /* do something with the item */
     }
}
```

```
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          up(&full);                    /* increment count of full slots */
     }
}


void consumer(void)
{
     int item;

     while (TRUE) {                     /* infinite loop */
          down(&mutex);                 /* decrement full count */
          down(&full);                  /* enter critical region */
          item = remove_item( );        /* take item from buffer */
          up(&mutex);                   /* leave critical region */
          up(&empty);                   /* increment count of empty slots */
          consume_item(item);           /* do something with the item */
     }
}
```

– Producer successfully DOWNs the mutex.
– Producer DOWNs empty. However the queue is full so this blocks.
– Consumer DOWNs mutex and blocks.
  * Consumer now never reaches the UP for empty and therefore cannot unblock the producer.
  * The producer in turn never reaches the UP for mutex and cannot unblock the consumer. **Deadlock!**

Reusable/Consumable Resources

* **Reusable** Resources - usually causes deadlocks
  - Examples: memory, devices, files, tables
  - Number of units is **constant**
  - Unit is either free or allocated; **no sharing** (no simultaneous using)
  - Process **requests, acquires, releases units**
* **Consumable** Resources
  - Examples: messages, signals
  - Number of units **varies** at runtime
  - Process **releases** (create) units (without acquire)
  - Other process **requests** and **acquires** (consumes)
  - Deadlock when A and B are waiting for each other's message/ signal ...

Method 4.1. Dealing with deadlocks

1. **Detection and Recovery**: Allow deadlock to happen and eliminate it
2. **Avoidance (dynamic)**: Runtime checks disallow allocations that might lead to deadlocks
3. **Prevention (static)**: Restrict type of request and acquisition to make deadlock impossible

Theorem 4.2. Conditions for Deadlock

1. Mutual exclusion: Resources not sharable
2. Hold and wait: Process must be **holding one** resource while **requesting another**
3. Circular wait: **At least 2** processes must be blocked on each other

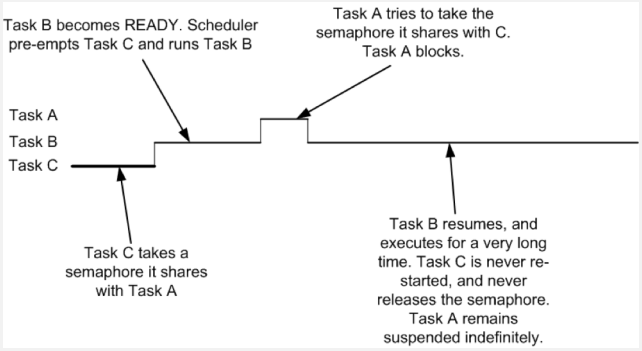
Definition 4.5. Spooling is a specialised form of multi-programming for the purpose of **copying data between different devices**. In contemporary systems it is usually used for mediating between a computer **application** and a slow **peripheral**, such as a printer. Spooling allows programs to "hand off" work to be done by the peripheral and then proceed to other tasks, or do not begin until input has been transcribed. A dedicated program, the **spooler**, maintains an orderly sequence of jobs for the peripheral and feeds it data at its own rate. Conversely, for slow input peripherals, such as a card reader, a spooler can maintain a sequence of computational jobs waiting for data, starting each job when all of the relevant input is available; see **batch processing**. The **spool** itself refers to the sequence of jobs, or the storage area where they are held. In many cases the spooler is able to drive devices at their full rated speed with minimal impact on other processing. **Spooling** is a combination of **buffering** and **queueing**.

Method 4.2. Deadlock Prevention

1. Eliminate mutual exclusion
   - Not possible in most cases
   - Spooling makes I/O devices sharable
2. Eliminate hold-and-wait
   - **Request** all **resources at once**
   - **Release** all resources **before a new request**
   - **Release** all resources if **current request blocks**
3. Eliminate circular wait

- Order all resources
- Process must request in **ascending order**

Problems with Semaphores: Priority Inversion priority(Process C) < priority(Process B) < priority(Process A), Process B effectively blocks out Process A, although Process A has higher priority!

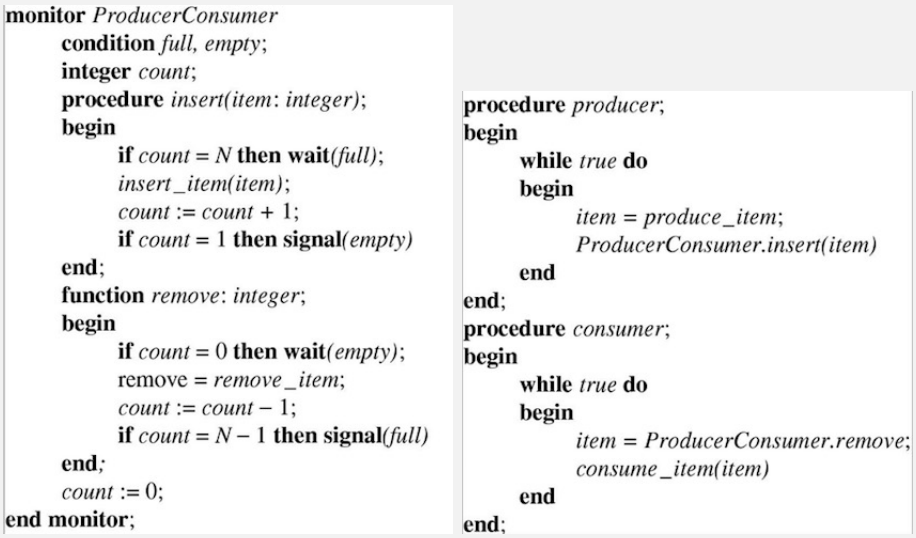


Definition 4.6. Monitor, similar to a class or abstract-data type in C++ or JAVA:

- **Collection of procedures**, variables and data structures grouped together in a package. Access to variables and data possible only through methods defined in the monitor.
- However, **only one** process can be active in a monitor at any point in time. I.e. if any other process tries to call a method within the monitor, it will block until the other process has exited the monitor.
- **Implementation**: (mutexes or binary semaphores)
  - When a process calls a monitor method, the method first checks to see if any other process is already using it.
  - If so, the calling process blocks until the other process has exited the monitor.
  - The mutex/semaphore operations are inserted by the compiler itself rather than by the user, reducing the likelihood of errors.

Definition 4.7. Condition Variable - mechanisms for coordination

1. One process WAITs on a condition variable and blocks.
2. Another process SIGNALs on the same condition variable, unblocking the WAITing process.



```
monitor ProducerConsumer
    condition full, empty;
    integer count;
    procedure insert(item: integer);
    begin
        if count = N then wait(full);
        insert_item(item);
        count := count + 1;
        if count = 1 then signal(empty)
    end;
    function remove: integer;
    begin
        if count = 0 then wait(empty);
        remove = remove_item;
        count := count - 1;
        if count = N - 1 then signal(full)
    end;
    count := 0;
end monitor;
```

```
procedure producer;
begin
    while true do
    begin
        item = produce_item;
        ProducerConsumer.insert(item)
    end
end;
procedure consumer;
begin
    while true do
    begin
        item = ProducerConsumer.remove;
        consume_item(item)
    end
end;
```

Similar to Sleep/Wake, however, the mutual exclusion from the monitor prevents the SIGNAL from being lost!

⊛ Monitors and Condition Variables Problems - Violation of mutual exclusion

- When a process encounters a WAIT, it is blocked and another process is allowed to enter the monitor.
- When theres a SIGNAL, the sleeping process is woken up.
- We will potentially now have two processes in the monitor at the same time:
  - The process doing the SIGNAL (the signaler).
  - The process that just woke up because of the SIGNAL (the signaled).

⊛ Ways to resolve

- We require that the signaler exits immediately after calling SIGNAL.
- We suspend the signaler immediately and resume the signaled process.
- We suspend the signaled process until the signaler exits, and resume the signaled process only after that.

Remark. Comparison between semaphore and condition variable

- Semaphore
  - If Process A UPs a semaphore with no pending DOWN, the UP is saved.
  - The next DOWN operation will not block because it will match immediately with a preceding UP.
- Condition variable
  - If Process A SIGNALs a condition variable with no pending WAIT, the SIGNAL is simply lost.
  - This is similar to the SLEEP/WAKE problem earlier on.

Remark.
- conditional variables can also be used together with mutexes:
  1. acquire mutex pthread_mutex_lock(&mutex)
  2. wait on a conditional variable pthread_cond_wait(&v,&mutex)
  3. When conditional wait has exited, the signal has been received, other stuffs can be done.

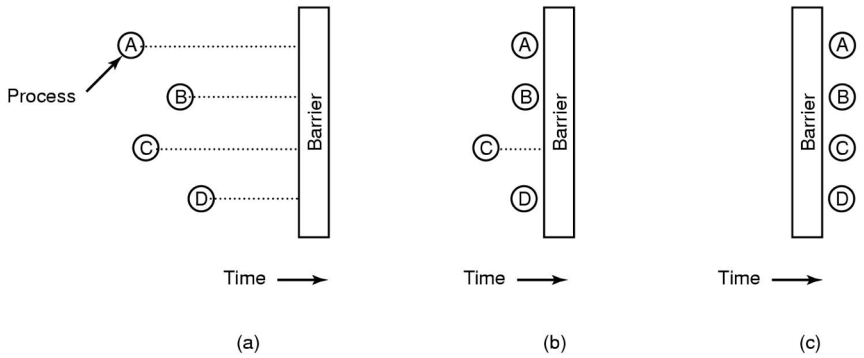
4. unlock the mutex pthread_mutex_unlock(&mutex)
5. **Note**: It is important for conditional variables to be used within a mutual exclusion: Mutual exclusion prevents a process from being pre-empted before it has had a chance to sleep, eliminating the lost-signal problem. pthread_cond_wait automatically gives up the mutex so that other process can do stuff and then wake up it with good 'results' to use.

- Implement conditional variables using only mutex and semaphores

```
// Our implementation of wait
void OSWait(sem_t *condvar, pthread_mutex_t *mut)
{
     // Surrender the mutex
     pthread_mutex_unlock(mut);

     // Go to sleep
     pthread_sem_wait(condvar);

     // Take back the mutex
     pthread_mutex_lock(mut);
}
void task1(void *p)
{
      pthread_mutex_lock(&mut);
      … other stuff …
      // Oops, need result from Task 2
      OSWait(&mut, &cv);
      … More stuff …
      pthread_mutex_unlock(&mut);
}
```

```
// Our implementation of signal
void OSSignal(sem_t *condvar)
{
      pthread_sem_post(condvar);
}

void task2(void *p)
{
      pthread_mutex_lock(&mut);
      … Stuff important to task 1 …
      OSSignal(&cv);
      … More stuff…
      pthread_mutex_unlock(&mut);
}
```

Definition 4.8. Barrier is a special form of synchronization mechanism that works with groups of processes rather than single processes.



The idea of a barrier is that all processes must reach the barrier (signifying the end of one phase of computation) before any of them are allowed to proceed.

- Process D reaches the end of the current phase and calls a BARRIER primitive in the OS. It gets blocked.
- Similarly processes A and B reach the end of the current phase, calls the same BARRIER primitive and is blocked.
- Finally process C reaches the end of its computation, calls the BARRIER primitive, causing all processes to be unblocked at the same time.

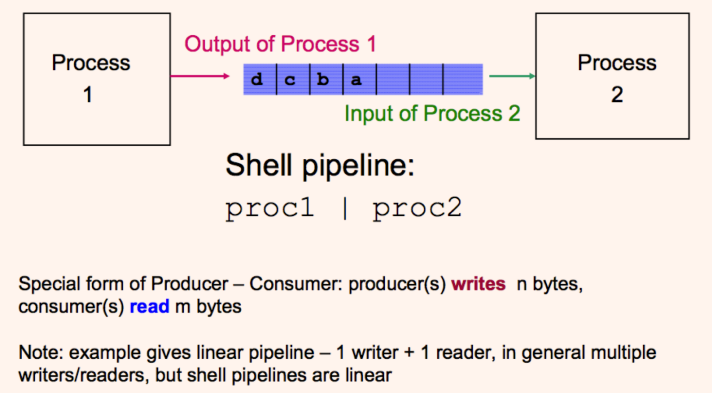
Definition 4.9. UNIX Pipe

- A pipe provides synchronisation
  - A process reading a pipe will block until there is data.
  - Data send is asynchronous but blocks when buffer is full.
- A pipe provides byte-level message transfer between processes.
- Traditional method of communication between processes in UNIX: Shell pipelines

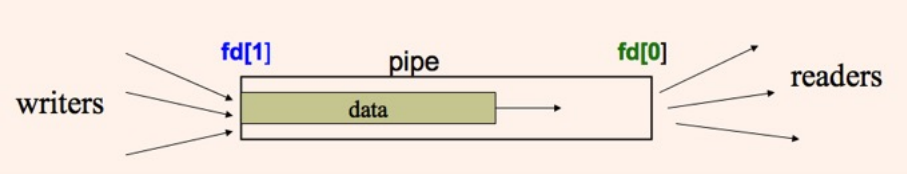
– grep buffer *.c | sort -u | wc

– Output from program to left of bar provides input to program on right.

– Meaning: search for occurrences of string "buffer" in C files (grep process), sort those lines making them unique (sort process), and count how many occurrences (wc process)



- Creating pipes: int pipe(int fd_array[]) returns 2 file descriptor for the (anonymous) pipe
  – Data is sent/received using normal write/read system calls
  – write on fd[1], read on fd[0], e.g., fd[1] is the write end, fd[0] is the read end.



  – Some versions of Unix support duplex pipes, can readwrite on either end – with corresponding write/read on opposite end; other Unixes only have one way pipes
  – **File Descriptor**: a reference to a file when making system call, come from opening a file with open() system call but also other system calls which deal with files such as pipe()

Remark. • Closing unused pipe descriptor is good practice (not necessary to close all unused pipe descriptors).

- Closing the write end of the pipe, allows reader to determine when there is no more data: when all pipe ends closed, read gives EOF.
- Data read is the minimum of what is available and requested size. (e.g., buffer size is 100 but the string written was 10 chats)
- Pipes only used for unstructured byte streams.

Definition 4.10. FIFO files (Named pipes)

- **Anonymous pipe**: can only use between related processes, e.g., parent + children.
- FIFO files are named pipes, pipes with a filename.
- Exist independent of process: any processes can use FIFO
- FIFO is a special file since it's really a pipe, cannot seek, no data is written to filesystem, every open FIFO corresponds to 1 pipe object.
- Can be created with mkfifo shell command or mknod() system call.

Example 4.3. Shell named pipe

1. mkfifo pipe; ls -l > pipe

2. cat pipe (in another shell login)

Example 4.4. Programming named pipe

Listing 1: writer.c

```
int fd;
char * myfifo = "/tmp/myfifo";

mkfifo(myfifo, 0666);

fd = open(myfifo, O_WRONLY);
write(fd, "Hi", sizeof("Hi"));
close(fd);

/* remove the FIFO */
unlink(myfifo);
```

Listing 2: reader.c

```
int fd;
char * myfifo = "/tmp/myfifo";
char buf[MAX_BUF];

/* open, read, and display */
fd = open(myfifo, O_RDONLY);
read(fd, buf, MAX_BUF);
printf("Received: %s\n", buf);
close(fd);
```

Note: When only one program is run it will hang. writer.c blocks at the "write" statement, which means it will not call unlink to delete the named pipe until the reader has read the pipe.

Example 4.5. UNIX shared memory

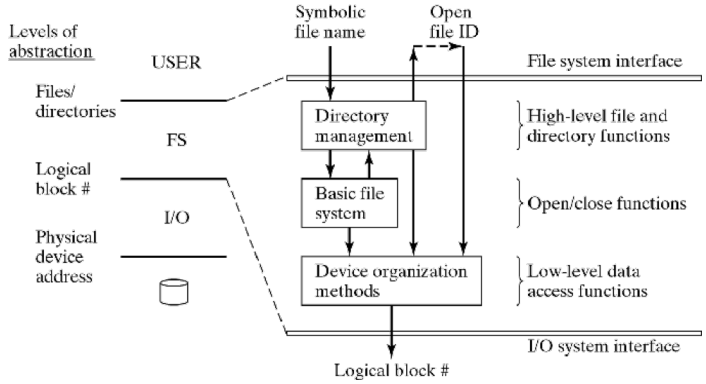
- Without an explicit delete command, the shared memory region stays around.
- The shared memory region is identified by a number (id). A memory address is generated only when you attempt to attach to the identified region.
- Permission bits can be set to allow other processes to use a particular shared memory region. If you use the most permissive setting, any process can access. (e.g. a permission bits of 0666).

5 File System

Definition 5.1. File system

- Present logical (abstract) view of files and directories
  - Accessing a disk is very complicated: (2D or 3D structure, track/surface/sector, seek, rotation, ...)
  - Hide complexity of hardware devices
- Facilitate efficient use of storage devices: Optimise access e.g. to disk.
- Support sharing
  - Files persist even when owner/creator is not currently active (unlike main memory)
  - Key issue: Provide protection (control access)

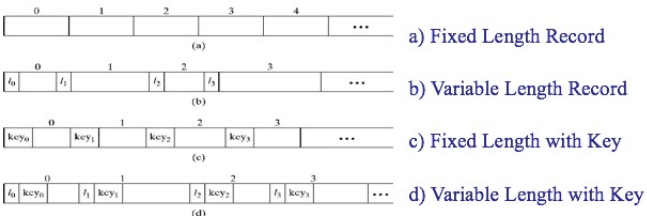
Definition 5.2. Hierarchical View of File system



- **Directory management**: map logical name tounique Id, file descriptor
- **Basic file system**: open/close files
- **Physical device organization**: map file data to disk blocks

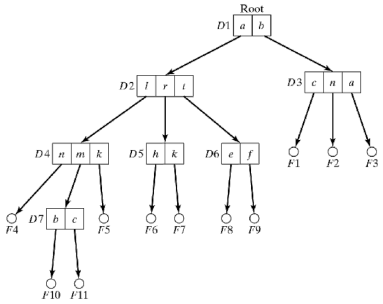
Definition 5.3. User-end view of File

- **File name and type**
  - Valid name: number or characters, lower or upper cases, illegal characters ...
  - Extension: tied to type of file, used by applications
  - File type is recorded in header
    - Cannot be changed (even when extension changes)
    - Basic types: text, object, load file, directory
    - Application-specific types, e.g., .doc, .ps, .html
- **Logical file organization**
  - Most common: byte stream
  - Fixed-size or variable-size records
  - Addressed: **Implicitly** (sequential access to next record), or **Explicitly** by position (record#) or key

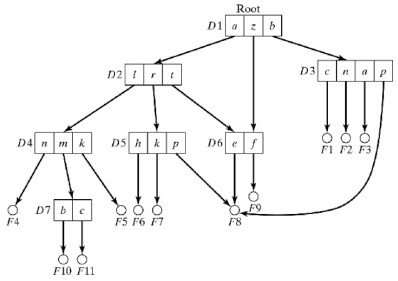


Definition 5.4. Directory Management

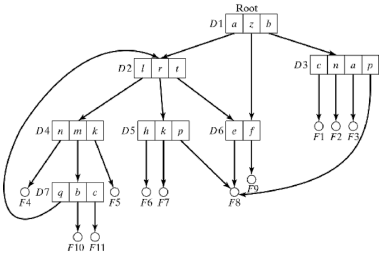
- **Main issues**:
  - **Shape** of the data structure
  - **What** info to keep about files
  - **Where** to keep the files in directory
  - **How** to organise entries for efficiency?
- **File directory data structure**:
  - **Tree-structured**
    - **Simple** search, insert, delete operations
    - Sharing is **asymmetric**



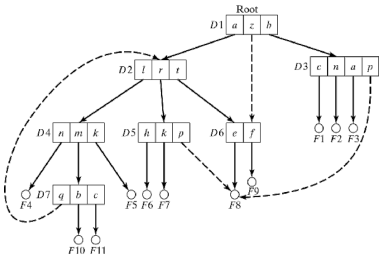
  - **DAG-structured**
    - **Symmetric** sharing
    - **Delete**: only last parent should remove files, so need **Reference count**



  - **DAG-structured with cycles**
    - Search is difficult with infinite loops
    - Deletion needs **garbage collection** (reference count not enough)



  - **Symbolic links (shortcuts)**
    - **Compromise** to allow sharing but avoid cycles.
    - For **read/write**: symbolic link is the same as actual link.
    - For **deletion**: only symbolic link is deleted.



Definition 5.5. UNIX Hard Links

- Unix allows the same underlying file to have more than 1 filename, i.e. can create multiple references

```
% echo hello >test1
% ln test1 test2
% ls -li test[12]

5000 -rw-r--r-- 2 joe users 6 Apr 1 00:00 test1
5000 -rw-r--r-- 2 joe users 6 Apr 1 00:00 test2

% cat test2
hello
```

- Inode #5000 indicates that test1 & test2 refer to same file object

- newly created regular file only has one reference, e.g. 1 link
- any file object can have multiple filenames (pathnames) which are aliases created with a hard link (`link()` system call)

  Eg: any change to test1 is reflected in test2 since its the same underlying file object, if either test1/test2 is deleted the other file test2/test1 is not affected
- no file removal: reference removal with `unlink()` system call, delete in Unix is just `unlink`

  file object can only be freed if it has no more links
- hard links restricted to within the same filesystem on same device
- directory entry `..` is a hard link (to parent)
- can only link non-directories with `link()` (except for superuser)

Definition 5.6. Symbolic Links

- Looks like hard link but NOT the same!
- Creating symbolic link

  ```
  % ln -s newpath file
  % ls -l file
  ```

  file -> newpath

  is an indirection giving a new pathname which can be resolved (again if another symbolic link)

  ```
  % ls -l /etc/X11
    lrwxrwxrwx 1 root root 14 Jan 1 04 X11 ->
    /var/X11R6/lib
  ```

  indirection continues if another symbolic link, repeats until final pathname is not a symbolic link (kernel has limit on # indirections, ELOOP open error)
- Symbolic link: special file where data is another pathname (absolute or relative), new pathname may itself be another symbolic link!

- provides a reference to pathname (hard link provides reference to underlying file object)
- does not correspond to making a new edge in graph like a hard link – rather another pathname (which may exist or not!)
  - Can link to non-existent file

    ```
    % ln -s nosuchfile testfile
    % ls
    testfile
    % cat testfile
    cat: cannot open testfile
    ```
- can link directories (user created hard links restricted to regular files) – so can create general graphs + loops!

Remark. Windows Shortcuts

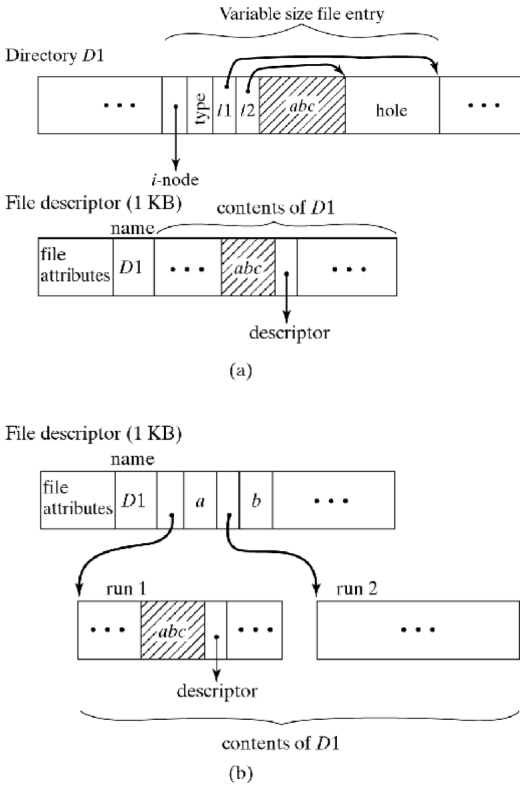
- Similar to symbolic links but does not re-expand further
- Only understood by GUI shell! Created also from GUI shell
- Win NTFS has hard links, symbolic links using junction mechanism (not normally used)

Remark. File Directories - Path name

- Concatenated local names with delimiter (. or / or \ )
- **Absolute** path name: start with root (/)
- **Relative** path name: start with current directory (.)
- Notation to move upward in hierarchy (..)

Method 5.1. Implementation of Directories

- **What information to keep in each entry**
  - **All** descriptive information, directory can become very large, searches are difficult / slow.
  - Only symbolic **name and pointer** to descriptor
    - Needs an extra disk access to descriptor
    - Variable name length
- **How to organise entries within directory**
  - **Fixed-size** entries: use array of slots
  - **Variable-size** entries: use linked list
  - **Size of directory**: fixed or expanding
- **Example**: Windows 2000: When # of entries exceeds directory size, expand using $B^+ - tree$.



Definition 5.7. File Descriptor Owner id; File type (whether it's a folder, a file, a symbolic link etc.); Protection information; Mapping to physical disk blocks (**TOC - table of contents**); Time of creation, last use, last modification; Reference counter.

Definition 5.8. OFT - Open file table keeps track of currently open files. **OFT entries**: current position (read to which part); information from descriptor (file length, disk location); pointers to allocated buffers. **Two types**: system OFT (system-wide), process OFT (open files by a process)

Definition 5.9. Basic File System Operations

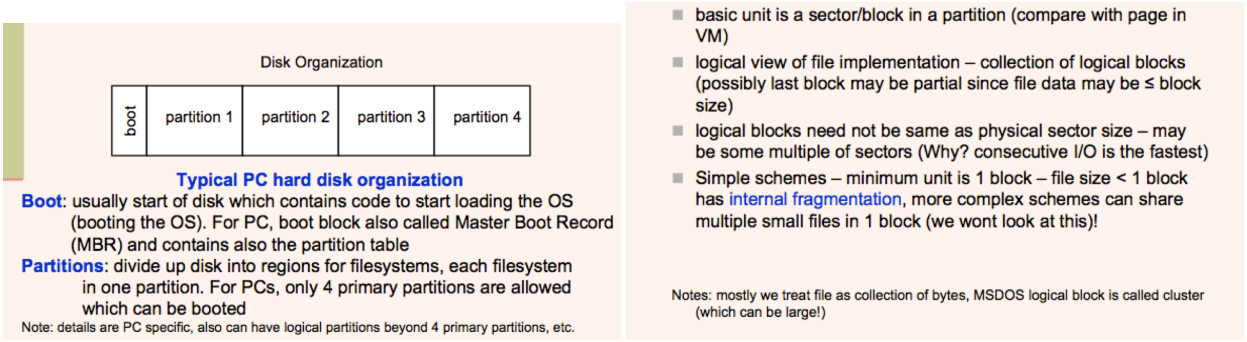
- **open file** FILE *fopen(const char *filename, const char *mode)
  1. Search directory for given file and verify access rights
  2. Allocate and fill in OFT entries and read/write buffers
  3. Return OFT index
- **close command** int fclose(FILE *stream)
  1. Flush modified buffers to disk and release buffers
  2. Update file descriptor (file length, disk location, usage information)
  3. Free OFT entry
- **read command** size_t fread(void *ptr, size_t size (of element), size_t nmemb (number of elements), FILE *stream)
  - assume file is open for **sequential** access
  - **Buffered read**: current block kept in r/w buffer
    1. copy from buffer to memory until desired count or end of file is reached: - update current position, return status

2. copy from buffer to memory until end of buffer is reached: write the buffer to disk if modified; read the next block; continue copying

– **Unbuffered read**: read the entire block containing the needed data from disk

- **write command (buffered)** size_t fwrite(const void *ptr, size_t size, size_t number, FILE *stream)
  1. Write into buffer,
  2. When full, write buffer to disk. If next block does not exist (file is expanding): - allocate new block -update file descriptor - update bit map (free space on disk).
  3. Update file length in descriptor
- **seek command** int fseek(FILE *stream, long int offset, int whence)
  1. Set current position as specified by parameter
  2. Read block containing current position into buffer
- **rewind command**: analogous to seek but position is zero

Definition 5.10. Organising data on a disk

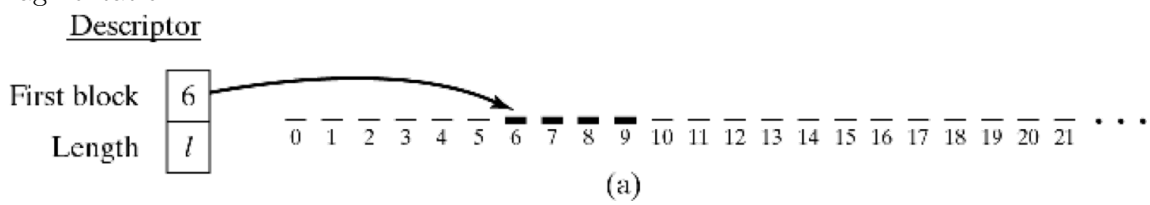


Definition 5.11. Fragmentation

- **Internal fragmentation**: Due to the rules governing memory allocation, more computer memory is sometimes allocated than is needed. Any process, no matter how small, occupies an entire partition. This waste is called internal fragmentation. (unused memory within the allocated region)
- **External fragmentation**: External fragmentation arises when free memory is separated into small blocks and is interspersed by allocated memory. (unusable storage is outside the allocated regions.)

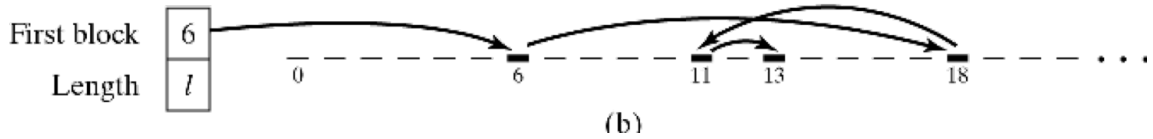
Definition 5.12. Data structures on Disk Note: need to record which block belongs to which part of files. Data structure must also be stored on disk.

- **Contiguous organization**
  1. **Advantages**: Simple implementation; Fast sequential access (minimal arm movement)
  2. **Disadvantages**: Insert/delete is difficult; How much space to allocate initially? External fragmentation



- **Linked organization**
  1. **Advantages**: Simple insert/delete, no external fragmentation

2. **Disadvantages**: Sequential access less efficient (seek latency); Direct access not possible; Poor reliability (when chain breaks)



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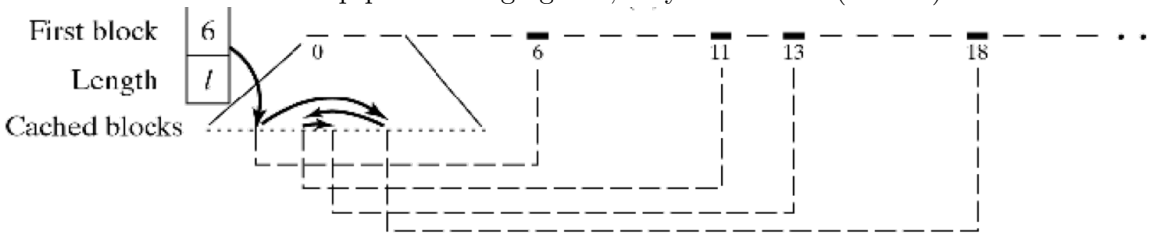
3. **Linked Variation 1**: keep pointers segregated, may be cached. (FAT32)



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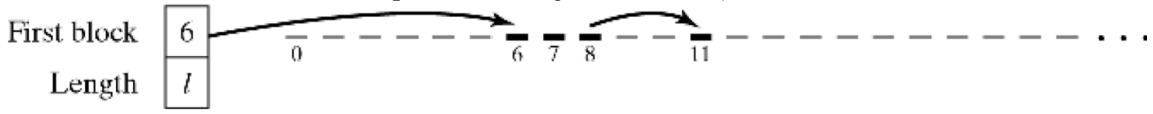
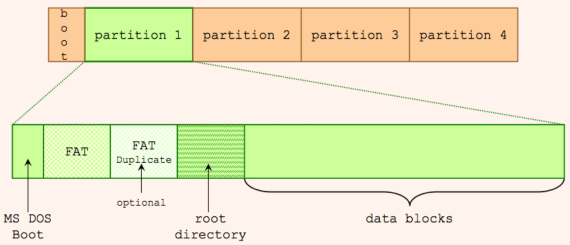
4. **Linked Variation 2**: Link sequences of adjacent blocks, rather than individual blocks



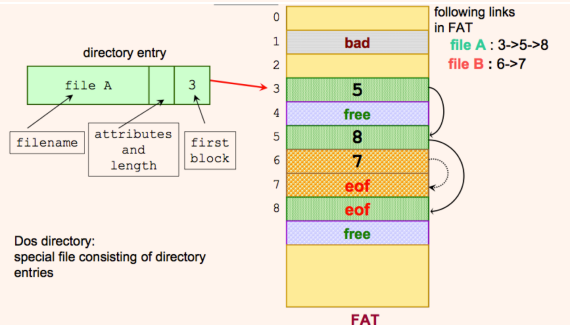
(d)

- MSDOS uses File Allocation Table (FAT)
- Linked allocation but stored completely in FAT (after reading from disk)
- FAT kept in **RAM** (stored in disk but duplicated in RAM) – gives fast access to the pointers
- FAT table contains either: **block number** of next block, **EOF** code (corresponds to NULL pointer), **FREE** code (block is unused), **BAD** block (block is unusable, i.e. disk error) – combines bitmap for free blocks with linked allocation for list of blocks
- FAT table is 1 entry for every block. Space management becomes an array method (but bigger than bitmap)



Notes: FS corresponds to 1 volume (logical drive, eg. C:), stored in 1 partition, eg: another drive (D:) in another partition etc. We dont cover extended partition

- special file (type directory) containing directory entries (32 byte structures, little endian)
- **fat directory entry**: **filename + extension** (8+3 bytes), file **attributes** [1 byte: readonly, hidden, system, **directory flag** (distinguish directories from normal files), archive, volume label (disk volume name is dir entry)], time+date created, last access (read/write) date, time+date last write (creation is write), **first block** (**cluster**) **number**
- root directory is special (already known, FAT16 has limited root dir size, 512 entries), other directories distinguished by type



- Linked list implemented as array of FAT entries:
  4 types: block number (part of a linked list), EOF type (end of linked list), special FREE type, special BAD type – some numbers are block numbers, some are reserved block numbers for EOF,FREE,BAD
- Blocks for file linked together in FAT entries, eg. file A: 3 -> 5 -> 8
- Free blocks indicated by FREE entry
- Bad blocks (unusable blocks due to disk error) marked in FAT entry: BAD cluster value

How MSDOS deletes file/directory:

- Set first letter in filename to 0xE5 (destroys first byte of original filename)
- Free data blocks: set FAT entries in link list to FREE (tags all the data blocks in file free)

Can attempt to **undelete** – some information lost but can guess!

- FAT16: fat entry block # is **16 bits** (16 bit numbers in FAT entries), sector size=512, how to deal with disks bigger than 64K*512 (32M)
- Logical block size = multiple of sectors. MSDOS calls this the **cluster size**
- Maximum cluster size = 32K (normally)
- Maximum file system size for FAT16 = 64K*32K = 2G
- Maximum file size: slightly less than 2G
- large cluster size means large internal fragmentation!

Note: can use 64K cluster size, so limits become 4G

- VFAT: adds long filenames (255 chars, introduced in Win95)
  - compatible with FAT16 by tricking it!
  - short FAT16 filename for FAT16 and long version, short filename created from long one (e.g. `longna~1.doc`)
  - for compatability: long name stored as multiple directory entries using illegal attributes (not used by FAT16)
  - trick: have to manage 2 kinds of names, old SW uses short names, aliasing issue due to 2 names

- Increase FAT size to 28 bits, cluster numbers 28-bits
- max filesystem size increased: Win98 ~127G limit, Win2K can only format up to 32G limit
- decreases internal fragmentation (cluster size can decrease)
- FAT table size increases
- FAT16 root directory size limit removed – normal directory
- Maximum file size 2^32 - 1

Notes: compare with direct paging, changing size of page and effect on page table given different sized virtual addresses

Fast disk access:
- contiguous blocks (from geometry/processing viewpoint)
- blocks in same cylinder

Suppose currently FS is optimally allocated (fresh install). Is this sustainable?
1. Delete files/blocks
2. Insert new files/blocks

After some operations – block ordering becomes more **random**!

Disk Fragmentation: logical contiguous blocks are "**far apart**" on disk (this is different from memory fragmentation)

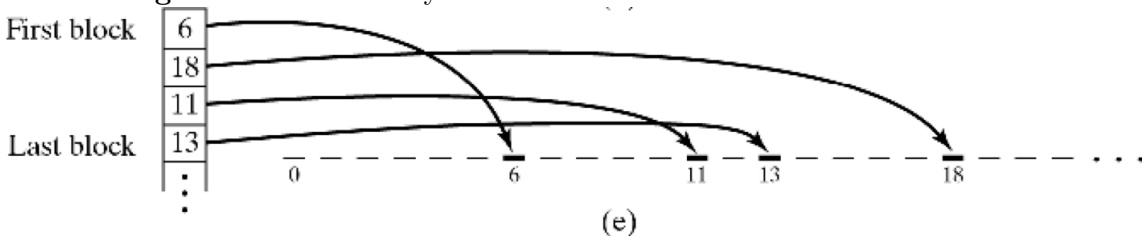
Notes: internal fragmentation still exists from block size

FAT:
- affects FAT FS
- fragmentation effect less with large cluster size (but **large** internal fragmentation!)
- MSDOS solution: run defragmentation (like compaction) on entire FS – move all used blocks to be contiguous .. one big free space chunk after defragmentation. May take a long time to defrag! (Windows: Disk Defragmenter)

Unix S5FS:
- also has disk fragmentation
- may be worse than DOS since smaller logical block size

Alternative (not covered): FS with **fragmentation resistance** (not necessarily optimal but dont need to defragment).

- **Indexed organization**
  1. **Index table**: sequential list of records; **implementation**: keep index list in descriptor
  2. **Advantage**: Insert/delete is easy; Sequential and direct access is efficient
  3. **Disadvantage**: file size limited by number of index entries



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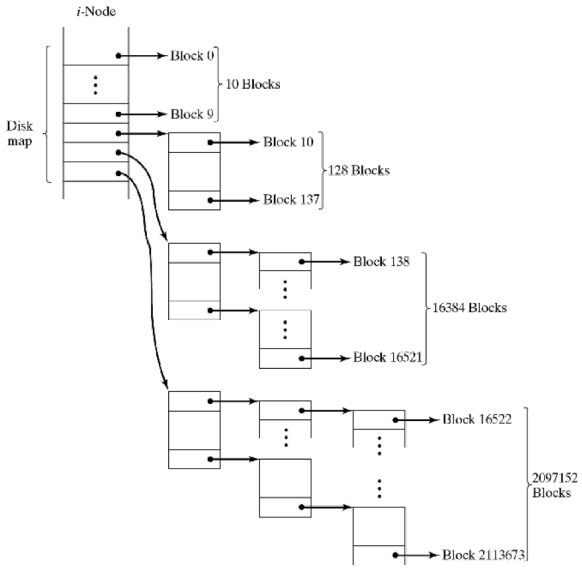
Block 6 contains bytes 0-1023, block 18 contains bytes 1024-2047, etc (1024 bytes block).

  4. **Multi-level index hierarchy**: Primary index points to secondary indices **Problem**: number of disk accesses increases with depth of hierarchy.
  5. **Incremental indexing**: number of disk accesses increases with depth of hierarchy; When insufficient, allocate additional index levels; **Example**: Unix, 3-level expansion.

- Look at System V File System (s5fs) – simpler than modern FS implementations (rather old but some of the design remains in current implementations)
- inodes: represents every file
- directories: contain names of files (recall maps filename to eventual file (hard link) or pathname (symbolic link))
- file allocation using a multi-level tree index

Note: s5fs is the original Unix v7 FS. It's much simpler and less sophisticated than more modern Unix FS.

- actual file object
- every file has one inode (many to one mapping because of hard links)
- contains all meta-data about file **except filename**
- contains reference count i.e. # hard links, reference count = 0 means file can be deleted [subjected to no open files condition - all file descriptors to file object are closed]
- meta-data in inode includes Table of Contents (TOC) which gives mapping of file data to disk blocks (TOC is per file - contrast with MSDOS which has only **global** TOC (FAT))



Incremental indexing in Unix (file size vs. speed of access)

- blocks 0-9: 1 access (direct).
- blocks 10-137: 2 access.
- blocks 138-16521: 3 access. etc.

- Direct block pointers:
  used for small files, no extra disk overhead, efficient direct access. VM analogy: TLB (however not a cache)
- Single indirect block:
  files bigger than direct blocks & smaller than double indirect. Disk overhead is 1 block. File access slightly slower than direct. VM analogy: direct mapped page table
- double + triple indirect blocks:
  files bigger than single indirect block (for sufficiently big block size, triple indirect usually not needed) . More disk overhead but is small fraction of file size. Random file access requires looking up the indirection blocks – slower than indirect. VM analog: 2-3 level page tables

File sizes: direct << single indirect << double indirect << triple indirect

- # of direct blocks (eg. s5fs: 10, ext2: 12)
- # indirection levels (eg. max is 2 or 3)
- logical block size - determines efficiency of disk I/O, can be composed of several contiguous physical blocks, space wastage from internal fragmentation, determines # block pointers in index blocks and max indirection levels (eg. ext2 can select 1,2,4K when creating filesystem)
- block pointer size - affects indexing, determines max addressable disk block)

- small files only use the direct blocks in TOC, number of direct blocks can vary
- larger file requires first indirect block (this is like 1-level page table)
- even larger file uses double indirect block which points to indirect blocks (similar to 2-level page table). Even larger may have triple indirect (but the number of indirection levels may vary)
- like page tables, can allow blocks which do not exist (**logical zero filled holes** in the file) – set the block pointer to NULL in the TOC, return zeroes for the logical block when read

- a file of type directory – accessing directory is like any other file
- only special directory operations allowed (read directory, link + unlink filenames)
- s5fs directory is array of 16 byte entries (inode: 16 bits, filename: 14 bytes), simplifies directory management (note dont need null pointer if filename length = 14)
- deleted file has inode 0
- note: most modern implementations allow long file names (ext2: 255-byte filenames), so space issues like in memory allocation

Inode Number	Filename
25	.
71	..
100	file1
200	file2

- Create new file: new directory entry with new inode
- Hard link: new directory entry (in appropriate dir) with inode of the linked file: eg. `link(path1, path2)`
  i1 = inode for file with path1;
  let path2 = dir2/file2; // dont allow linking directories
  add new directory entry to dir2: [i1, file2]; // assume file2 // not there
- Deleting (deleting is unlink since graph is DAG): remove directory entry, decrement inode link count, free file object when link count = 0 (plus open fd's condition)

Definition 5.13. Free storage space management

- **Linked list organization**
  1. Linking **individual** blocks: inefficient; no blocks clustering to minimise seek operations; groups of blocks are allocated/released one at a time.
  2. Better: Link **groups** of consecutive blocks
- **Bit map organization** (residing in super block)
  1. Analogous to main memory
  2. A single bit per block indicating if free or occupied

6 I/O System

Definition 6.1. I/O Devices

- **Communication devices**: Input only (mouse, keyboard); output only (display); Input/output (network card)
- **Storage devices**: Input/output (disk, tape); Input only (CD-ROM)

Definition 6.2. Main tasks of I/O System

- Present **logical** (abstract) view of devices (**hide**: details of hardware interface and error handling)
- Facilitate **efficient** use: overlap CPU and I/O
- Support **sharing** of devices: protection when device is shared (disk), scheduling when exclusive access needed (printer)

Definition 6.3. Block-Oriented Device Interface

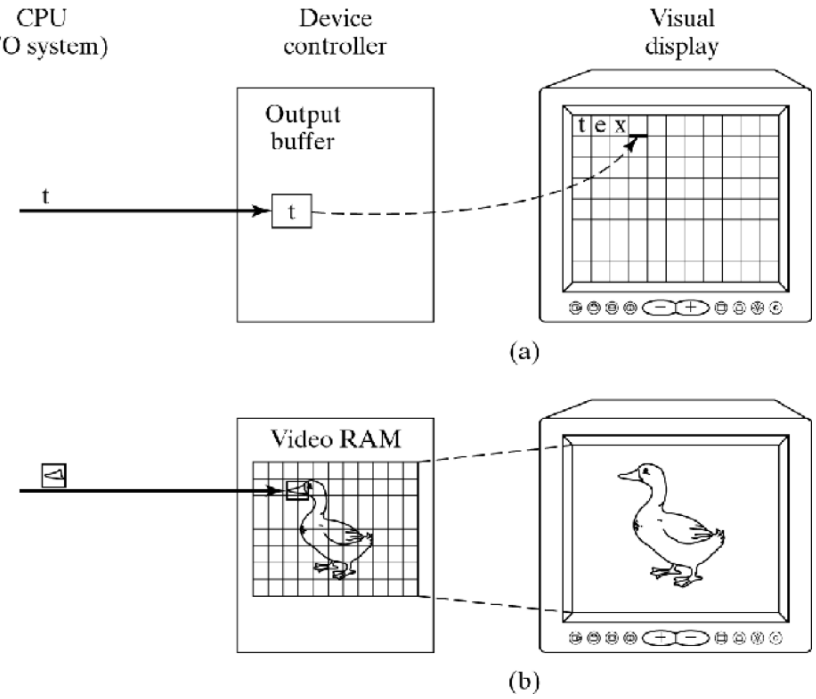
- **Description**: direct access, contiguous blocks, usually fixed block size
- **Operation**:
  - **Open**: verify device is ready, prepare it for access
  - **Read**: Copy a block into main memory
  - **Write**: Copy a portion of main memory to a block
  - **Close**: Release the device
  - ***Note**: these are lower level than those of the FS
- **Application**: Used by File System and Virtual Memory System; Applications typically go through the File System

Definition 6.4. Stream-Oriented Device Interface

- **Description**: character-oriented, sequential access
- **Operation**:
  - **Open**: reserve exclusive access
  - **Get**: return next character of input stream
  - **Put**: append character to output stream
  - **Close**: release exclusive access
  - ***Note**: these too are different from those of the FS but some systems try to present a uniform view of files and devices

Definition 6.5. I/O Devices - Ouput

- **Display monitors**:
  - character or graphics oriented
  - Different data rates: 25 x 80 characters vs 800 x 600 pixels (1B allows 256 colors) Refresh 30-60 times/s for video
- **Printers (ink jet, laser)**
- **Interface**:
  - **write** to controller buffer
  - **wait** for completion
  - handle **errors**

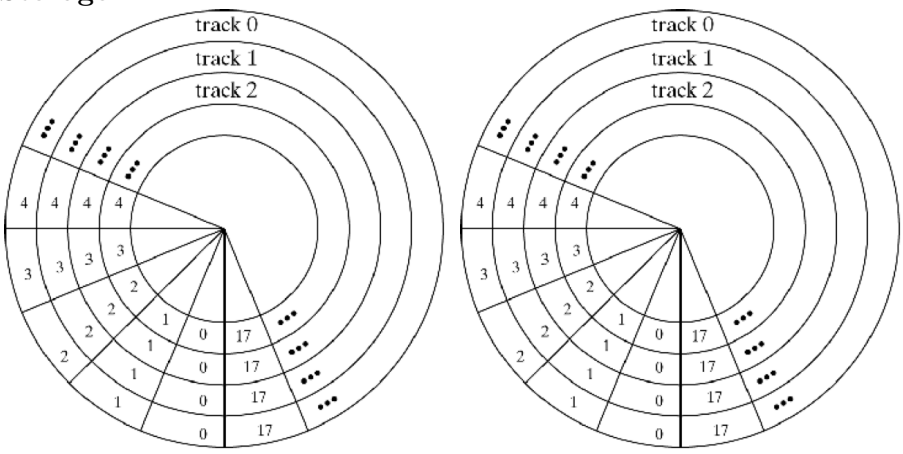


Definition 6.6. I/O Devices - Input Keyboards, pointing devices (mouse, trackball, joystick), scanners. **Interface**:

- device generates interrupt when data is ready
- read data from controller buffer
- low data rates, not time-critical

Definition 6.7. I/O Devices - Storage

- Surface, tracks/surface, sectors/track, bytes/sector
- All sectors numbered sequentially $0..(n-1)$, device controller provides mapping

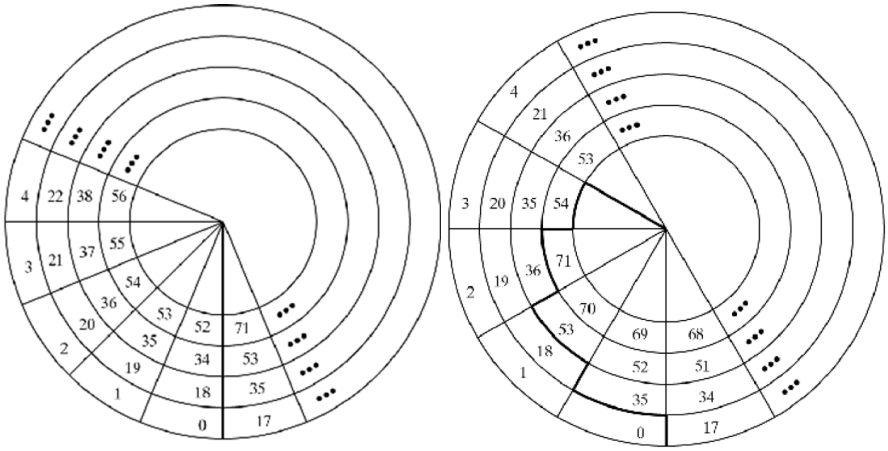


Track skew: account for seek-to-next-track to minimise rotational delay

$$\frac{\text{track to track seek time}}{\text{rotational time per track}} \times \text{sect}$$

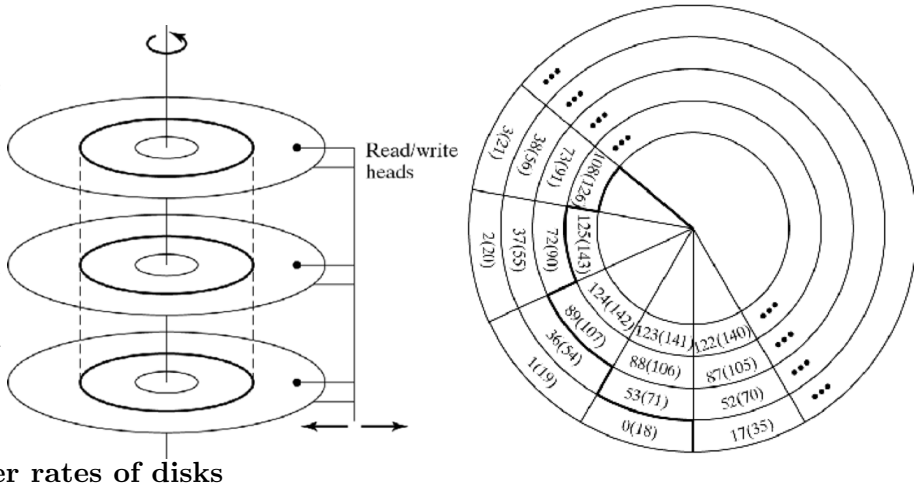
ors per track = offset

Round up the result



Double-sided or multiple surfaces

- Tracks with same diameter = **cylinder**
- Sectors are numbered within cylinder consecutively to **minimise seek time**



Critical issue: data transfer rates of disks

- **Sustained** rate: continuous data delivery
- **Peek** rate: : transfer once read/write head is in place; depends on rotation speed and data density

Example 6.1. Transfer rate calculation: 7200 rpm, 100 sectors/track, 512 bytes/sector

- What is the **peak** transfer rate?

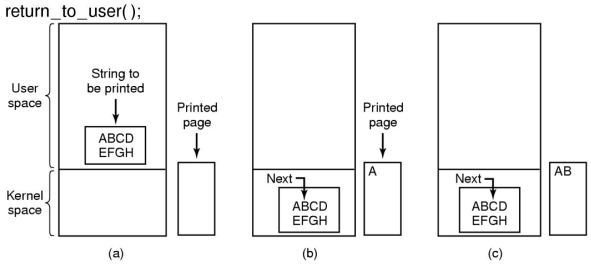
$$\frac{7200}{60} \times 100 \times 512\text{byte/s}$$

- What is the **sustained** transfer rate? - Depends on file organization

Definition 6.8. I/O programming - access the I/O devices

- **Polling** (You with a broken ringer)
  - Consider a process that prints ABCDEFGH on the printer: The OS then copies character by character onto the printers latch, and the printer prints it out.
    1. Copy the first character and advance the buffers pointer.
    2. Check that the printer is ready for the next character. If not, wait. This is called "busy-waiting" or "polling".
    3. Copy the next character. Repeat until buffer is empty.

```
copy_from_user(buffer, p, count);          /* p is the kernel bufer */
for (i = 0; i < count; i++) {              /* loop on every character */
      while (*printer_status_reg != READY) ;  /* loop until ready */
      *printer_data_register = p[i];       /* output one character */
}
return_to_user( );
```



Issue: It takes perhaps 10ms to print a character. During this time, the CPU will be busy-waiting until the printer is done printing. On a 3.2 GHz processor this is equivalent to wasting 320,000,000 instructions! Extremely inefficient use of CPU as most polls are likely to fail. On the other hand not polling risks losing data.

- **Interrupt-driven I/O** (You with a fully functioning phone)

– After the string is copied, the OS will send a character to the printer, then switch to a task.

– When the printer is done, it will interrupt the CPU by asserting one of the interrupt request (IRQ) lines on the CPU.

– **Comment**: Some overhead when the hardware is ready, but much less than with polling.

Main Routine

```
copy_from_user(buffer, p, count);
enable_interrupts( );
while (*printer_status_reg != READY) ;
*printer_data_register = p[0];
scheduler( );
```

(a)

Interrupt Service Routine (ISR)

```
if (count == 0) {
    unblock_user( );
} else {
    *printer_data_register = p[i];
    count = count – 1;
    i = i + 1;
}
acknowledge_interrupt( );
return_from_interrupt( );
```

(b)

- **Direct memory access** (You have an answering machine)
  - **Driver (CPU) operation to input sequence of bytes:**

```
write_reg(mm_buf, m); // give parameters
write_reg(count, n);
write_reg(opcode, read); // start op
block to wait for interrupt;
```

    * Writing opcode triggers DMA controller
    * DMA controller issues interrupt after n chars in memory
  - **Cycle Stealing**:
    * DMA controller competes with CPU for memory access
    * generally not a problem because: 1. Memory reference would have occurred anyway; 2. CPU is frequently referencing data in registers or cache, bypassing main memory.

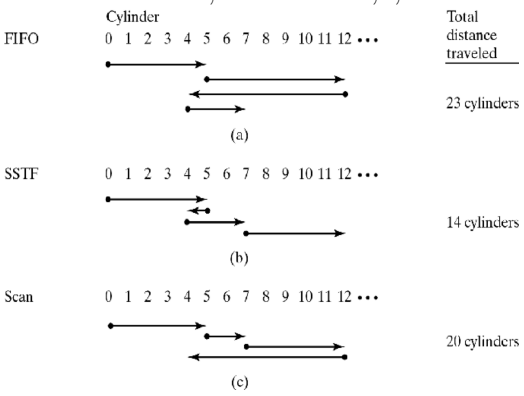
Definition 6.9. Device Management

- **Disk Scheduling**: Requests for different blocks arrive concurrently from different processes
- Minimize **rotational delay**: re-order requests to blocks on each track to access in one rotation
- Minimize **seek time**: Conflicting goals: Minimize total travel distance; Guarantee fairness

Algorithm 6.1. Device Management

- **FIFO**: requests are processed in the order of arrival: simple, fair, but inefficient
- **SSTF** (Shortest Seek Time First): most efficient but prone to starvation
  - always go to the track thats nearest to the current positions
- **Scan** (Elevator): fair, acceptable performance
  - maintain a direction of travel
  - always proceed to the nearest track in the current direction of travel
  - if there is no request in the current direction, reverse direction

Example: assume moving from 0 to 5; then 12,4,7 arrive



Remark. block size trade off Larger block sizes means fewer blocks that the OS needs to manage, less overhead. Disadvantage is that there will be greater wastage within each block (internal fragmentation)

Method 6.1. Disk access time calculation Time is takes to read one block of data:

1. **Switch time**: This is the time it takes for the drive to choose the correct side of the correct platter. (can be negligible)
2. **Seek time**: This is the time it takes a drive's arm to move to the correct track.
3. **Rotational delay**: This is the time it takes for the correct block to move underneath the head. Conventionally, taken to be $\frac{T_r}{2}$, where T_r is the time for one revolution.
4. **Transfer delay**: This is the time taken to actually transfer the block. If the disk can transfer M bytes per second and a block is B bytes long, then this time is $\frac{B}{M}$.

- **Peak data transfer rate**: The drive cannot be transferring more in one second than the amount of data in one track, multiplied by the number of times that track goes past the head per second

$$\text{Blocks / Track} = 16, \text{Bytes / Block} = 32768$$

$$\text{Bytes / Track} = 16 \times 32768 = 524288 \text{ bytes}, 7200rpm = 120rps$$

$$\text{peak throughput} = 120 \times 524288 = 62.9\text{Megabytes/Sec}(1\text{megabyte/sec} = 10^6\text{bytes/sec})$$

- **Time taken on average to read one block of data**:

$$\text{Average disk read time} = \text{switching time+seek time+rotational delay+transfer time}$$

$$\text{rotational delay} = \frac{1}{2} \times \frac{1}{7200/60} = 0.0042s$$

$$\text{Data through put} = 50 \text{ megabits per second}$$

$$\text{data transfer time} = 32768 \times 8/(50,000,000) = 0.0052s = 5.2ms$$

Note: For storage we conventionally use 1KB = 1024 bytes, not 1000 bytes. However we use 1KB = 1000 bytes for throughput.

Remark. Why interrupts have overheads? Overheads involved include detecting the interrupt, consulting the vector table to get the interrupt handler address, pushing the current PC to the stack, switching to kernel mode, and vectoring to the interrupt handler and switching back to user mode.

Example 6.2. Compare different I/O Programming methods

Question: Printing 250 characters, how many cycles are wasted on polling?

Assumption: Assuming the printer is currently free, (polling) time for the first character should be negligible. Almost all CPUs can execute at least 1 instruction per cycle

- **Polling**: For subsequent 249 characters, there is a 10ms poll time between characters. Each clock cycle is 10ns, so this corresponds to approximately 1,000,000 clock cycles per poll, or total of about 249,000,000 cycles to print the entire 250 characters.
- **Interrupt Driven**: For subsequent 249 characters we have total 300ns interrupt time, = 74,700 ns. Each clock cycle is 10ns, so this is equal to 7,470 clock cyles, a great reduction from the original 249,000,000 cycles.
- **DMA**: Total time taken = setup time + end of transfer interrupt processing time = 700ns. This is equal to 70 instructions.

Example 6.3. Disk access time calculation

- **What is the total number of blocks read by this program?**
  Bytes per block =128; Total number of bytes read and written (calculated from the program) = 32768; Number of blocks to be read is $\frac{32768}{128} = 256$. Assuming one directory block read and one inode block read per file, then total = 256 + 2 = 258.

- **Assume that there is no caching or buffering (so not affected by the caching policies), and that the disk blocks are *not skewed*. What is the total time in milliseconds that this program spends reading and writing the files?**
  - **Calculation of # of cylinders to read**
    # of tracks per cylinder = 4; # of blocks per cylinder = 16 × 4= 64;
    # of cylinders to read = 256 / 64 = 4 (for the file itself)
  - **Time to read directory and inode**
    Seek time to directory block: 12ms
    Rotational delay to directory block: 3600rpm=60rps. Delay=1/(2×60)=8.3ms
    Transfer delay (to read directory / inode Block): 128 / 100,000,000=0.00128ms
    Total: (12+8.3+0.00128)×2=40.6ms
  - **Time to read first cylinder**
    Seek time to first cylinder: 12ms
    Rotational delay to first block: 8.3ms
    Bytes per cylinder = 64 × 128 = 8192
    Time to read one cylinder = 8192 / 100,000,000=0.08192ms
    Total: (12+8.3+0.08192)=20.382ms
  - **Time to read the remaining 3 cylinders**
    Seek time to adjacent track: 2ms
    Rotation delay still 8.3ms; Total time to read data still: 0.08192ms
    Total: $3 \times (2 + 8.3 + 0.08192) \times 3 = 31.146$ms

  Total time taken: 40.6+20.382+31.146=92.128ms
- **Once again assuming that there is no caching or buffering, repeat part b. assuming that the blocks are *skewed* such that rotational delay is completely eliminated when the head moves to the next cylinder to continue writing.**
  Same timing, except no rotational delay for additional 3 cylinders. $92.128 - 3 \times 8.3 = 67.228$ms

7 Memory Management

Definition 7.1. Memory & OS responsibility

- **Memory** used to store: kernel code and data; user code and data
- **OS Responsibilities**:
  - Allocate memory to new processes.
  - Manage process memory.
  - Manage kernel memory for its own use.
  - Provide OS services to: get more memory, free memory, protect memory

Definition 7.2. Physical Memory Organization

- The actual matrix of capacitors (DRAM) or flip-flops (SRAM) that stores data and instructions.
- Arranged as an array of bytes.
- Memory addresses serve as byte indices.

Definition 7.3. Word: CPU data transfer unit

- 1 byte in 8-bit machines (ATMega328P, Intel 8080), 2 bytes in 16 bit machines (Intel 80286), 4 bytes in 32-bit machines (Intel Xeon), 8 bytes in 64-bit machines (Intel Celeron)

Definition 7.4. Endianness

How to store multibyte word (object > 1 byte), 2 general schemes, Eg: 0x87654321 (4 byte int)

- **Big Endian**: higher order bytes at lower addresses

	87	65	43	21
Address	a	a+1	a+2	a+3

- **Little Endian**: lower order bytes at lower addresses

	21	43	65	87
Address	a	a+1	a+2	a+3

x86: little endian ; Sparc: big endian ; powerpc: configurable

Definition 7.5. Alignment Issues

- **Data can be fetched across word boundaries.**

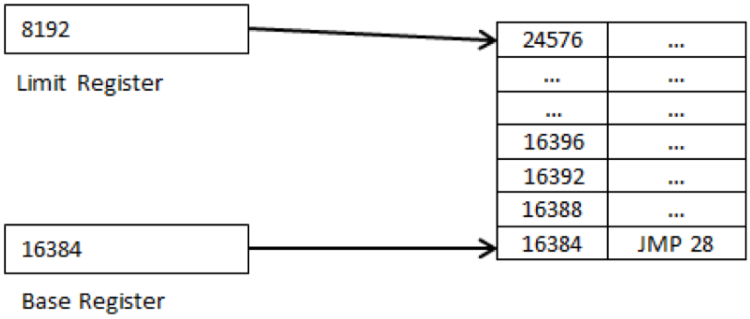
- E.g. fetching from address 1 in a 32-bit machine:
  - ✓Bytes from addresses 0 to 3 are fetched.
  - ✓Bytes from addresses 4 to 7 are fetched.
  - ✓Bytes from addresses 0, 5 to 7 are discarded.
  - ✓Bytes from addresses 1 to 3, 4 are merged.
- SLOW!!

Add unused bytes to ensure data structures always in units of words. Instructions fetched across word boundaries trigger "Bus Error" faults.

Why Memory Management?

- We want to use memory efficiently
- We want to protect processes from each other

- **Logical addresses**: These are the addresses as seen by executing processes code.
- **Physical addresses**: These are addresses that are actually sent to memory to retrieve data or instructions.



Note: **Having multiple processes complicates memory management**:

- **Conflicting addresses**: What if > 1 program expects to load at the same place in memory?

- **Access violations**: What if 1 program overwrites the code/data of another? Worse, what if 1 program overwrites parts of the operating system?
- The ideal situation would be to give each program a section of memory to work with. Basically each program will have its own address space!

To do this we require extra hardware support:

- **Base register**: This contains the starting address for the program. All program addresses are computed relative to this register.
- **Limit register**: This contains the length of the memory segment.

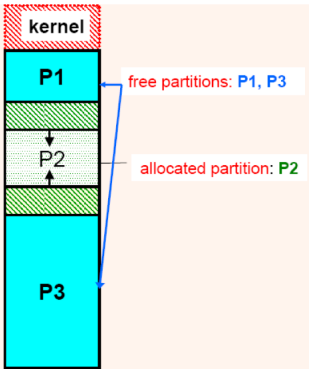
These registers solve both problems:

- We can resolve address conflicts by setting different values in the base register.
- If a program tries to access memory below the base register value or above the (base+limit) register value, a "segmentation fault" occurs!
- All memory references in the program are relative to the Base Register. E.g. "jmp 28" above will cause a jump to location 16412.
- Any memory access to location 24576 and above (or 16383 and below) will cause segmentation faults. (Other programs will occupy spaces above and below the segment given to the program shown here.)
- Base and limit registers allow us to partition memory for each running process: Each process has its own fixed partition, assuming that we know how much memory each process needs.

Definition 7.6. Fragmentation Issues

- **Internal fragmentation**:
  - Partition is much larger than is needed.
  - Cannot be used by other processes.
  - Extra space is wasted.
- **External fragmentation**:
  - Free memory is broken into small chunks by allocated memory.
  - Sufficient free memory in TOTAL, but individual chunks insufficient to fulfil requests.

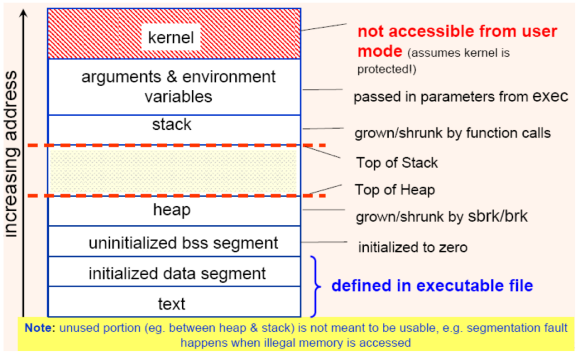
  Resolution: Internal fragmentation can be reduced by smaller size of allocation blocks. External fragmentation can be reduced by relocating occupied blocks.



Definition 7.7. Managing Memory within processes OS allocates memory for instructions. Global variables are created as part of the programs environment, and dont need to be specially managed. A **"stack"** is used to create local variables and store local addresses. A **"heap"** is used to create dynamic variables.

E.g. in UNIX, process space is divided into:

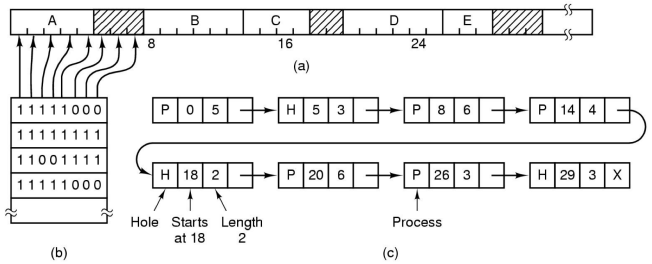
- **Text segments**: Read-only, contains code (like machine instruction). May have > 1 text segments.
- **Initialised Data**: Global data initialized from executable file. E.g. when you do:
  char *msg[]="Hello world!";
- **BSS Segment**: Contains uninitialized globals.
- **Stack**: Contains statically allocated local variables and arguments to functions, as well as return addresses.
- **Heap**: Contains dynamically allocated memory.



Definition 7.8. Managing Free Memory

Memory is divided up into fixed sized chunks called **"allocation units"**. Common sizes range from several bytes (e.g. 16 bytes) to several kilobytes,(a).

- **Bit maps**
- **Free/Allocated List**

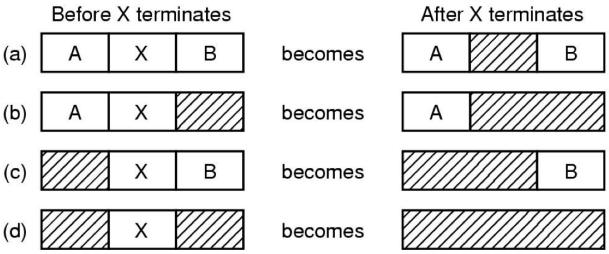


Bit Map (b)

- Each bit corresponds to an allocation unit. A "0" indicates a free unit, a "1" indicates an allocated unit.
- If a program requests for 128 bytes:
  1. Find how many allocation units are needed. E.g. if each unit is 16 bytes, this corresponds to 8 units.
  2. Scan through the list to find 8 consecutive 0's.
  3. Allocate the memory found, and change the 0's to 1's.
- If a program frees 64 bytes: Mark the bits corresponding to the 4 allocation units as "0".

Linked list (c)

- A single linked list is used to track allocated ("P") units and free ("H") units. Each node on the linked list also maintains where the block of free units start, and how many consecutive free units are present in that block.
- Allocating free memory becomes simple: Scan the list until we reach a "H" node that points to a block of a sufficient number of free units.
  - The list is implemented as a double-linked list.
    - Diagram below shows possible "neighbor combinations" that can occur when a process X terminates.
    - The "back pointer" in a double-linked list makes it easy to coalesce freed blocks together.

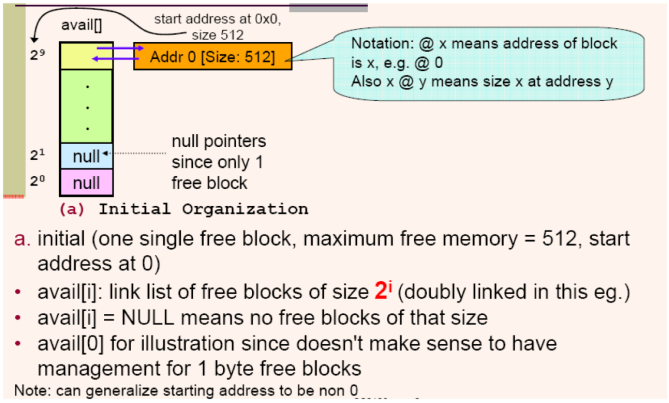


Definition 7.9. Allocation Policies

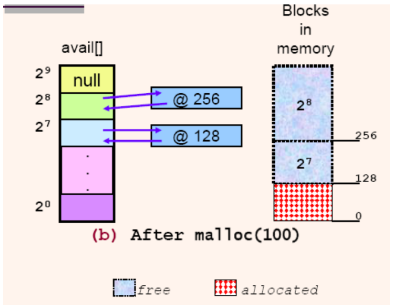
- **First Fit**:
  - Scan through the list/bit map and find the first block of free units that can fit the requested size.
  - Fast, easy to implement.
- **Best Fit**:
  - Scan through the list/bit map to find the smallest block of free units that can fit the requested size.
  - Theoretically should minimise "waste".
  - However can lead to scattered bits of tiny useless holes.
- **Worst Fit**:
  - Find the largest block of free memory.
  - Theoretically should reduce the number of tiny useless holes.
- **Note**: We can sort the free memory from smallest to largest for best fit (worst case unchanged), or largest to smallest for worst fit. This minimises search time. However coalescing free neighbours will be much harder.

Quick Fit: Buddy Allocation, Binary splitting

- Half of the block is allocated.
- The two halves are called "buddy blocks".
- Can coalesce again when two buddy blocks are free.



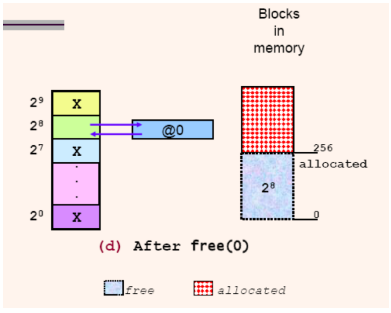
Example 7.1. Buddy Allocation



malloc(100)

1. Split 512 byte block into 2 blocks of 256 bytes.
2. Split one 256 byte block into two 128 byte blocks.

free(0): block Coalesces



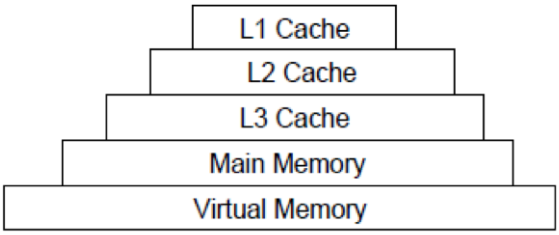
Remark. Trade offs of using allocation units of multiple bytes versus allocation units of 1 byte (particularly in systems with large amounts of memory.)

- Bigger allocation units = faster and more efficient allocation because fewer units to maintain, but bigger internal fragmentation.
- Single byte units = no internal fragmentation, but can be slow and unwieldy to manage.

8 Virtual Memory

Definition 8.1. Memory Hierarchy

- Topmost layer is the fastest, but most expensive and therefore the smallest.
- Bottom-most layer is the cheapest and biggest, but the slowest.
- Each layer above contains a small portion of the layer below: Use **"replacement policies"** to decide which portions to copy.



Definition 8.2. Principles of Locality

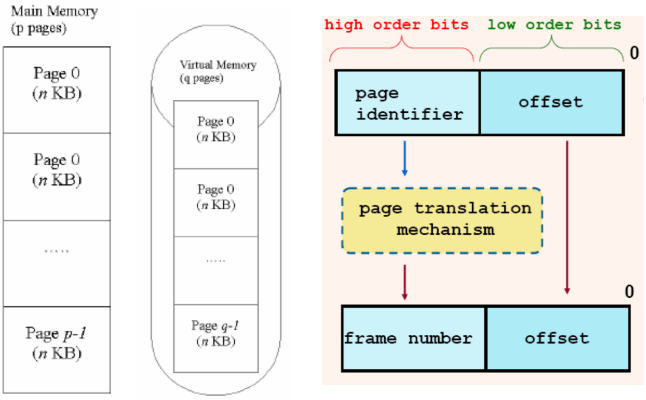
- **Spatial Locality**: If you've accessed a memory location, there's a very high chance that the next location you access is right next to it. E.g. executing instructions sequentially, accessing elements of an array.
- **Temporal Locality**: If you've accessed a memory location, there's a very high chance that you will access it again. E.g. Loops.
- **Note**: Because of locality, memory hierarchy allows you to have:
  - **Very fast memory**, since most accesses come from the fast top layer.
  - **Very large memory**, since we can continue to keep what we don't (yet) need in the lowest layer.

Definition 8.3. Virtual Memory It is implemented on your hard disk! The layer above (your "main memory") maintains a copy of a small portion of the VM.

We can do this by having instructions and data that the CPU is currently interested in, in main memory. Everything else stays on the VM. In this way we can squeeze MUCH MORE instructions and data than otherwise possible!

Paging

- VM is divided into fixed equal sized blocks called "pages".
- Physical memory is divided into "frames" that are the same size as a VM page. A "Virtual page" in the VM can be loaded to any "physical frame" in main memory.
- The CPU always generates "virtual addresses". I.e. any CPU address always points to a page in virtual memory.

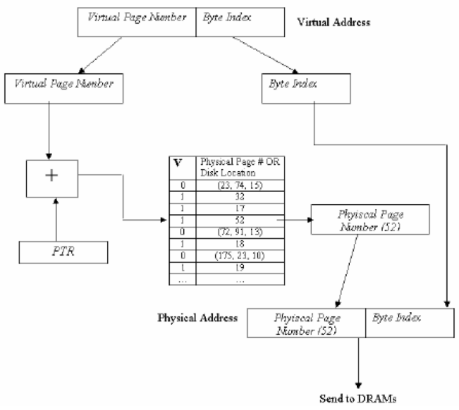


Virtual to Physical Address Mapping

- Virtual Page Number = Page Identifier; Frame number = Physical Page Number; Offset = Byte Index.
- Specialised hardware on the CPU, together with virtual memory services in the OS, work together to translate virtual addresses into physical addresses that correspond to locations in main memory.
- "page table": V=1 means the information requested is in main memory.

V	Physical Page # OR Disk Location
0	(23, 74, 15)
1	32
1	17
1	52
0	(72, 91, 13)
1	18
0	(175, 23, 10)
1	19
...	...

1. The virtual address forms an index into the page table. If the "virtual page" is in memory, a "memory translation" process takes place that locates which frame this virtual page has been loaded into.
2. This information is used to generate the "physical address" to access main memory.



- Given an N bit virtual addressing space, P bit physical addressing space with B byte page/frame size:

$$\#\text{ of bits in offset} = \log_2(B)$$

$$\#\text{ of bits in page identifier (or VPN)} = N - \log_2(B)$$

$$\#\text{ of bits in frame number} = P - \log_2(B)$$

- So if we have 32KB pages, a 4GB virtual addressing space and 2 GB of physical memory:

$$\text{offset} = log2(32KB) = 15 \text{ bits}$$

$$\text{Page identifier} : \log_2(4GB) - 15 = 32 - 15 = 17 \text{ bits}$$

$$\text{Frame number} : \log_2(2GB) - 15 = 31 - 15 = 16 \text{ bits}$$

  There will be 2^{17} pages in this system, with 2^{16} frames.

- **Note**:
  1. **No external fragmentation**: Pages that should be contiguous can be mapped to non-contiguous frames.
  2. **Internal fragmentation**: Basic allocation unit is now 1 page. Can be quite large!
  3. **Mapping is transparent** to programs. Programs only "see" virtual addresses.
  4. Can grow process segments by adding more pages. Growth is now limited to multiples of one page.
- **Page Faults**: The V flag will be "0". The hardware sees this and generates a "page fault" interrupt. This is vectored to a page fault ISR within the OS.
  1. Locates where the missing page is on the disk: When V=0, the page table contains the location on disk where the page is (in cylinder/side/block format).
  2. Finds a free frame to load the VM page into.
  3. Updates the page table. Set V=1, and changes the entry to show which frame the virtual page has been loaded into.
  4. The VM then goes through the rest of the address translation process to allow the CPU to access the faulting data/instruction.
- **Page loading policy**:
  - **Demand Paging**: Page is loaded when an access is made to a location inside it.
  - **Pre-paging**: Other pages (e.g. surrounding pages) can be loaded together with the fault page. Pages can be pre-loaded when a process starts.
  - Can be a mix of strategies.
- **Replacement policy**:

- **FIFO**:
  - **Principle**: First page in = first page out.
  - Use a FIFO queue of pages read in. New pages are added to the tail, pages at the head are swapped out when no more frames.
  - **Belady's anomaly**: In a FIFO replacement policy, having more frames can increase paging instead of decreasing it.
  - **Resolution**: consider frequency of use (i.e. temporal locality) instead of age. Optimal Page Replacement (OPT), Least Recently Used (LRU) and Clock Replacement (CR). None of these suffer from Belady's Anomaly.
- **LRU - Least Recently Used**
  - Each page table entry (PTE) has an p-bit counter c_i. At each access to page i, the c_i is set to $2^p - 1$. Counter for all other pages is decremented by 1.
  - When it is time to replace a page: Perform a search through page table to find smallest c_i. Swap that page back to disk.
  - If > 1 page has smallest c_i, choose the first one we encountered.
  - **Note**: only approximation version of LRU as the counting range (p bit) cannot be too big.

- **Rewriting pages back to disk**: Pages are large. Writing swapped out pages back to disk is expensive. Have a "D" (Dirty) bit in each PTE. **Note**: requires hardware support to update D.

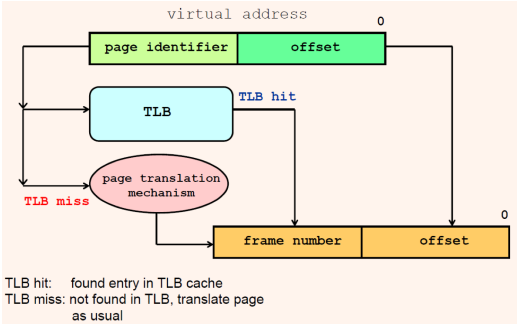
Definition 8.4. Thrashing: a performance disaster When the amount of data/instructions in VM is much, much greater than available physical memory.

1. Accessing instructions/data might frequently be in pages that aren't yet in physical memory.
2. Shortage of physical memory causes frames to be frequently swapped out to disk.
3. The swapped out frames are accessed again, causing other frames to be swapped out so that these can be swapped back in.
4. Huge array, 4 million bytes. Random accesses will likely cause pages to be swapped out and back in again.

Definition 8.5. Translation Lookaside

The page table is in main memory. **Two access**: One access to consult the page table. One access to actually read/write the physical memory. (Main memory is slower than the cache, therefore store parts of the page table in cache)

- This special cache is called the "Translation Lookaside Buffer" or TLB. This is often located on the CPU die itself.



Example 8.1. Virtual memory calculation example

- **Question**: consider a virtual memory system with 64 bytes per page, 10 bit virtual addresses and 9 bit physical addresses.
- Maximum size in bytes of the virtual memory is $2^{10} = 1024$ bytes. Maximum size of the physical memory is $2^9 = 512$ bytes.
- Byte index is 6 bits ($2^6 = 64$), leaving 4 bits for VPN or 16 virtual pages, and 3 bits for PPN or 8 physical pages.
- **translation procedure**: convert virtual address into binary → get the VPN → look up at the page table to get the PPN → add the byte index (last few bits just now) → convert the PPN and byte index from binary to decimal, this is the physical address.

9 Acronym & Abbreviation Checklist

A:

B: `BSD`: Berkeley Software Distribution;

C: `CPU`: Central Processing Unit; `CIA`: Critical Instance Analysis; `COW`: Copy on Write; `CR`: Clock Replacement;

D: `DAG`: Directed Acyclic Graph; `DMA`: Direct Memory Access; `DRAM`: Dynamic random-access memory;

E: `EDF`: Earliest Deadline First Schedling; `EOF`: End Of File;

F: `FAT`: File Allocation Table; `FCFS`: First Come First Served; `FIFO`: First In First Out; `FD`: File Descriptor;

G:

H:

I: `ISR`: Interrupt Service Routine; `IO`: Input Output; `IPC`: Inter-process communication; `IRQ`: Interrupt Request;

J:

K:

L: `LRU`: Least Recently Used;

M: `MBR`: Master Boot Record; `MSW`: Machine Status Word;

N:

O: `OS`: operating system; `OFT`: Open File Table; `OPT`: Optimal Page Replacement;

P: `PC`: Program Counter; `PID`: Process ID; `PPID`: Parent Process ID; `PCB`: Process Control Block; `PTE`: Page Table Entry; `PPN`: Physical Page Number;

Q:

R: `RR`: Round Robin; `RMS`: Rate Monotonic Scheduling; `RAM`: Random Access Memory;

S: `SREG`: Status Register; `SJF`: Shortest Job First; `SRT`: Shortest Remaining Time; `SSTF`: Shortest Seek Time First; `SRAM`: Static random-access memory;

T: `TSL`: Test and Set Lock; `TOC`: Table of Contents; `TLB`: Translation Lookaside Buffer;

U: `USB`: Universal Serial Bus;

V: `VM`[1]: Virtual Machine; `VS`: Voluntary Scheduling; `VM`[2]: Virtual Memory; `VPN`: Virtual Page Number;

W:

X: `XCHG`: Exchange Register/Memory with Register;

Y:

Z: