Advanced Topic in Operating Systems
Lecture Notes

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Contents

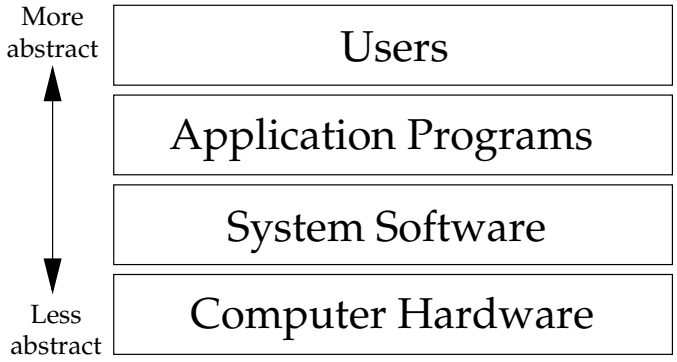
1 Introduction to Operating Systems

1.1 What is an Operating System?

Textbook reference: Stallings ppg 53 – 100; Tanenbaum & Woodhull ppg 1 – 5

Without software, a computer is effectively useless. Computer software controls the use of the hardware (CPU, memory, disks etc.), and makes the computer into a useful tool for its users.

In most computers, the software can be regarded as a set of layers, as shown in the following diagram. Each layer hides much of the complexity of the layer below, and provides a set of abstract services and concepts to the layer above.



For example, the computer's hard disk allows data to be stored on it in a set of fixed-sized blocks. The system software hides this complexity, and provides the concept of files to the application software. In turn, an application program such as a word processor hides the idea of a file, and allows the user to work with documents instead.

Computer software can be thus be divided into 2 categories:

- system software, which manages the computer's operation, and
- applications software, which allows users to do useful things.

The most fundamental of all system software is the operating system. It has three main tasks to perform.

- The operating system must shield the details of the hardware from the application programs, and thus from the user.
- The operating system has to provide a set of abstract services to the application programs, instead. When applications use these abstract services, the operations must be translated into real hardware operations.
- Finally, the resources in a computer (CPU, memory, disk space) are limited. The operating system must act as a resource manager, optimising the use of the resources, and protecting them against misuse and abuse. When a system provides multiuser or multitasking capabilities, resources must be allocated fairly and equitably amongst a number of competing requests.

operating system: (Often abbreviated 'OS') The foundation software of a machine, of course; that which schedules tasks, allocates storage, and presents a default interface to the user between applications. The facilities an operating system provides and its general design philosophy exert an extremely strong influence on programming style and on the technical cultures that grow up around its host machines.

1.2 Kernel Mode and User Mode

Textbook reference: Tanenbaum & Woodhull pg 3

Because an operating system must hide the computer's hardware, and manage the hardware resources, it needs to prevent the application software from accessing the hardware directly. Without this sort of protection, the operating system would not be able to do its job.

The computer's CPU provides two modes of operation which enforce this protection. The operating system runs in kernel mode, also known as supervisor mode or privileged mode. In kernel mode, the software has complete access to all of the computer's hardware, and can control the switching between the CPU modes.

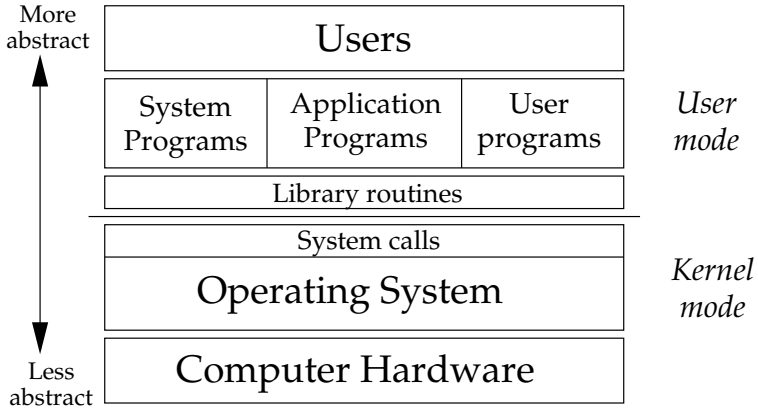
The rest of the software runs in user mode. In this mode, direct access to the hardware is prohibited, and so is any arbitrary switching to kernel mode. Any attempts to violate these restrictions are reported to the kernel mode software: in other words, to the operating system itself.

By having two modes of operation which are enforced by the computer's own hardware, the operating system can force application programs to use the operating system's abstract services, instead of circumventing any resource allocations by direct hardware access.

1.3 Other System Software

Textbook reference: Tanenbaum & Woodhull pg 2

Before we go on with our introduction to operating systems, we should look at what other system software there is.



At the top of the operating system are the system calls. These are the set of abstract operations that the operating system provides to the applications programs, and thus are also known as the application program interface, or API. This interface is generally constant: users cannot change what is in the operating system.

Above the system calls are a set of library routines which come with the operating system. These are functions and subroutines which are useful for many programs.

The programs do the work for the user. Systems programs do operating system-related things: copy or move files, delete files, make directories, etc.

Other, non-system software are the application programs installed to make the computer useful. Applications like Netscape Navigator, Microsoft Word or Excel are examples of non-system software. These are usually purchased separately from the operating system.

Of course, in many cases software must be written for a special application, by the users themselves or by programmers in an organisation.

Regardless of type, all programs can use the library routines and the system calls that come with an operating system.

1.4 Types of Operating Systems

Every operating system is different, and each is designed to meet a set of goals. However, we can generally classify operating systems into the following categories.

- A **simple monitor** provides few services to the user, and leaves much the control of the hardware to the user's own programs. A good example here is MS-DOS.
- A **batch system** takes user's **jobs**, and segregates them into batches, with similar requirements. Each batch is given to the computer to run. When jobs with similar system requirements are batched together, this helps to streamline their processing. User interaction is generally lacking in batch systems: jobs are entered, are processed, and the output from each job comes out at a later time. The emphasis here is on the computer's utilisation. An example batch system is IBM's VM.
- An **embedded system** usually has the operating system built into the computer, and is used to control external hardware. There is little or no application software in an embedded system. Examples here are the Palm Pilot, the electronic diaries that everybody seems to have, and of course the computers built into VCRs, microwaves, and into most cars.
- A **real-time system** is designed to respond to input within certain time constraints. This input usually comes from external sensors, and not from humans. Thus, there is usually little or no user interaction. Many embedded systems are also real-time systems. An example real-time system is the QNX operating system.
- Finally, a **multiprogramming system** appears to be running many jobs at the same time, each with user interaction. The emphasis here is on user response time as well as computer utilisation. Multiprogramming systems are usually more general-purpose than the other types of operating systems. Example multiprogramming systems are Unix and Windows NT.

In this course, we will concentrate on multiprogramming systems: these are much more sophisticated and complex then the other operating system types, and will give us a lot more to look at. We will also concentrate on *multi-user* systems: these are systems which support multiple users at the same time.

2 Design Principles & Concepts

Textbook reference: Stallings ppg 53 – 100; Tanenbaum & Woodhull ppg 15 – 20

The services provided by an operating system depends on the **concepts** around which the operating system was created; this gives each operating system a certain 'feel' to the programmers who write programs for it.

We are talking here not about the 'look & feel' of the user interface, but the 'look & feel' of the *programmer's interface*, i.e the services provided by the API.

Although each operating system provides its own unique set of services, most operating systems share a few common concepts. Let's briefly take at look at each now. We will examine most of these concepts in detail in later topics.

2.1 The Process

Most operating systems provide the concept of a process. Here, we need to distinguish between a **program** and a **process**.

- A **program** is a collection of computer instructions plus some data that resides on a storage medium, waiting to be called into action.
- A **process** is a program during execution. It has been loaded into the computer's main memory, and is taking input, manipulating the input, and producing output.

Specifically, a process is an enviroment for a program to run in. This environment protects the running program against other processes, and also provides the running program with access to the operating system's services via the system calls.

2.2 Memory

Part of every computer's hardware is its main memory. This is a set of temporary storage locations which can hold machine code instructions and data. Memory is volatile: when the power is turned off, the contents of main memory are lost.

In current computers, there are usually several megabytes of memory (i.e millions of 8-bit storage areas). Memory contents can be accessed by reading or writing a **memory location**, which has an integer **address**, just like the numbers on the letter boxes in a street.

Memory locations often have a hardware protection, allowing or preventing read and writes. Usually, a process can only read or write to a specific set of locations that have been given to it by the operating system.

The operating system allocates memory to processes as they are created, and reclaims the memory once they finish. As well, processes can usually request more memory, and also relinquish this extra memory if they no longer require it.

2.3 Files

Files are storage areas for programs, source code, data, documents etc. They can be accessed by processes, but don't disappear when processes die, or when the machine is turned off. They are thus *persistent* objects.

Operating systems provide mechanisms for file manipulation, such as open, close, create, read and write.

As part of the job of hiding the hardware and providing abstract services, the operating system must map files onto areas on disks and tapes. The operating system must also deal with files that grow or shrink in size.

Some operating systems don't enforce any structure to files, or enforce particular file types types. Others distinguish between file types and structures, e.g Pascal source files, text documents, machine code files, data files etc.

Most operating systems allow files to have **permissions**, allowing certain types of file access to authorised users only.

Directories may exist to allow related files to be collected. The *main* reason for the existence of directories is to make file organisation easier and more flexible for the user.

2.4 Windows

Nearly all operating systems these days provide some form of graphical user interface, although in many cases a command-line interface is also available.

In these operating systems, there are services available to allow processes to do graphical work. Although there are primitive services such as line and rectangle drawing, most GUI interfaces provide a abstract concept known as the **window**.

The window is a logical, rectangular, drawing area. Processes can create one or more windows, of any size. The operating system may decorate each window with borders, and these may include *icons* which allow the window to be destroyed, resized, or hidden.

The operating system must map these logical windows onto the physical display area provided by the video card and computer monitor. As well, the operating system must direct the input from the user (in the form of keyboard input, and mouse operations) to the appropriate window: this is known as changing the input focus.

2.5 Operating System Services

Textbook reference: Tanenbaum & Woodhull ppg 21 – 26

From a programmer's point of view, an operating system is defined mainly by the Application Program Interface that it provides, and to a lesser extent what library routines are available.

It follows, therefore, that a number of different operating system products may provide exactly the same Application Program Interface, and thus appear to be the same operating system to the programmer. The most obvious example of this is Unix.

Unix is really not a single operating system, but rather a collection of operating systems that share a common Application Program Interface. This API has now been standardised, and is known as the POSIX standard. Solaris, HP-UX, SCO Unix, Digital Unix, System V, Linux, Minix and FreeBSD are all examples of Unix operating systems.

What this means is that a program written to run on one Unix platform can be recompiled and will run on another Unix system. As long as the set of systems calls are the same on both systems, the program will run on both systems.

Another group of operating systems which share a common API are the Windows systems from Microsoft: Windows CE, Windows 95 or 98 and Windows NT. Although structurally different, a program can be written to run on all three.

2.6 Unix and Laboratory Work

The aim of this course is not to examine the implementation of a particular operating system. Instead, we will be looking at the abstractions provided by operating systems, and the design tradeoffs that must be made when constructing an operating system.

In the laboratory work in this course, we will be using the Unix operating system to look at some of its abstract concepts, and to see some of their implementation details. It is in your best interests to learn a bit about Unix and what it provides to the programmer and the user.

Section 1.3 of Tanenbaum's textbook gives a good overview of the main Unix concepts. For the programmers who are interested in Unix's system calls, an overview of these are given in Section 1.4.

Note that Sections 1.3 and 1.4 cover the Minix system. As noted above, Minix is a particular implementation of Unix. Sections 1.3 and 1.4 cover the core concepts and system calls that are available in all Unix systems.

2.7 Operating System Structure

Textbook reference: Tanenbaum & Woodhull ppg 37 – 44

The implementation of an operating system is completely up to its designers, and throughout the course we will look at some of the design decisions that must be made when creating an operating system.

In general, none of the implementation details of an operating system are visible to the programmer or user: these details are hidden behind the operating system's Application Program Interface. The API fixes the "look" of the operating system, as seen by the programmer.

This API, however, can be implemented by very different operating system designs. For example, Solaris, Linux and Minix all provide a POSIX API: all three systems have a very different operating system architecture.

We will examine the two most common operating system designs, the monolithic model and the client-server model.

2.8 The Monolithic Model

In the monolithic model, the operating system is written as a collection of routines, each of which can call any of the other routines as required. At build-time, each routine is compiled, and then they are all linked together to create a single program called the operating system *kernel*.

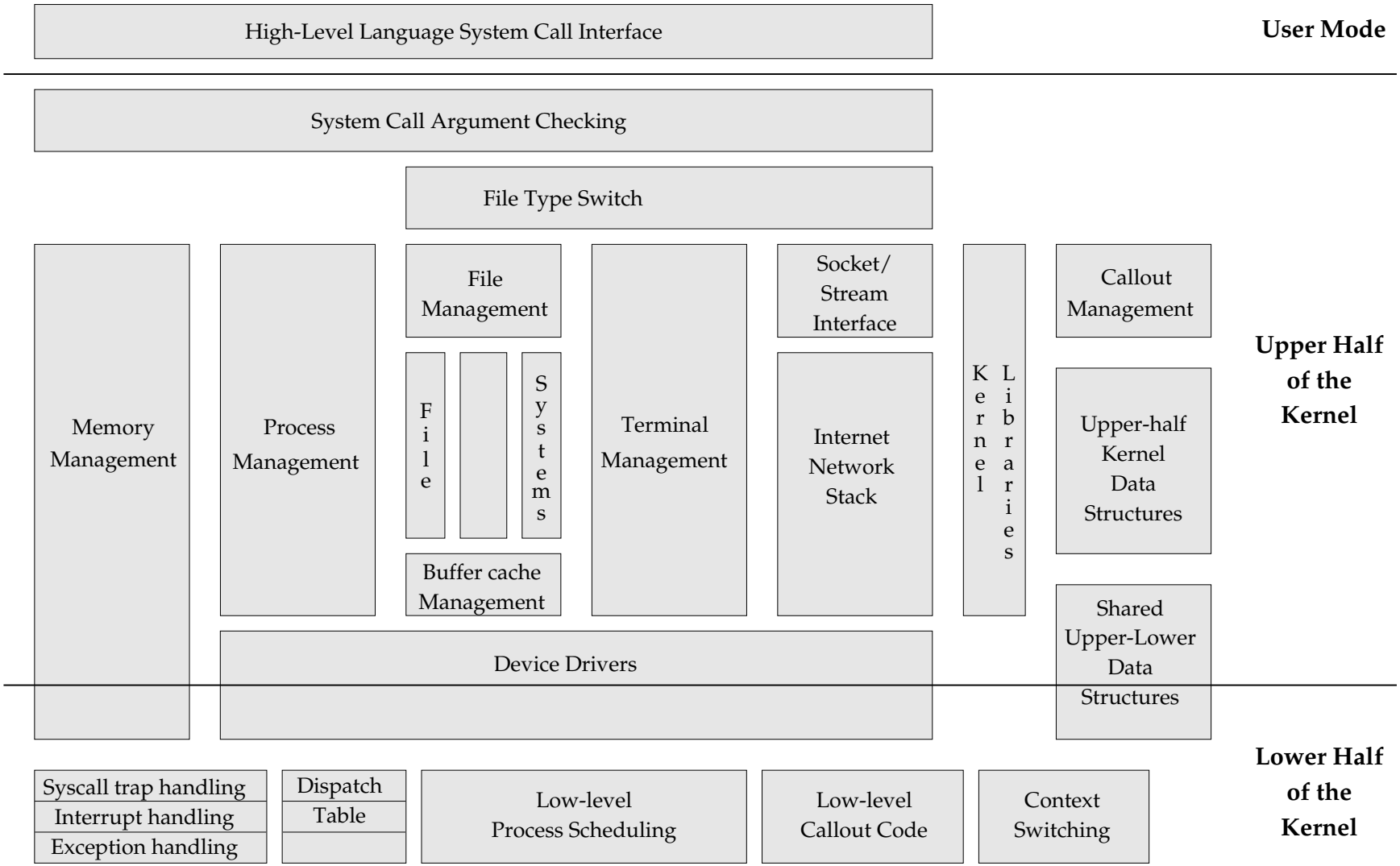
When the operating system is started, this kernel is loaded into the computer's memory, and runs in *kernel mode*. Most versions of Unix, including Linux, use the monolithic design model.

The monolithic design model suffers from the fact that every part of the operating system can see all the other parts; thus, a bug in one part may destroy the data that another part is using. Recompilation of the operating system can also be slow and painful.

To reduce this shortcoming, most designers place some overriding structure on their operating system design. Many of the routines and data structures are 'hidden' in some way, and are visible only to the other routines that need them.

An abstract map of Unix's architecture is shown in the diagram on the following page. As you can see, the functionality provided by the kernel is broken up into a number of sections. Each section provides a small number of interface routines, and it is these routines which can be used by the other sections.

Because Unix is monolithic, nothing stops one section of the operating system from calling another with *function calls*, or using another section's data. Each box is a set of C source files.



Overview of the Unix Kernel Architecture

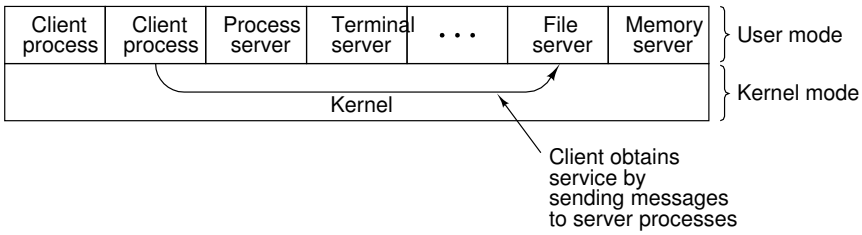
2.9 Client-Server Model

An alternative method of operating system design, called the client-server model, tries to minimise the chance of a bug in one part of the operating system from corrupting another part.

In this model, most of the operating system services are implemented as privileged processes called **servers**. Remember, each process is protected against interference by other processes. These servers have some ability to access the computer's hardware, which ordinary processes cannot.

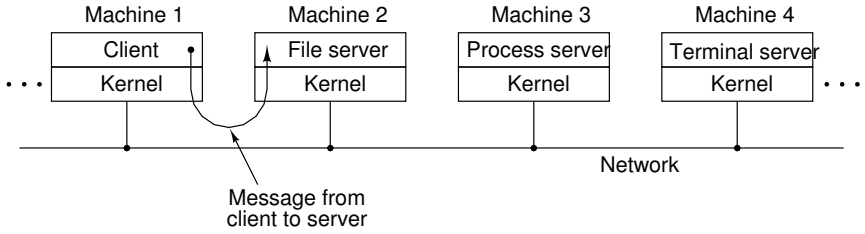
Ordinary processes are known as **clients**. These send requests in the form of **messages** to the servers, which do the work on their behalf and return a reply.

The set of services that the servers provide to the user processes thus form the operating system's Application Program Interface.



The messages sent between the clients and servers are well-defined 'lumps' of data. These must be copied between the client and the server. This copying can slow the overall system down, when compared to a monolithic system where no such copying is required. The servers themselves also may need to intercommunicate.

There must be a layer in the operating system that does message passing. This model can be implemented on top of a single machine, where messages are copied from a client's memory are into the server's memory area. The client-server model can also be adapted to work over a network or distributed system where the processes run on several machines.



Windows NT uses the client-server model, as shown in the diagram below. Most of the subsystems are privileged processes. The NT executive, which provides the message-passing capability, is known as a monolithic *microkernel*. Other client-server based operating systems are Minix and Plan 9.

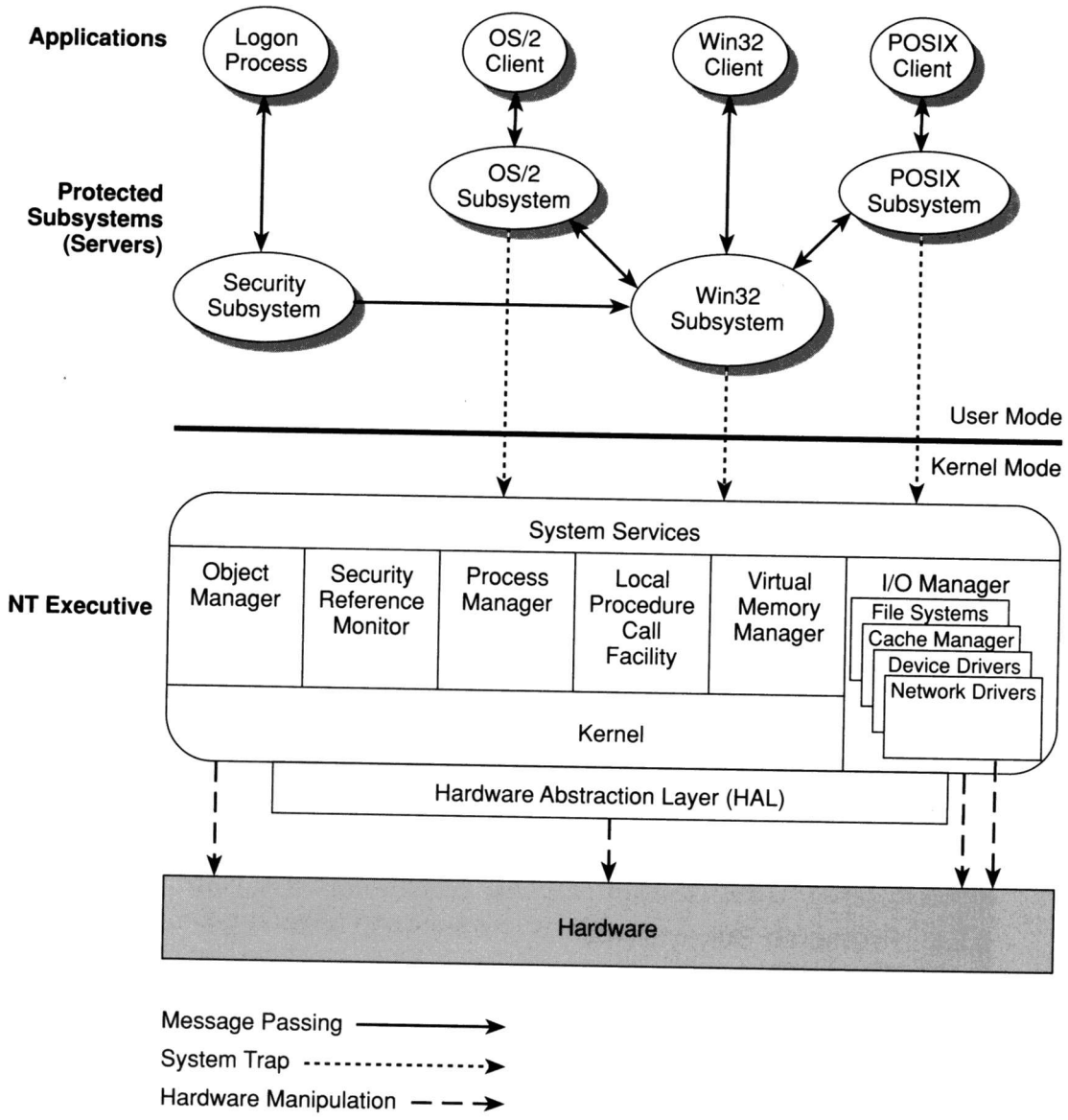


Figure 2-6. Windows NT Block Diagram

3 The OS/Machine Interface

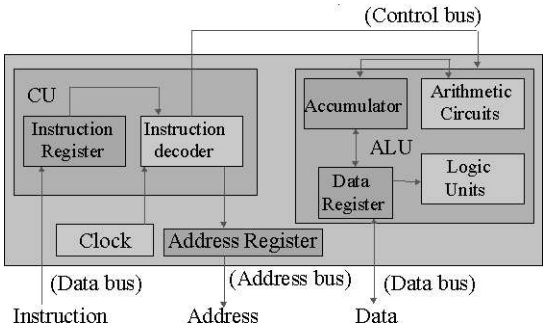
Textbook reference: Stallings ppg 9 – 38

The operating system must hide the physical resources of the computer from the user's programs, and fairly allocate these resources. In order to explore how this is achieved, we must first consider how the main components of a computer work.

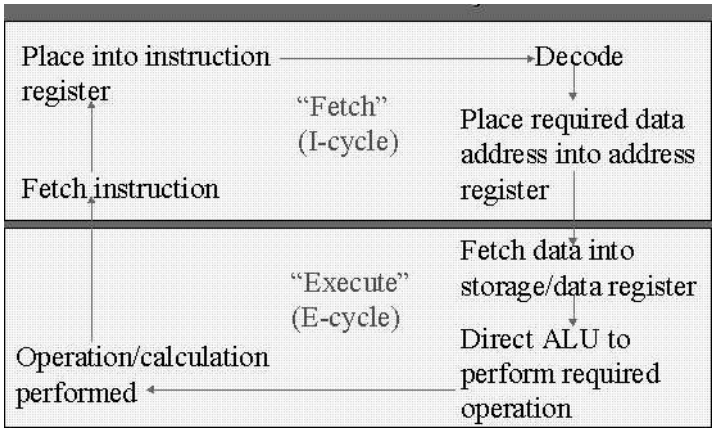
There are several viewpoints on how a computer works: how its electronic gates operate, how it executes machine code etc. We will examine the main functional components of a computer and their abstract interconnection. We will ignore complications such as caches, pipelines etc.

3.1 The CPU

The CPU is the part of the computer where *instructions* are executed, as shown below. We won't delve too much into the operation of the CPU in this course. However, you should note that the CPU contains a small amount of extremely fast storage space in the form of a number of *registers*.



In order to execute an instruction, the CPU must *fetch* a word (usually) from main memory and decode the instruction: then the instruction can be performed.



The *Program Counter*, or PC, in the CPU indicates from which memory location the next instruction will be fetched. The PC is an example of a register.

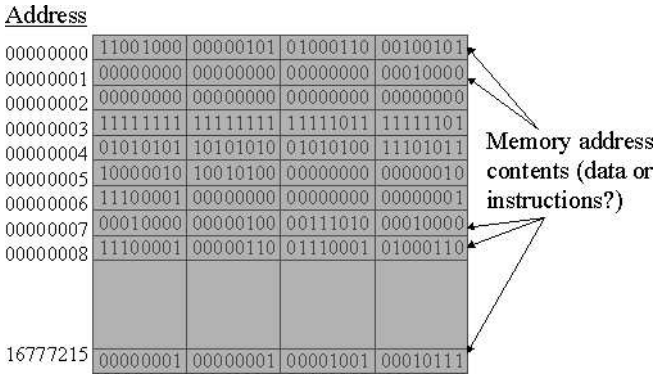
Some instructions may cause the CPU to read more data from main memory, or to write data back to main memory. This occurs when the data needed to perform the operation must be loaded from the main memory into the CPU's registers. Of course, if the CPU already has the correct data in its registers, then no main memory access is required, except to fetch the instruction.

As the number of internal registers is limited, data currently in a registers often has to be discarded so that it can be replaced by new data that is required to perform an instruction. Such a discard is known as a *register spill*.

3.2 Main Memory

The main memory is the storage place for the instructions which are being executed by the CPU, and also the *data* which is required by the running program. As we have seen, the CPU fetchs instructions, and sometimes data, from main memory as part of its normal operation.

Main memory is organised as a number of *locations*, each with a unique address, and each holding a particular value.



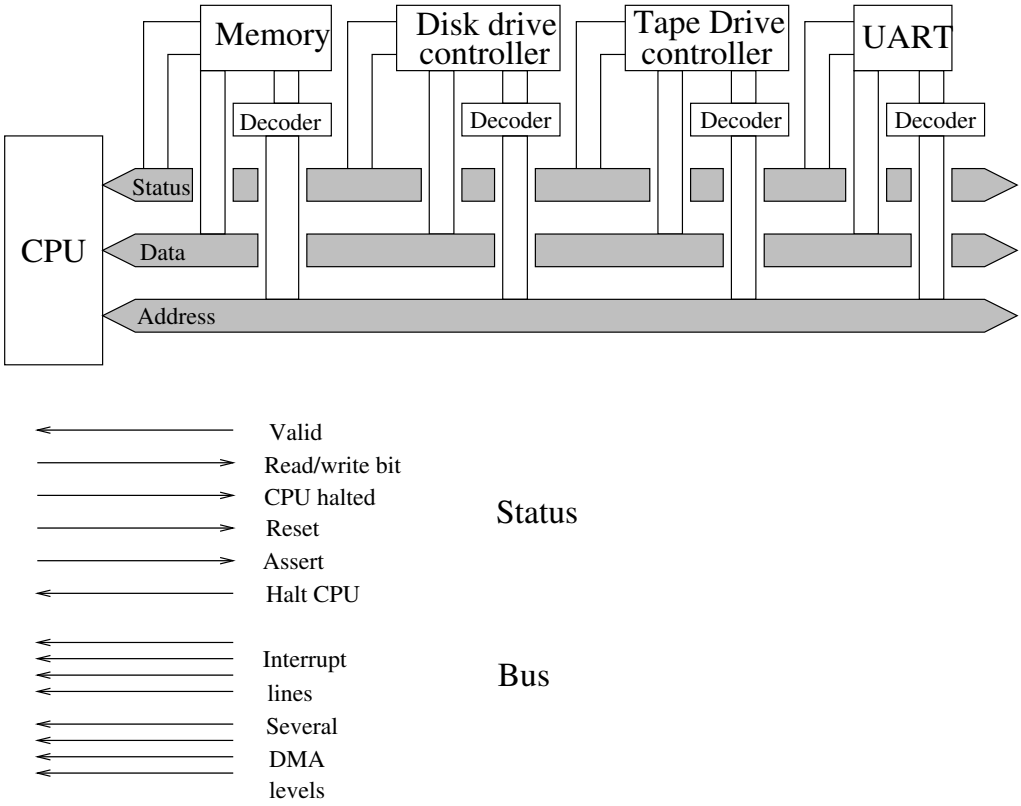
Main memory is typically composed of *Random Access Memory* (RAM), which means that the CPU can read from a memory location, or the CPU can *overwrite* the contents of a memory location with a new value. When registers are spilled, the CPU often saves the old register value into a location in the main memory. Main memory is also used to hold buffers of data which will be written out to permanent storage on the disk.

Parts of main memory may be occupied by *Read Only Memory* (ROM). Write operations to ROM are electrically impossible, and so the write has no effect on their contents.

3.3 Buses

The CPU and main memory are connected via three buses:

- The *address bus*, which carries the address in main memory which the CPU is accessing. Its size indicates how many memory locations the CPU can access. A 32-bit address bus allows 2^{32} address locations, giving 4 Gigbytes of addressable memory.
- The *data bus*, which carries the data being read to/from that address). Its size indicates the natural data size for the machine. A 32-bit machine means that its data bus is 32-bits wide.
- The *status bus*, which carries information about the memory access and other special system events to all devices connected to the three buses.



Here is how an instruction is fetched from main memory:

- The CPU places the value of the program counter on the address bus.
- It asserts a 'read' signal on the read/write line (part of the status bus).
- Main memory receives both the address request and the type of request (read).
- Main memory retrieves the value required from its hardware, and places the value on the data bus. It then asserts the 'valid address' line on the status bus.
- Meanwhile, the CPU waits a period of time watching the 'valid address' line.
- If a 'valid address' signal is returned, the value (i.e the next instruction) is loaded off the data bus and into the CPU.
- If no 'valid address' returned, there is an error. The CPU will perform some exceptional operation instead.

Read accesses for data, and the various write requests, are performed in a similar fashion. Note that main memory needs an address *decoder* to work out which addresses it should respond to, and which it should ignore. Most computers don't have their entire address space full of main memory. This implies that reads or writes to certain memory locations will always fail.

Here are some example computers and their address & data bus sizes:

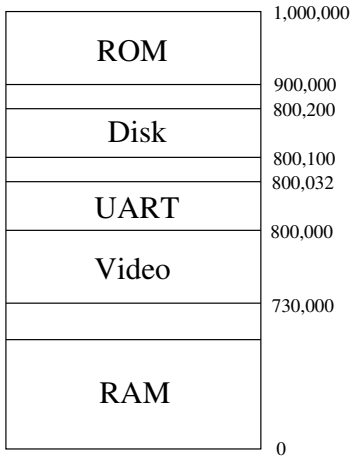
Computer	Address Bus	Data Bus
IBM XT	20-bit	8-bit
IBM AT	24-bit	16-bit
486/Pentium	32-bit	32-bit
68030/040	32-bit	32-bit
Sparc ELC	32-bit	32-bit
DEC Alpha	64-bit	64-bit

3.4 Peripheral Devices

Textbook reference: Tanenbaum & Woodhull ppg 154 – 157

The computer must be able to do I/O, so as to store data on long-term storage devices, and to communicate with the outside world. However, we don't want the CPU to be burdened with the whole task of doing I/O, i.e controlling every electrical & mechanical aspect of every peripheral. Therefore, most devices have a *device controller* which takes device commands from the CPU, performs them on the actual device, and reports the results (and any data) back to the CPU.

The CPU communicates with the device controllers via the three buses. Therefore, the controllers usually appear to be memory locations from the CPU's point of view. Each device controller has a **decoder** which tells the device if the asserted address belongs to that device. If so, parts of the address and the data is written to/from the device. Usually, this means that the device controller is **mapped** into the computer's address space. And because main memory has its own decoder, we can say that the locations in main memory are also mapped into the computer's address space:



I/O Decoding Addresses

In the diagram above, the UART (serial I/O) controller decodes addresses 800,000 to 800,031, which is 32 addresses. It ignores addresses outside this region, and the decodes passes values 0 to 31 to the controller, when the address is inside the region.

Assume this UART uses the following addresses:

Decoded Location	Real Location	Use of this location	Format of this location
0	800,000	Output format	Speed (4), Parity (2), Stop bits (2)
1	800,001	Output status register	
2	800,002	Output character	
3	800,003	Input format	Speed (4), Parity (2), Stop bits (2)
4	800,004	Input status register	
5	800,005	Input character	

These special addresses are known as **device registers**, and are similar to the registers inside a CPU. To output a character, first the operating system must set up the output characteristics:

- CPU asserts the address 800,000 on the address bus
- It places a word of data onto the data bus. This describes the format of output to be used by the UART.
- It asserts 'write' on the r/w line.

- It waits a period of time.
- If no 'valid address' returned, error.

Then, to output a character, the character is sent to 800,002 as above. The UART *latches* the character, and it is transmitted over the serial line at the bit rate set in the output format.

Input from a device is more complicated. There are three types: polling, interrupts, and direct memory access (DMA). We will leave DMA until later.

With **polling**, the UART leaves the input character at the address 800,005 and an indicator that a character has arrived at the address 800,004. The CPU must periodically scan (i.e read) this address to determine if a character has arrived. Because of this periodic checking, polling makes multitasking difficult if not impossible: the frequent reading cannot be performed by the operating system if a running program has sole use of the CPU.

> **poll**: v.,n. 1. [techspeak] The action of checking the status of an input line, sensor, or memory location to see if a particular external event has been registered. 2. To repeatedly call or check with someone: "I keep polling him, but he's not answering his phone; he must be swapped out."

3.5 Interrupts

An alternative way for the operating system to find out when input has arrived, or when output has been completed, is to use **interrupts**. If a computer uses interrupts for I/O operations, a device will assert an *interrupt line* on the status bus when an I/O operation has been completed. Each device has its own interrupt line.

For example, when a character arrives, the UART described above asserts its interrupt line. This sends a signal in to the CPU along the status bus. If the interrupt has priority greater than any other asserted interrupt line, the CPU will stop what it is doing, and jump to an **interrupt handler** for that line. This interrupt handler is a section of machine code places at a fixed location in main memory.

Here, the interrupt handler will collect the character, do something with it and then return the CPU to what it was doing before the handler started i.e the program running before the interrupt came in. Generally speaking, interrupt handlers are a part of the operating system.

Interrupts are prioritised. The CPU is either running the current program, or dealing with the highest interrupt sent in from devices along the status bus. If an interrupt's priority is too low, then the interrupt will remain asserted until the other interrupts finish, and the CPU can handle it. Alternatively, if a new interrupt has a priority higher than the one currently being handled by the CPU, then the CPU diverts to the new interrupt's handler, just as it did when it left the running program.

The CPU has an internal status register which holds the value of the current interrupt being handed. Normal programs run at a level below the lowest interrupt priority.

3.6 Interrupt Vectors

To ensure that the CPU goes back to what it was doing, old values of the **program counter** are *stacked* in interrupt-level order somewhere. Each time an interrupt handler is called, the **program counter**'s value is stacked, and the PC is set to the address of the first instruction in the interrupt handler.

The last instruction in an interrupt handler must unstack an old PC value, and put it back into the **program counter**. All CPUs have a special instruction (often known as *ReTurn from Interrupt* or RTI) which does the unstacking.

Each interrupt level has its own interrupt handler. How does the CPU know where each handler is stored in main memory? A table of *vectors* is kept in main memory for each interrupt level. It holds the address of the first instruction in the appropriate interrupt handler.

Address	Holds Address Of	For Example
0	Reset Handler	1,000,870
1	IRQ 1 - Keyboard	1,217,306
2	IRQ 2 - Mouse	1,564,988
15	IRQ 15 - Disk	1,550,530
16	Zero Divide	1,019,640
17	Illegal instruction	1,384,200
18	Bad mem access	1,223,904
19	TRAP	1,758,873

The above fictitious table shows where the vectors might be stored in main memory, their value (i.e where the first address of each interrupt handler is), and what interrupt is associated with each.

Most CPUs keep vectors for other 'abnormal' events, such as the attempt to execute an illegal instruction, to access a memory location which doesn't exist etc. These events are known as **exceptions**. If any of these exceptions occur, the CPU starts running the appropriate handler for the error.

All vectors should point to interrupt handlers within the operating system, and not to handlers written by users. Why?

3.7 The OS vs The User

The operating system must hide the actual computer from the users and their programs, and present an abstract interface to the user instead. The operating system must also ensure fair resource allocation to users and programs. The operating system must shield each user and her programs from all other users and programs.

Therefore, the operating system must prevent all access to devices by user programs. It must also limit each program's access to main memory, to only that program's memory locations.

These restrictions are typically built into the CPU (i.e into unchangeable hardware) as two operating modes: user and kernel mode. In **kernel mode**, all memory is visible, all devices are visible, all instructions can be executed. The operating system must run in kernel mode, why? In **user mode**, all devices are hidden, and most of main memory is hidden. This is performed by the *Memory Management Unit*, of which we will learn more later. Instructions relating to device access, interrupt handling and mode changing cannot be executed either.

When user programs run, the operating system forces them to run in user mode. Any attempt to violate the user mode will cause an *exception*, which starts an interrupt handler running. Because the interrupt handler is part of the operating system, the operating system can thus determine when user mode violations have been attempted.

Every interrupt or exception causes the CPU to switch from its current mode into kernel mode. Why? The previous mode is stacked so that the correct mode is restored when an interrupt handler finishes.

Finally, because a user program runs in user mode and can only see its own memory, it cannot see the operating system's instructions or data. This prevents nosy user programs from subverting the working of the operating system.

3.8 Traps and System Calls

Textbook reference: Tanenbaum & Woodhull ppg 37 – 38

If the operating system is protected, how does a program ask for services from the OS? User programs can't call functions within the operating system's memory, because it can't see those areas of memory.

A special user-mode machine instruction, known as a **TRAP** instruction, causes an exception, switches the CPU mode to **kernel mode**, and starts the handler for the TRAP instruction.

To ask for a particular service from the operating system, the user program puts values in machine registers to indicate what service it requires. Then it executes the TRAP instruction, which changes the CPU mode to privileged mode, and moves execution to TRAP hander in the operating system's memory.

The operating system checks the request, and performs it, using a **dispatch table** to pass control to one of a set of operating system service routines.

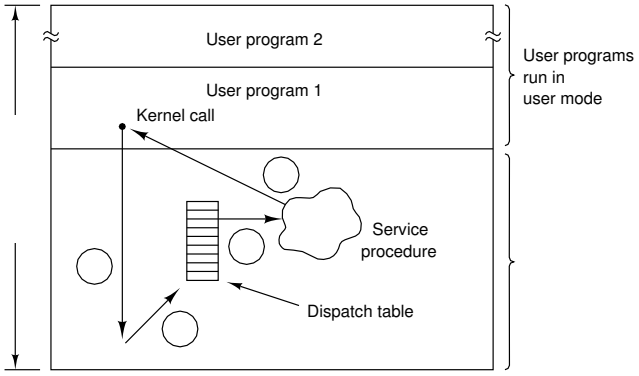


Figure 1-16. How a system call can be made: (1) User program traps to the kernel. (2) Operating system determines service number required. (3) Operating system calls service procedure. (4) Control is returned to user program.

When the service has been performed, the operating system returns control to the program, lowering the privileges back to user-mode. Thus, the job only has access to the privileged operating system via a single, well-protected entry point.

This mechanism for obtaining operating system services is known as a **system call**. The set of available system calls is known as that operating system's **Application Program Interface** or API.

trap: 1. n. A program interrupt, usually an interrupt caused by some exceptional situation in the user program. In most cases, the OS performs some action, then returns control to the program. 2. vi. To cause a trap. "These instructions trap to the monitor." Also used transitively to indicate the cause of the trap. "The monitor traps all input/output instructions."

4 Operating System History and Evolution

Textbook reference: Stallings ppg 58 – 68; Tanenbaum & Woodhull ppg 5 – 13

The history and development of operating systems is described in some detail in the textbook. We will only cover the highlights here.

4.1 1st Generation: 1945 – 1955

The first computers were built around the mid 1940's, using vacuum tubes. On these computers, a program's instructions were hard-wired. The computer needed to be manually rewired to change programs. The MTBF for these machines was on the order of hours.

These 1st generation machines were programmed by individuals who knew the hardware intimately, in machine code, Later, assembly code was developed to make the programming slightly easier. There was no mode disctinctions; effectively, all instructions ran in privileged mode.

At the time, machines had no operating system: you wrote all the code yourself, or used other programmers routines. Eventually, groups of people developed *libraries* of routines to help the task of programming.

You usually had to book time slots to use the computer. Often the slot was too short. Sometimes (if your program worked), the slot was too long. This of course led to CPU wastage.

Most early programs were numerical calculations, and very CPU-intensive. The early 1950s saw the introduction of punched cards to speed programming.

bare metal: n. 1. New computer hardware, unadorned with such snares and delusions as an operating system, a high-level language, or even an assembler. Commonly used in the phrase 'programming on the bare metal', which refers to the arduous work needed to create these basic tools for a new machine. Real bare-metal programming involves things like building boot proms and BIOS chips, implementing basic monitors used to test device drivers, and writing the assemblers that will be used to write the compiler back ends that will give the new machine a real development environment.

Stone Age: n., adj. 1. In computer folklore, an ill-defined period from ENIAC (ca. 1943) to the mid-1950s; the great age of electromechanical dinosaurs, characterised by hardware such as mercury delay lines and/or relays.

4.2 2nd Generation: 1955 – 1965

The introduction of the transistor made computers more reliable. It was now possible for companies to sell/lease the computers they built to 3rd parties. Computers were used more efficiently by employing people to run the machines for the customer. High-level languages such as FORTRAN and COBOL invented, which made programming much easier and somewhat more portable.

To run a program, a user would punch their code/data onto cards, give the deck of cards to operators, who would feed them to the computer, and return printout/new cards to user. Each program run was known as a *job*. Doing this this way made programs hard to debug due to the slow turnaround, but meant that the CPU was utilised more. However, the CPU still sat idle between jobs.

The next idea was to **batch** similar jobs to make the execution faster, e.g all FORTRAN jobs. Similar jobs were batched and copied from card to magnetic **tape**. The tape was then fed to the computer, and output also sent to tape, converted to printout.

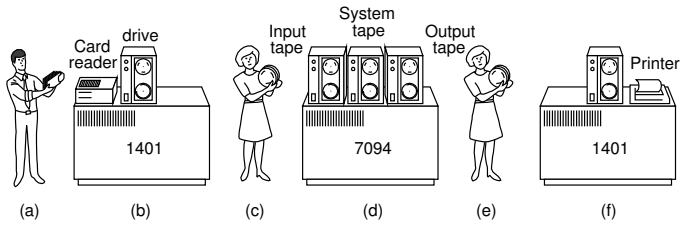


Figure 1-2. An early batch system. (a) Programmers bring cards to 1401. (b) 1401 reads batch of jobs onto tape. (c) Operator carries input tape to 7094. (d) 7094 does computing. (e) Operator carries output tape to 1401. (f) 1401 prints output.

CPU was thus less idle as the tape could be read/written to faster than the punched cards. However, the CPU was still mostly idle when reading from or writing to the tape.

Whyis this? Reading a piece of data from main memory is very quick, because it is completely electronic. Reading the same piece of data from tape is much slower, as the tape is a mechanical device. Punched cards are even slower.

The first basic operating system performed batch operations: for each job on the input tape load the job, run it, send any output to a second tape, and move onto the next job. Because the operating system must keep its instructions in main memory to work, it had to be **protected** to prevent itself from being destroyed by the jobs that it was loading and running. In this generation, the jobs were mainly scientific and engineering calculations.

Bronze Age: n. 1. Era of transistor-logic, pre-ferrite-core machines with drum or CRT mass storage.

4.3 3rd Generation: 1965 – 1980

In the 3rd Generation, integrated circuits (ICs) make machines smaller and more reliable, although they were initially more expensive. Companies found they outgrew their machines, but each model had different batch systems. This meant that each change of computer system involved a recoding of jobs and retraining of operators.

To alleviate these problems, IBM decided to create a whole *family* of machines, each with a similar hardware architecture, with a single operating system that ran on every family member. This was the System/360 family, and OS/360. OS/360 ran to millions of lines of code, with a constant number of bugs, even in new system releases.

Computer usage moved away from purely scientific work to business work e.g inventories. These type of jobs were more I/O intensive (lots of reading/writing on tape). The CPU became idle waiting for the tape while processing these I/O intensive jobs, and so CPU utilisation dropped again.

The solution to the problem of CPU utilisation on I/O jobs was **multiprogramming**:

- Have >1 jobs in memory, each protected from the others.
- As one job goes idle waiting for I/O, the operating system can switch to another job which is waiting for the CPU. Alternatively, the operating system could start up another job if no current jobs are waiting for the CPU.

This could give over 90% CPU utilisation, but with some overhead caushed by the switching between jobs. To improve performance further, disks were used to **cache/spool** jobs (i.e both the programs to execute and their associated data). Disks were faster to access than tape, especially for **random access** where the data is accessed in no particular order from the disk.

These system still suffered from slow job turnaround: the users had to wait for a job to run to termination (or crash) before they could do any reprogramming.

Iron Age: n. In the history of computing, 1961–1971 — the formative era of commercial mainframe technology, when big iron dinosaurs ruled the earth. These began with the delivery of the first PDP-1, coincided with the dominance of ferrite core, and ended with the introduction of the first commercial microprocessor (the Intel 4004) in 1971.

4.4 Timesharing

A method of overcoming the slow job turnaround was introduced at this point *timesharing*. on a timesharing system, the operating system swapped very quickly between jobs (even if the current job was still using the CPU), allowing input/output to come from users on terminals instead of tape or punched cards.

This switching away from a job using the CPU is known as *pre-emption*, and is the hallmark of an interactive operating multiprogramming operating system. The Multics operating system was designed at this time, to support hundreds of users simultaneously. Its design was good, and introduced many new ideas, but was very expensive hardware-wise, and fizzled out with the introduction of minicomputers.

Multics: n. [from "MULTiplexed Information and Computing Service"] A late 1960s timesharing operating system co-designed by a consortium including MIT, GE, and Bell Laboratories. Very innovative for its time — among other things, it introduced the idea of treating all devices uniformly as special files. All the members but GE eventually pulled out after determining that second-system effect had bloated Multics to the point of practical unusability. One of the developers left in the lurch by the project's breakup was Ken Thompson, a circumstance which led directly to the birth of UNIX.

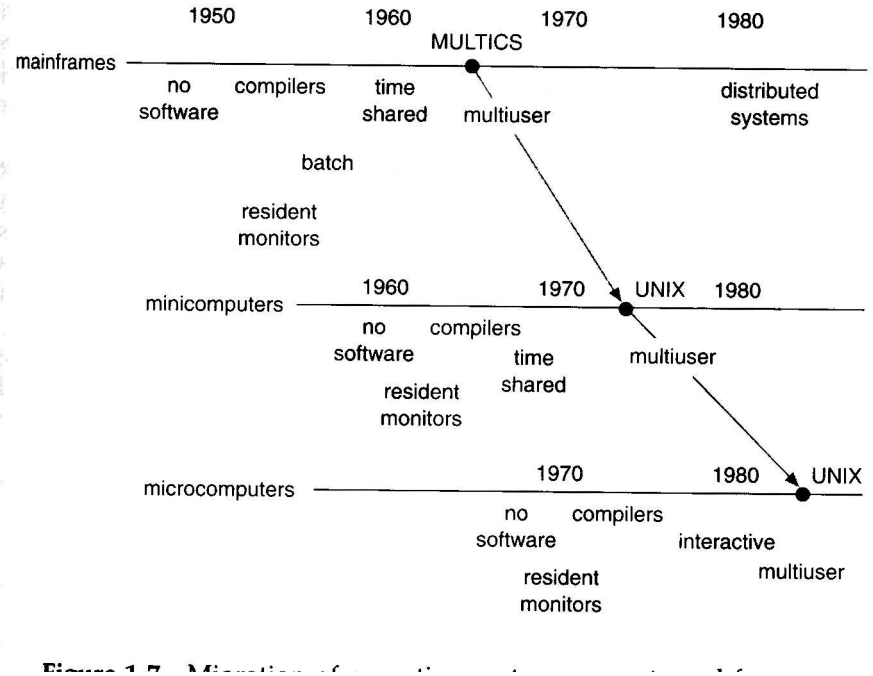
4.5 3rd Generation – Part 2

Minicomputers arrived, introduced with the PDP-1 in 1961. These machines were only 5% the cost of mainframes, but gave about 10% – 20% of their performance. These made minicomputers affordable to individual departments, not just to large companies.

Although Multics died, many of its ideas were passed on to Unix. Unix was mostly written in a high-level language called 'C', thus aiding **ports** to new hardware. In fact, it was one of the first portable operating systems.

Both minicomuters and mainframes got faster/cheaper and minis picked up more mainframe operating system ideas as time went on.

4.6 4th Generation: 1980 onwards



Microcomputers brought computers to individuals. They began by using the 1st generation operating system ideas, but have been catching up ever since. Networking was introduced, allowing machines to be connected over small/large distances. Operating systems had functionality added to allow the files (or other services) of machines to be accessible by other machines over the network. Such systems are known as *network operating systems*.

In another approach to using the connectivity provided by a network, *distributed operating systems* were created. These make all the machines on a network appear to be part of *one* single machine.

Because of the immense power of the new machines, the emphasis on software design shifted away from system performance and efficiency to user interface and applications.

killer micro: n. A microprocessor-based machine that infringes on mini, mainframe, or supercomputer performance turf. Often heard in "No one will survive the attack of the killer micros!", the battle cry of the downsizers. Used esp. of RISC architectures.

5 Processes

Textbook reference: Stallings ppg 107 – 147; Tanenbaum & Woodhull ppg 47 – 52

5.1 What is a Process?

The primary function of an operating system is to provide an environment where user programs can run. The operating system must provide a framework for program execution, a set of services (file management etc.) and an interface to these services. On a multiprogramming system, the operating system must also ensure that the many programs loaded into memory do not interfere with each other.

This restricted form of program execution, with access to the services of the operating system, is known as a *process*. Specifically, a process is a sequence of computer instructions executing in an *address space*, with access to the operating system services. An address space is an area of main memory to which the process has exclusive access.

The process consists of: the machine code instructions in main memory, a data area and a stack in main memory, and the CPU's registers which the process uses while it is using the CPU.

The data area holds the process' global data, e.g the internal memory representation of a word processor document. The stack usually holds the process' local data e.g local variables in functions and subroutines, plus program counters for subroutine returns.

5.2 The Process Environment

As noted before, the operating system ensures that a process lives in a **protected** environment: it is protected against any interference from other processes currently in main memory. The operating system also prevents a process from seeing or altering other processes, and of course the operating system itself.

This is achieved by running all of the machine code instructions of all processes in user mode. In this mode, certain privileged machine instructions are 'disabled', areas of memory not owned by a process are made invalid, and access to all hardware is prevented by the CPU.

5.3 System Calls

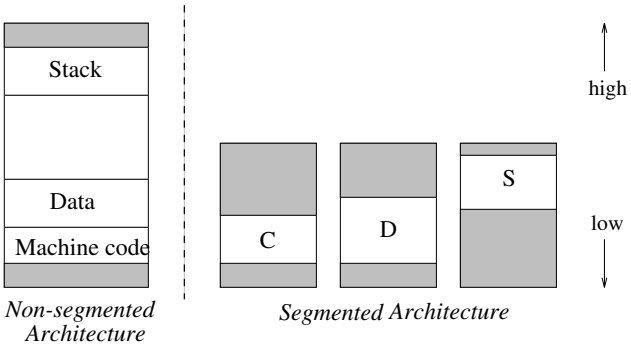
If the process can execute its instructions and read/write its data, but nothing else, how does it actually do anything useful, like read from a file, get mouse movements etc.? There needs to be a mechanism to allow a process to ask for specific services from the operating system, without compromising the protected environment that constrains the process.

This is achieved by a special instruction built into the CPU: the *TRAP* instruction. A process accesses the services of the operating system by using the TRAP instruction, which passes execution directly from the process to the operating system. Information placed in the CPU's registers by the process tells the operating system what service the process wants. This mechanism of obtaining services via a TRAP instruction is known as a **system call**.

Each operating system has its own set of available system calls. The set of available system calls is known as that operating system's **Application Program Interface** or API.

5.4 Layout of a Process

A typical Unix process memory map looks like the following:

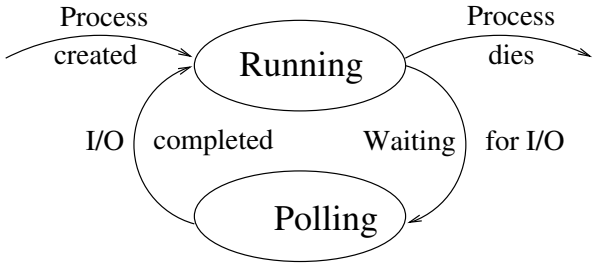


Memory map is another term for 'address space'. The memory map allows the stack to grow down and the data area to grow up: in other words, the process is able to use more main memory that the operating system initially allocates. Areas above or below the process' memory are invalid because of protections set by the operating system; they usually contain other processes. On some machine architectures, such as segmented architectures, the three sections are separated.

5.5 Process Models

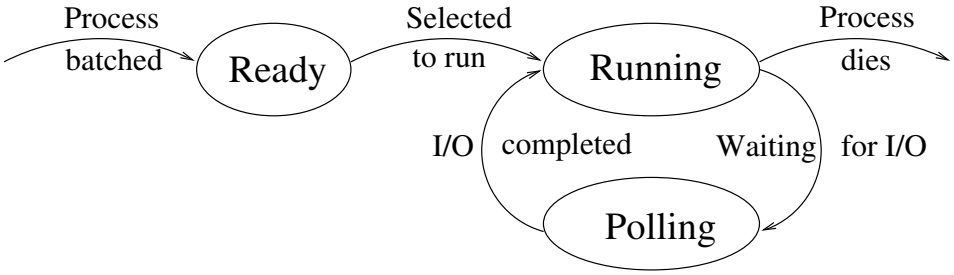
Although I've said a process is in memory and doing something, often a process can't do anything, either because another process is running or it is waiting for I/O. A **state diagram** shows what states a process can be in, and how it moves to new states.

On a **simple monitor** system, only one process in memory at any one time. Therefore the process in memory is either running, or idle waiting for I/O.

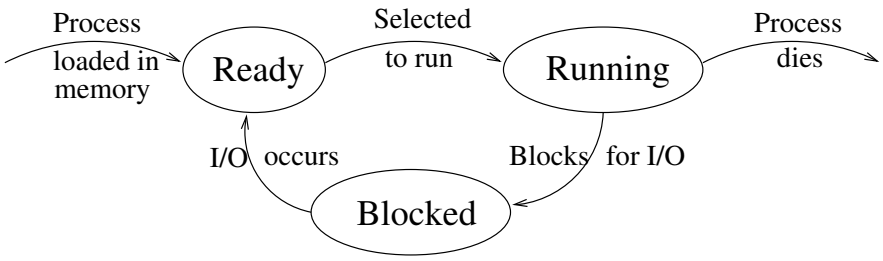


The word 'idle' is a misnomer; because there is only one process loaded on a simple monitor, either the operating system or the process itself is repetetively querying a device to see if the I/O has completed. This technique is called *polling*. As you would imagine, polling is very wasteful of the CPU resources.

A **batch** system may have many processes (jobs) in memory simultaneously, but when one is started, it *runs to completion* before the next can begin running. Polling is still used by the operating system to detect the completion of I/O.



To reduce the waste of the CPU resource by polling, on some batch systems the processes *run to block*. Instead of waiting for I/O, the operating system **blocks** the process (puts it to sleep), and selects another ready-to-run process to run.



When the I/O is finished, the operating system finds which sleeping process requested the I/O, delivers any incoming data (if required), and moves the process from the **blocked** state to the **ready** state, as it can now execute more instructions.

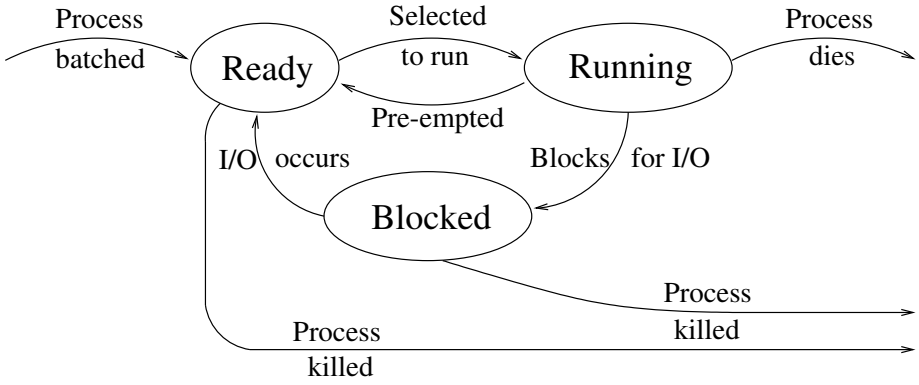
As we saw in a previous lecture, in this situation an *interrupt* from the hardware would have told the operating system that the I/O operation had finished.

There can be more than one process in the ready state, and more than one process in the blocked state, but as there is only one CPU, there can only be **one** process in the running state. On multiprocessor systems, there can be up to one running process per CPU.

Question: Why is this type of system unsuitable for interactive use? Think about this for a minute or two before going on to the next paragrah.

It is unsuitable for interactive use for the following reason. Imagine a word processor process which was blocked waiting for some keyboard input from the user. Once the user types a key, an interrupt informs the operating system that some input is available. The operating system delivers this to the word process, and moves it to the ready state. At this point, there is **no** guarantee that this process will ever run. If a CPU-bound process (i.e one that never does any I/O) is currently running, then it will never relinquish the CPU and allow the word processor to run.

The solution here is simple. On an interactive **multiprogramming** system, the system may **pre-empt** a running process to allow fast and fair use of the computer. Periodically, the operating system takes the running process off the CPU, puts it back on the ready queue, and selects another ready process to move to the running state. Thus, although the CPU is running only one process at any time, the quick switching between processes makes it appear as if many are running simultaneously.



The characteristic of an interactive operating system is the transition from 'Running' to 'Ready'.

5.6 How the Operating System Deals with System Calls

In a pre-emptive multitasking operating system, processes don't see the pre-emption, and system calls appear to happen instantaneously. A process cannot 'see' the period of time when it is not running, because it doesn't execute any instructions during this period.

The **top-half** of the operating system deals with system call requests from the running process. This part of the operating system knows that system calls, especially those dealing with I/O, may take some time.

Therefore, instead of *busy-waiting* or polling, the top-half blocks the process until the operation completes. In other words, the state of the running process is changed to blocked, and the operating systems chooses another running process from the ready queue.

The **bottom-half** of the operating system reacts to all of the interrupts sent by the various devices. These tell the operating system that I/O is done. The bottom half finds the blocked process that asked for the I/O operation, changes its state from blocked to ready, and returns back to the currently running process.

To summarise, the *process*:

- lives in a transparently pre-emptive scheduling environment,
- cannot block itself, and
- can be scheduled by the operating system.

The *top-half* of the operating system:

- is only used when a system call is performed by a process,
- is never scheduled (it isn't a process), and
- runs until the system call is done, or blocks the calling process.

The *bottom-half* of the operating system:

- reacts to hardware interrupts,
- is never scheduled (it isn't a process),
- can never be blocked or stopped, and
- wakes up the blocked process, making it ready to run.

5.7 Process Control Blocks

Textbook reference: Tanenbaum & Woodhull ppg 52 – 53

When the operating system moves a process from the running state, it must ensure that the process' bits and pieces are kept so it can be restarted. This means that the operating system must:

- Preserve the process' areas of memory,
- Protect these from other processes,
- Save copies of the CPU registers used by the process,
- Save information about any other resources used,
- Mark the process' new state, and
- If blocked, record which I/O operation the process is blocked on. so when I/O completes, the process can be moved back to 'Ready'.

All of this information is stored in the **Process Control Block** in the operating system. There is one Process Control Block per process, and it usually contains several sections:

- **Machine dependent section:**
  - Register copies
  - Information about the process' memory areas
- **Machine independent section:**
  - The process' state

  - The process' priority, other scheduling information
  - Open files and their state
  - The process id
  - The user id of the user running the process
  - On what the process is blocked

- **Statistics section:**
  - Total time the process has been running, etc.

The above is an example only of the possible types of information that must be recorded. Each operating system stores different things in its PCBs. The statistics section is used to aid the operating system in deciding how/when to allocate resources to the process, as will be seen in future lectures.

An example PCB (from Minix) is:

Process management	**Memory management**	**File management**
Registers	Pointer to text segment	UMASK mask
Program counter	Pointer to data segment	Root directory
Program status word	Pointer to bss segment	Working directory
Stack pointer	Exit status	File descriptors
Process state	Signal status	Effective uid
Time when process started	Process id	Effective gid
CPU time used	Parent process	System call parameters
Children's CPU time	Process group	Various flag bits
Time of next alarm	Real uid	
Message queue pointers	Effective	
Pending signal bits	Real gid	
Process id	Effective gid	
Various flag bits	Bit maps for signals	
	Various flag bits	

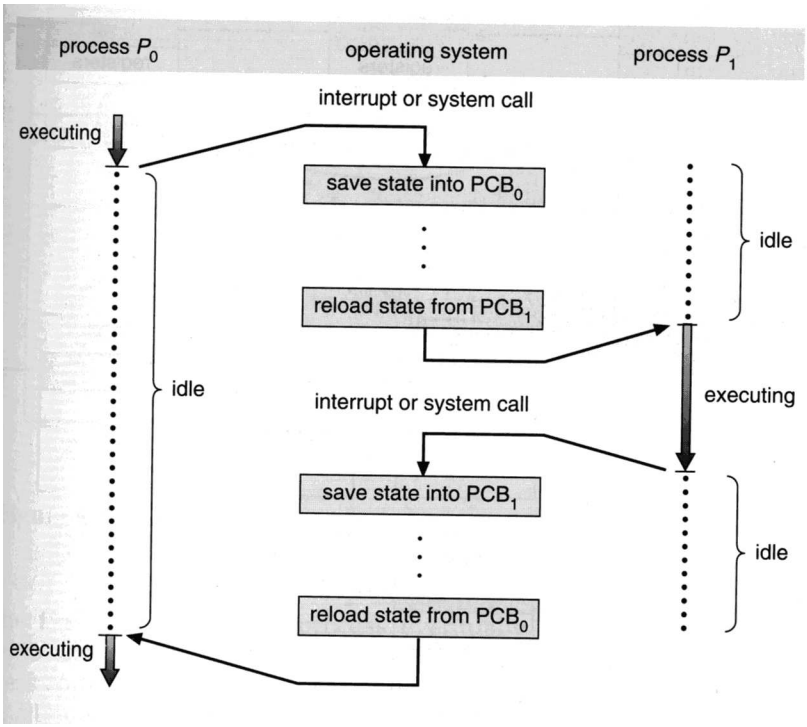
Figure 2-4. Some of the fields of the MINIX process table.

5.8 Context Switching

Once a process has moved out of the ready state, the operating system must choose a ready process to run. It must perform the reverse operation, i.e:

- Enable the process' areas of memory,
- Reload the registers used by the process,
- Mark the process' new state as running,
- Start the process from where it left off, and
- Return the result of any system call to the process.

The operation of changing running processes is known as a **context switch**, and often has a significant overhead (typically hundreds of machine instructions). This goes against the philosophy of operating system design which tries to minimise the number of instructions not used by user processes.



6 Process Scheduling

Textbook reference: Stallings ppg 391 – 425; Tanenbaum & Woodhull ppg 82 – 93

6.1 Introduction

On a batch or multiprogramming system, there is usually a queue of processes blocked waiting for I/O, and a queue of processes waiting to run. There is only ever 0 or 1 processes actually running. Context switching between processes in the ready queue and the running position takes the operating system some time, thus wasting resources that could be used by user processes.

Operating systems **schedule** processes in order to try and achieve certain goals:

a) Fairness: each process gets a fair share of the CPU.

b) Efficiency: keep the CPU as busy as possible.

c) Response time: minimise response time for interactive users.

d) Turnaround time: maximise the number of jobs processed per hour.

However, not all of these can be satisfied at the same time, because the CPU is a finite resource. For example, to satisfy goal d), you would process only batch jobs and never do any pre-emptions, to minimise switching time; this unfortunately would violate goal c).

Some schedulers use **run to block/completion** scheduling: wait until a process blocks or dies before rescheduling. This is only useful on batch systems, as the running process may not block for days if it is CPU-bound.

Other schedulers use **pre-emptive** scheduling, and suspend the running process after a period of time known as the process' **quantum** or **timeslice**. This allows other processes to run, even if the original process hadn't blocked. Pre-emption is needed for interactive systems.

6.2 Scheduling Algorithms – Interactive (Pre-emption)

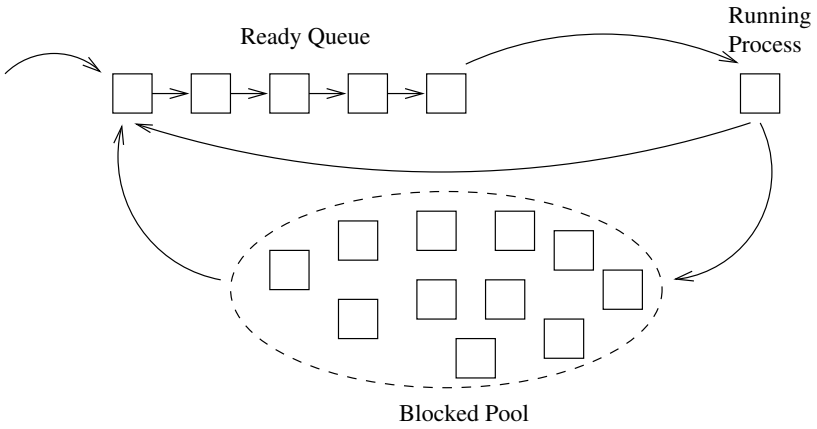
There are several algorithms available to choose a process from the list of ready-to-run processes when the running state has been vacated. Each one reflects a certain system policy for process scheduling. Each algorithm has its advantages and disadvantages. Wee will look at:

- First Come First Served/Round Robin
- Timeslice Priority
- Multiple Priority Queues
- Long Term Schedulers

6.3 First Come First Served/ Round Robin

This scheduling algorithm works as follows:

- Created processes are put on the tail of the **ready queue**.
- When the running process blocks, move it to the **blocked pool**.
- As each process unblocks, place it at the tail of the ready queue.
- Alternatively, when the running process is pre-empted, place it at the tail of the ready queue.
- When the running state is vacant, move the process at the head of the ready queue to the running state.



This scheduling algorithm is easy to implement, but has one big disadvantage: one **CPU-bound** process will hog the CPU, thus reducing the overall **throughput**.

How can this happen? It should be obvious that all processes will get equal opportunity to enter the running state. However, once there, CPU-bound processes will use up all of their *timeslice*, whereas processes that do lots of I/O will block, giving up the CPU to another processes. They must then cycle through the blocked state before they can get back to the ready state. Small **I/O bound** processes therefore tend to wait in the ready state for the CPU-bound process to give up the CPU.

6.4 Timeslice Priority

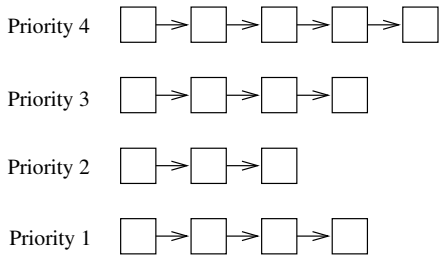
One solution to this is timeslice priority. In this algorithm, the operating system gives a process a timeslice according to a static priority. For example, lecturers' processes may have priority 4, tutors with priority 3, students with priority 2 and long-term CPU jobs with priority 1. The operating system looks up the priority in a table, for example:

Priority	Timeslice (ms)
4	500
3	200
2	100
1	50

This helps to limit the impact of CPU-bound processes on the system, and give certain processes more access to the CPU than others. The system administrator is the person responsible for setting up the priority table according to the system policy. This algorithm doesn't lead to starvation, as all ready-to-run processes will get some CPU-time.

6.5 Multiple Priority Queues

In this scheme, the operating system has several ready queues, and when processes start, they are given a priority value set from a table made by the system administrator according to system policy.



When choosing the next process to move to the running state, the operating systems schedules the process from the highest priority non-empty queue. This can lead to *starvation* of lower priorities if one queue has many CPU bound processes, as the lower queues only get CPU time when the upper queues are empty (no processes or processes blocked).

6.6 Long-Term Schedulers

So far we have only discussed short-term schedulers: algorithms which choose the next running process from a pool of ready-to-run processes. These algorithms must be very fast, because their operation is performed in the *lower-half* of the operating system.

Long-term schedulers are algorithms which operate at a slower pace, and which can collect data and change process priorities and timeslice values over a period of time. Their operation is performed in the *upper-half* of the operating system.

The main of a long-term scheduler is to enforce a more sophisticated system policy with regards to process scheduling. For example, a long-term scheduler may lower a process down through the priority queues if the system is an interactive one and the process is CPU-bound. The aim here is to lessen the effect of the CPU-bound process on the interactive ones.

6.7 The Unix Long-Term Scheduler

Unix uses multiple priority queues, and has a long-term scheduler which moves processes up or down in priority. The policy is to give priority to low-CPU usage processes, as they are usually interactive processes I/O bound on user input. There are priority levels from 0 to 32, with level 0 being the highest priority. A process' priority is recalculated just before it is placed on the multiple ready queues:

Priority = Recent CPU Usage / 4;

Every 10 milliseconds (i.e every timeslice), the running process' Recent CPU Usage is incremented to a maximum value of 127. Every second, *all* processes' CPU Usage values are halved.

Thus, a process which uses little CPU has its CPU Usage repetetively halved, and the Priority value tends towards 0. A process which uses a lot of CPU keeps accumulating Recent CPU Usage and hence maintains a Priority value well above 0.

Here is a snapshot of a set of processes running on a Unix machine:

```
load averages:   0.29,  0.11,  0.11
31 processes:  2 running, 29 sleeping
Cpu states: 97.7% user,  0.0% nice,  1.9% system,  0.4% interrupt,  0.0% idle

  PID USER PRI   SIZE   RES STATE   TIME   WCPU    CPU COMMAND
 3071 wkt  57    608K  228K run     0:03 88.08% 15.98% gunzip
  715 wkt  18    636K  480K sleep   0:14  0.00%  0.00% tcsh
  714 wkt  18    584K  432K sleep   0:02  0.00%  0.00% tcsh
   95 wkt  18    416K  120K sleep   0:09  0.00%  0.00% sendmail
   86 wkt  18    280K  104K sleep   0:06  0.00%  0.00% cron
   25 wkt  18    216K    0K sleep   0:00  0.00%  0.00% <adjkerntz>
  685 wkt  10    488K    0K sleep   0:00  0.00%  0.00% <sh>
    1 wkt  10    364K    0K sleep   0:00  0.00%  0.00% <init>
  701 wkt  10    200K    0K sleep   0:00  0.00%  0.00% <xinit>
  718 wkt   3    200K   44K sleep   0:08  0.00%  0.00% rlogin
 1077 wkt   3    200K    0K sleep   0:07  0.00%  0.00% <rlogin>
  137 wkt   3    156K    0K sleep   0:00  0.00%  0.00% <getty>
  136 wkt   3    156K    0K sleep   0:00  0.00%  0.00% <getty>
```

The `gunzip` process is running and has a low-ish priority of 57. Processes like `tcsh`, `sendmail` and `cron` have run recently (which is why they have a priority of 18), but are currently blocked on I/O. Processes like `rlogin` and `getty` have not run recently (which is why they have a priority of 3), and are also currently blocked on I/O.

The load averages give the number of jobs in the Ready queues averaged over 1, 5 and 15 minutes.

6.8 Which is the Right Scheduling Algorithm to Use?

There is no simple answer to this question. The right choice of algorithm depends heavily on the type of system, and the types of processes running on the system. A good algorithm can be selected by gathering data on the current scheduling algorithm and the types of processes that are run by the users, simulating new algorithms using the data collected, developing analytic models of the CPU usage patterns, and testing the new algorithms out on a real system.

It is also important to note that no matter how good a scheduling algorithm is, the available CPU resources are finite. The number of processes completed by an operating system doesn't increase as more processes are loaded into memory; in fact, the throughput decreases due to the overhead of context switching between the processes. Some operating systems (such as batch systems) have algorithms that limit the burden on the CPU by preventing new processes from being loaded. Interactive systems generally don't do this, as users would get frustrated if they could not launch a new application. This does mean that users on an interactive system can accidentally or intentionally cause a CPU *denial of service*.

6.9 The Idle Process

What does the CPU do when there are no processes in the ready queue, and a process must be chosen to move to the vacant running position? Here the operating system schedules an **idle process**, which is a CPU-bound process built into the operating system. The idle process is given the lowest priority possible, so it is not executed if there are any ready processes in the system.

7 Introduction to Input/Output

Textbook reference: Stallings ppg 471 – 511; Tanenbaum & Woodhull ppg 153 – 165

7.1 Why does the Operating System do I/O?

One of the main functions of an operating system is to control all the I/O devices: disks, tapes clocks, terminals, network devices etc. This harks back to the idea that the operating system provides an abstract interface to the system. Thus the operating system must control the hardware for the user. Because of this, it can also manage the system resources fairly and efficiently.

To control all the I/O devices, the operating system must issue commands to the devices, catch **interrupts** returned by the device controllers, and handle andy device errors. The operating system must then provide an interface between the devices and the processes that is simple and easy to use by programmers. If possible, the operating system should also make this interface device-independent.

The reasons for this all: the user doesn't want to worry about physical attributes of devices, their programming quirks, and how to handle errors. They just want to deal with abstract I/O such as mouse events, files and documents, windows on the screen, and data sent across the network. Leaving the management of I/O to the operating system makes the programmers' and users' lives easier, and allows scheduling algorithms to be created for the devices.

interrupt: 1. [techspeak] n. On a computer, an event that interrupts normal processing and temporarily diverts flow-of-control through an "interrupt handler" routine. See also trap. 2. interj. A request for attention from a hacker. Often explicitly spoken. "Interrupt — have you seen Joe recently?"

interrupts locked out: When someone is ignoring you. In a restaurant, after several fruitless attempts to get the waitress's attention, a hacker might well observe "She must have interrupts locked out". The synonym 'interrupts disabled' is also common.

7.2 Devices and the Machine Architecture

We have seen how devices are accessed via the CPU. Here is a reiteration. Devices are seen by the CPU through device *registers*, which are often mapped to specific physical memory addresses. Each register controls, or shows, an aspect of the device's operation. You might like to review the example UART that we described previously. I/O is performed by examining/modifying the values in the device's registers. The device controller, in turn, observes these changes and performs the requested I/O.

The CPU can *poll* the device registers to see when any I/O has been completed by the device. This is usually undesirable, as it wastes CPU time when no I/O has been done. Alternatively, the device may send the CPU an *interrupt* to inform it when I/O has completed, or when some error has occurred. Each device has its own interrupt line.

Interrupts typically have a set of priority levels: interrupt handling at a low priority is delayed until a higher priority interrupt has been handled. Alternatively, handling of a low priority interrupt will itself be *interrupted* when a higher priority interrupt arrives.

Interrupts allow multitasking, because any running process is automatically interrupted when input arrives, and resumes when the I/O operation has been completed by the interrupt handler.

poll: v.,n. 1. [techspeak] The action of checking the status of an input line, sensor, or memory location to see if a particular external event has been registered. 2. To repeatedly call or check with someone: "I keep polling him, but he's not answering his phone; he must be swapped out."

7.3 Direct Memory Access

Textbook reference: Tanenbaum & Woodhull ppg 157 – 158

Using polling or interrupts to transfer data can be quite CPU intensive. Consider a UART that interrupts each time a character arrives from a serial port. Now imagine that the serial port is connected to a 56Kbps modem downloading a large JPEG image from the Internet. 56Kbps is roughly 5,600 characters per second. Therefore, while the image is being downloaded, the UART is interrupting the current running process 5,600 times a second.

On each interrupt, the CPU is diverted to the UART interrupt handler. The handler must read the incoming character, find the process waiting for it, copy the character to the process, change its state to ready before returning to the running process. You can imagine that this takes a lot of the CPU away from the running process.

A better method is to use direct memory access (**DMA**). Here, the device controller delivers the data to the appropriate process location in main memory, and sends an interrupt when the transfer is complete. And if the device can buffer and deliver a bundle of data (e.g 16 characters with the 16550AN UART), then this can again reduce the interrupt handling load on the CPU.

DMA requires some intelligence to be built into the device controller. For example, consider a disk drive controller which has the following registers:

Location	Meaning of Register
10,000	Disk address: cylinder, head, sector
10,004	Operation to perform: read or write
10,008	Start of DMA buffer in main memory

Imagine the operating system wants to write one disk block (say 1,000 bytes) from address **34,500** to cylinder 159, head 7, sector 5. The operating system also knows that the disk device can perform DMA. To make the write to disk occur, the operating system writes the value 34,500 into address **10,008**, the disk address 'cyl 159, hd 7, sc 5' into address **10,000**, and finally the command 'write' into address **10,004**.

The disk device controller reads these values, and understands that it must write the buffer starting at location 34,500 to disk location 'cyl 159, hd 7, sc 5'. It then uses the address/data/status buses to read the 1,000 bytes from main memory into a buffer on the controller. The device **asserts** each address in turn (just like the CPU does), and can thus temporarily stop the CPU (or any other device) from accessing the bus.

Once the data is copied into the disk controller, it can command the disk hardware to write the data at the requested disk location. Once the operation is complete, the disk controller sends an interrupt into the CPU to indicate completion. Only now is the operating system's disk interrupt handler brought into action, and it has much less work to do now.

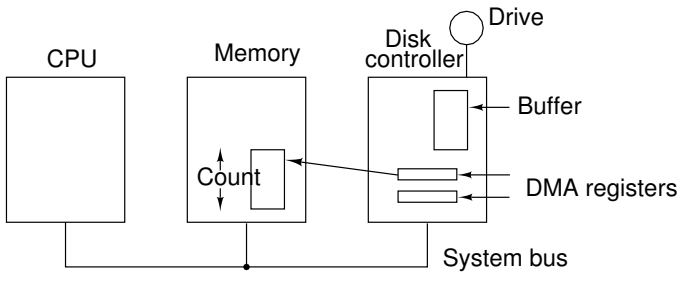


Figure 3-3. A DMA transfer is done entirely by the controller.

Usually DMA is slower than the CPU, as the I/O devices don't operate as fast as the CPU. Thus, DMA may prevent the CPU from using the bus on average about 1 access out of every N machine cycles; this is known as "stealing a cycle" from the CPU.

If the CPU needs to read/write data from its internal registers and main memory, this denial of memory access can slow it down. But with modern computers, this is often a rare situation. Modern CPUs have large numbers of registers, and a lot of memory cache. CPUs can continue to run the current program by using the data in registers and cache, and minimise the use of the main memory. The CPU can usually continue to work temporarily without requiring main memory access.

As with the DMA write operation described above, reads from the disk can be performed without supervision from the operating system/CPU. Many peripheral device controllers (disks, UARTs, network cards, printer ports etc.) support DMA data transfers. Good operating systems make use of this support to improve their performance.

8 Principles of Input/Output

Textbook reference: Stallings ppg 471 – 511; Tanenbaum & Woodhull ppg 159 – 165

8.1 Introduction

As we have noted previously, devices are usually **memory-mapped**: the operating system sees the device controller and its registers but not the actual device itself. Devices usually interrupt when input arrives, or when an error as occurred. The operating system must have an **interrupt handler** to perform the tasks when interrupts occur. On most machines, interrupts are *prioritised*.

There are usually two types of devices:

- Character-based: keyboards, screens, serial connections, printers, mice, network cards. These device do I/O operations one byte at a time, or sometimes a variable number of bytes at a time.
- Block-based: disks, tapes, scanners. These device do I/O operations one **block** at a time. The size of the blocks depend on the device, and can range from 128 bytes to over 4,096 bytes.

Some devices in a computer, like clocks (which only send interrupts at fixed intervals), or ROM/RAM, don't fit the above category.

8.2 Goals of I/O Handling

As potential operating system designers, we would like to construct our operating system so that it is easy to debug, easy to extend as new features and devices become available; we also want to handle the complexities of the devices, but hide this from the users, while providing them with an abstract view of these devices.

Generally, this is achieved by having the I/O part of an operating system organised as a series of **layers**. The lower layers worry about hiding a device's peculiarities from the upper ones. The upper layers present a simple, clean interface for I/O to the users.

A major goal is **Device Independence**: users should be able to perform I/O on devices regardless of the actual devices themselves. This allows the operating system itself to be ported to another hardware platform, and allow the existing applications to continue to run. This also allows hardware to be upgraded (e.g a new video card, sound card or hard disk) without modification of the applications.

Another goal is the method of **Error Handling**: errors should be handled as close to the hardware as possible. For example:

- If the controller finds an error, it should try to fix it.
- If not, the device driver may retry the operation.
- If lower layers cannot handle it, only then report to upper layers, and maybe the user.

Because I/O devices are much slower than the CPU and main memory, the operating system must be prepared to do **Blocking/unblocking**: user processes must expect to be blocked on I/O operations, if they cannot be immediately satisfied. The top-half of the operating system usually passes the request to the appropriate device controller. It then blocks the process, and schedules another one. The bottom-half of the operating system must unblock the process when I/O completes.

The operating system must deal with device **Sharing**: some devices are shareable (e.g disks); others are not (e.g printers), or at least not at the same instant. The operating system must provide device sharing, must deny access by processes when appropriate, and must cope with **deadlocks**, which we will discuss later.

For all of the above reasons, it's convenient to design (and also conceptualise) an operating system's I/O software as four separate layers:

- User-level software.
- Device-independent software.
- Device drivers.
- Interrupt handlers.

I/O Layer	**OS Level**	**Examples**
User-level software	User Programs and Libraries	
Device-independent software	Top Half of the OS	*The Filesystem* *Terminal handling* *Network protocols*
Device drivers		*Disk drivers* *Terminal drivers* *Ethernet drivers*
Interrupt handlers	Bottom Half of the OS	

8.3 Interrupt Handlers

The interrupt handlers exist at the bottom layer, and have to deal with the ugliness of the device controllers and the command language that each talks. Every controller has a unique interrupt line; when some I/O is completed, or if an error occurs, the controller sends an interrupt to the CPU.

The appropriate interrupt handler gets called when an interrupt occurs. It checks the controller's registers. It must then:

- Find the process that requested the I/O,
- Deliver the data to the process,
- Unblock the process, and
- Move the process to the appropriate ready queue.

As many devices offer DMA operations, which helps to take the I/O load off the CPU, it is pertinent to ask: why can't a DMA I/O operation deliver data directly to the memory of a process?

There are several reasons why this can't be achieved. First, the device might have less (or more) data available to deliver than was requested by the process. This is especially true with block devices, who

can only do I/O in block-sized units. The process may have crashed or terminated since the request was made. Another reason is that the operating system may prefer to *cache* the data from the I/O operation. More on that later.

Interrupt handlers cannot be put to sleep, as they are in the lower-half of the kernel. However, a low-priority interrupt handler will be interrupted by a high-priority interrupt.

Interrupt handlers should be as fast as possible, as while running, the CPU is taken away from the task of running users' processes. Thus, large or complicated interrupt handlers can degrade the processing performance of a computer. Similarly, a large high-priority handler slows down the system's response to low-priority interrupts.

8.4 Device Drivers

Device drivers hold the *device-dependent* software for one device, or sometimes for a *class* of devices, e.g all terminals. A driver knows about the registers of the controller, and the characteristics of the device (e.g number of tracks/heads on each disk).

If the interrupt handler passes the data from an I/O to the operating system and not directly to the process, then it delivers it to the device driver, and notifies the driver of success/error. The driver takes the data and converts it to an abstract format, with corresponding abstract success/error events for the device-independent layer.

Similarly, the device driver takes abstract requests for I/O from the device-independent layer and converts them to requests that the device controller can perform.

For example, the device-independent layer may know that a particular disk has 1,700,000 512-byte blocks. A read request from the device-independent layer for disk block **X** must be converted to the correct cylinder/head/sector number. The device driver can then load this information into the controller, ask it to read the block, and place the incoming data into a certain location using DMA. On some drives, the controller must be asked to *seek* to the track first before data can be read.

> **driver**: n. 1. The main loop of an event-processing program; the code that gets commands and dispatches them for execution. 2. [techspeak] In 'device driver', code designed to handle a particular peripheral device such as a magnetic disk or tape unit.

8.5 The Device-Independent Layer

A large fraction of the I/O software in an operating system is device-independent. The boundary between this layer and the drivers varies, and depends upon the design of the particular system.

Typically, this layer does:

- Uniform interfacing for the device drivers;
- Device naming;
- Device protection;
- Providing a device-independent block size;
- Buffering;
- Storage allocation;
- Allocating and releasing dedicated devices; and
- Reporting of abstract I/O errors.

The basic function of this layer is to perform I/O functions that are common to all devices in a particular grouping, and to provide a uniform interface to the user-level software.

For example, a terminal-layer performs terminal operations, even when the devices used are keyboards & screens, remote serial terminals or network-linked terminals. Similarly, a filesystem provides files, directories, file permissions and read/write operations, even when the devices used are floppies, hard disks, CD-ROMs, network drives and RAM disks.

A uniform interface makes writing user software easier. Similarly, a uniform naming method makes it easier to use devices or the abstract objects available on those devices (e.g files). Protection of devices or their services is also important, and it is best to do it here, so that all devices get protection in the same manner, and the user sees consistency in the protection.

Different block devices have different block sizes. This layer must provide a standard block size. To do so it may need to buffer incoming blocks, or to read/write multiple real blocks. Buffering must be done as a user may only want to read/write half a block, or to read one character from a device where 20 are available to be read. Allocating device blocks to store data is also done at a device-independent level in a device-independent fashion. We will cover this in the filesystem lectures.

The operating system must ensure that only one user is accessing particular devices, e.g a printer. Thus, new opens on opened devices must fail. User access may lead to **starvation** and the operating system should attempt to prevent starvation. To avoid this, the operating system may use **spooling**, and operating system services to regulate device access, for example:

- Output to printer is spooled in a file on a disk.
- When the printer becomes ready, the file is queued for printing.
- The queue is FIFO, and the operating system opens/closes the printer.

Without spooling, one user could open the device indefinitely.

Error reporting must be done at the device-independent level, and is done only if the lower levels cannot rectify the error.

buffer overflow: n. What happens when you try to stuff more data into a buffer (holding area) than it can handle. This may be due to a mismatch in the processing rates of the producing and consuming processes, or because the buffer is simply too small to hold all the data that must accumulate before a piece of it can be processed. The term is used of and by humans in a metaphorical sense. “What time did I agree to meet you? My buffer must have overflowed.”

spool: [from early IBM ‘Simultaneous Peripheral Operation Off-Line’, but this acronym is widely thought to have been contrived for effect] vt. To send files to some device or program (a ‘spooler’) that queues them up and does something useful with them later. The spooler usually understood is the ‘print spooler’ controlling output of jobs to a printer, but the term has been used in connection with other peripherals (especially plotters and graphics devices).

8.6 Clocks – Hardware

Textbook reference: Tanenbaum & Woodhull ppg 222 – 227

As mentioned above, clocks don’t really ‘do’ I/O. As they are hardware devices, they are included here. Clocks usually do two things:

- Send interrupts to the CPU at regular intervals (**clock ticks**). These can be used to prompt process rescheduling and allow the operating system to calculate time-specific statistics.
- Send an interrupt after a requested time (alarm clock).
- A few clock devices provide the time of day values in registers. The time of day is often battery-backed.

Most clocks have settable clock tick periods. The usual speeds are 50Hz, 60Hz or 100Hz. Alarm clocks are achieved by writing a value into a clock register. This is decremented each clock tick, and an interrupt is sent when the value reaches zero.

8.7 Clocks – Software

The clock interrupt handler receives the clock tick interrupt. The software must:

- Maintain the time of day clock when the clock hardware doesn't have one.
- Pre-empt processes when their timeslice has been exhausted.
- Handle any 'alarm calls' that have been requested, e.g by processes like `cron`.
- Provide 'alarm calls' for the operating system itself, e.g for network retransmissions.
- Perform time-based statistics gathering for the operating system.

Maintaining the time of day is hard because, at 60Hz, a 32-bit value overflows in 2 years. It is most often achieved by keeping two counters, a tick counter, and a seconds counter. Under Unix, the seconds counter has its epoch at 1st January 1970. For MS-DOS and Windows, the epoch is 1980.

Each process has a timeslice. When scheduled, this is copied into an operating system variable as a number of clock ticks, and is decremented on each tick. At value zero, the process can be pre-empted by the operating system.

Some operating systems allow processes to set up 'alarm calls'. When the alarm goes off, exceptional things happen to the process e.g under Unix, a signal can be sent to the process. The clock driver simulates alarm calls by keeping a linked list of calls and their differences. The head node's difference is decremented until zero, at which time the alarm 'goes off'. The node is removed, and the next node becomes the head.

Because of the overhead of context switching, there is no guarantee of accuracy for the alarm call. Generally processes are only guaranteed that the alarm will not go off earlier than requested. The operating system uses alarm calls to timeout on I/O operations, e.g a disk read which never occurs, a network transmission.

Most operating systems gather time-based statistics to aid adaptive scheduling algorithms. The statistics are used by high level process schedulers, user information, system administration.

> **jiffy**: n. 1. The duration of one tick of the system clock on the computer. Often one AC cycle time (1/60 second in the U.S. and Canada, 1/50 most other places), but more recently 1/100 sec has become common. "The swapper runs every 6 jiffies" means that the virtual memory management routine is executed once for every 6 ticks of the clock, or about ten times a second. 2. Indeterminate time from a few seconds to forever. "I'll do it in a jiffy" means certainly not now and possibly never. This is a bit contrary to the more widespread use of the word.

9 Device Drivers and Interrupt Handlers

Device drivers and interrupt handlers live at the bottom of the Input/Output stack. They perform device-dependent I/O operations at the request of the device-independent I/O layer.

A device driver and associated interrupt handler need to communicate with each other. This is usually performed through memory shared by the various parts of the operating system, or via messages in a microkernel system.

There may be several instantiations of a single device driver in progress, because several processes have made I/O requests. The device driver must:

- Convert the DIL command into the matching device command.
- Send command to the device through its controller's registers.
- Move the current process to the blocked list.

All of the above is done by the top-half of the operating system at the behest of the calling process. All of this is done at interrupt priority level zero. This implies that the operating system could pre-empt the process (and the I/O operation in progress) anywhere in the above three lines. This is how several instantiations of the driver at any one time.

The device driver may also be interrupted by its interrupt handler. Therefore, both the device driver and the interrupt handler must be **re-entrant**: the code can be in use by several threads of execution, and all non-private data structures are properly shared. Note that on a single CPU machine, only one device driver instantiation or the interrupt handler is actually in execution; the others are temporarily suspended.

Because of the multiple driver instantiations, any access to shared memory by the driver or the interrupt handler must by *synchronised*, to prevent the corruption of shared data structures. Under most systems, this is achieved by *masking out* the interrupts that may pre-empt the device driver or start the interrupt handler. This may disable all interrupts below a certain level, and is known as *raising the interrupt level*. Here is an example from the FreeBSD IDE disk device driver:

```
/* queue transfer on drive, activate drive and controller if idle */
s = splbio();          /* Raise int. level to stop block I/O */

disksort(dp, bp);
if (dp->b_active == 0) wdustart(du);     /* start drive */

splx(s);              /* Return int. level to previous level */
```

Device drivers provide a set of operations to the device-independent I/O layer. Here are some of the device driver operations provided by Unix device drivers. In Unix, a 'character' device is a 'non-block' device.

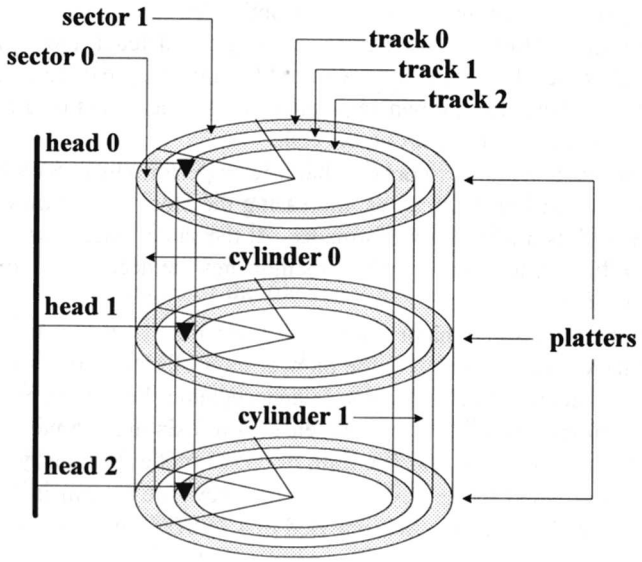
Function	Device Type	Description
d_open	Block and character	Initialise device when first used
d_close	Block and character	Used when device is released. May shutdown device or take it off-line.
d_strategy	Block	Read/write interface, allows event re-ordering.
d_read	Character	Reads data from device.
d_write	Character	Writes data to device.
d_ioctl	Block and character	Generic control operations on device.

Writing and debugging devices drivers and interrupt handlers is a real pain. There is no protected process environment, and many device drivers or interrupt handlers cannot be single-stepped or stopped at a breakpoint. We will look at two example devices: disks and terminals/keyboards.

10 The Disk Device

Textbook reference: Tanenbaum & Woodhull ppg 200 – 208

10.1 Disk Hardware



Hard disks consist of a number of **platters,** each of which is flat and circular. Each platter **platter** has 2 surfaces, and both are covered with magnetic material which is used to record information. Disks spin at high speeds, often 3600 rpm or sometimes 7200 rpm.

For each available platter surface, there is a read/write head, which records a **track** on the surface. There are usually hundreds or thousands of tracks on each platter. The head is mounted on an **arm**, which moves or **seeks** from track to track. The tracks form concentric circles on the platter's surface, and are invisible to the naked eye.

Each track can hold a lot of information (10 to 100K), so tracks are usually broken into **sectors**, each holding a portion of the data. Sectors can store a fixed amount of data, generally 512 bytes or sometimes 1,024 bytes. A vertical group of tracks is known as a **cylinder**. Cylinders are important, because all heads move at the same time. Once the heads arrive at a particular track position, all the sectors on the tracks that form a cylinder can be read without further arm motion.

To access a track, the arm must seek to it. The average **seek time** on drives is 10-50 milliseconds. Then, the disk must rotate to bring the data to the head: the **latency time**. Finally, the data is read: the **transfer time**. Generally, a disk's seek time $\gg$ latency time $\gg$ transfer time.

washing machine: n. Old-style 14-inch hard disks in floor-standing cabinets. So called because of the size of the cabinet and the 'top-loading' access to the media packs — and, of course, they were always set on 'spin cycle'.

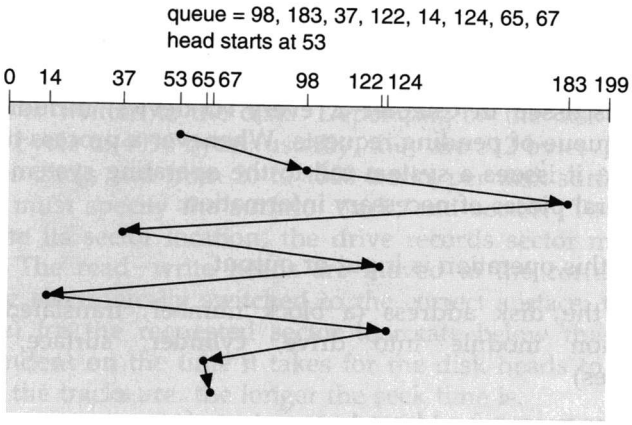
10.2 Disk Software

Disks usually use DMA. The software must tell the controller: what operation to perform (read, write, format), which cylinder to move to, which sector is required and which head, and which DMA address to put or get the sector. The controller then performs the operation, and sends in an interrupt on success or error.

On a multiprogramming operating system, an operating system may have a queue of requests, as several processes may have passed through the running state and issued a disk I/O operation. Disk operations take a long time, when compared with the speed of the CPU and main memory. If software can minimise the overall I/O time, then disk I/O performance can be improved. Let us look at some algorithms that can schedule the motion of the arm.

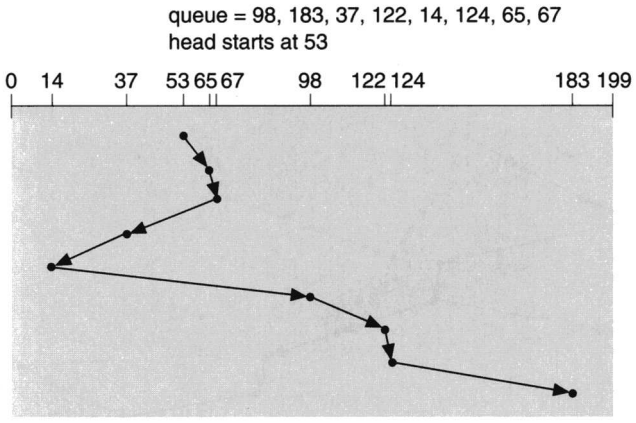
10.3 Arm Scheduling – FCFS

With this disk scheduling algorithm, disk requests are serviced as they arrive. Because we can't predict what proceses will make requests when and for what, the set of disk requests on a normal system usually causes a lot of head movement. However, the algorithm does treat all requests equally, so the method is fair.



10.4 Shortest Seek Time First

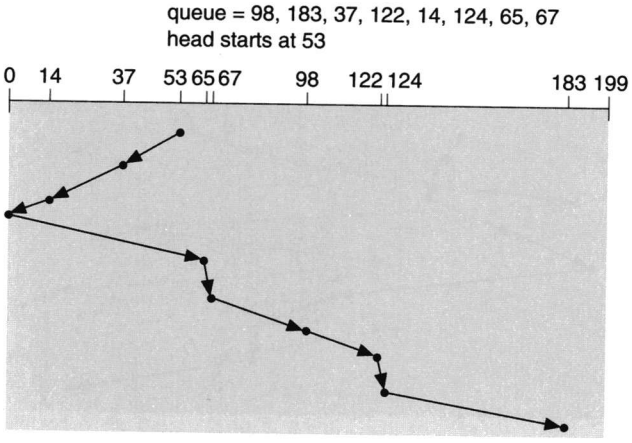
If the queue if pending disk requests is bigger than one, we could improve the disk's performance by reordering the requests so that the request with the smallest seek is chosen to be next.



By reordering the queue in this way, the movement of the arm (and hence the seek time) minimised. Thus, on average, a pending disk request is serviced faster than with FCFS. However, this reordering or requests can lead to starvation on big seek requests, especially if new requests are continually arriving. This most affects disk requests for tracks on the extreme edge of the disk, whereas the middle tracks are preferentially selected by the algorithm. In other words, the algorithm is unfair.

10.5 SCAN Algorithm

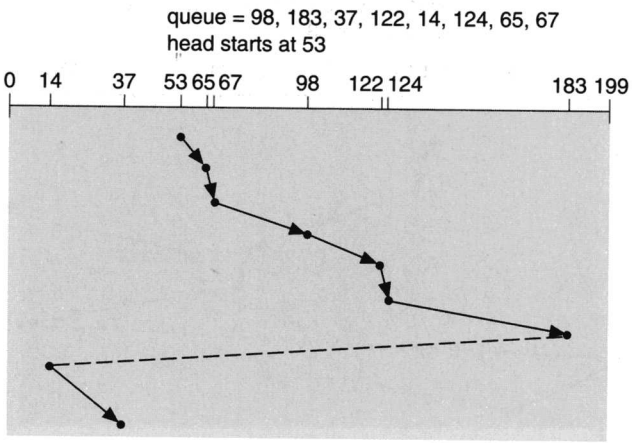
This queue reordering algorithm is also known as the **elevator** algorithm. Here, the head starts at one end of the disk, and moves towards the other end, servicing requests in that order, until there are no more requests in that direction. The arm then reverses direction, and services requests the other way.



Because requests are reordered so that they are performed in ascending or descending order, this again helps to minimise seek time, and thus improve overall disk I/O performance. One nice property of SCAN is that, given any collection of requests, the upper bound on the motion of the arms is fixed at exactly 2 $*$ the number of tracks.

10.6 C-SCAN Algorithm

This is a modified SCAN algorithm which lowers the average response time. Unlike SCAN, C-SCAN always services requests in the **same** direction, for example, ascending. This helps to make coding of the algorithm easier. When there are no more requests above the last request, the head is moved to the lowest request, and requests are again serviced in an ascending motion.



Note the following: if the queue is usually of size 1 or less, then no request reordering scheme is going to be useful, and you end up with FCFS by default. But on most multiprogramming systems, disk request reordering is useful, and generally C-SCAN is the preferred algorithm.

walking drives: n. An occasional failure mode of magnetic-disk drives back in the days when they were huge, clunky washing machines. Those old dinosaur parts carried terrific angular momentum; the combination of a misaligned spindle or worn bearings and stick-slip interactions with the floor could cause them to 'walk' across a room, lurching alternate corners forward a couple of millimeters at a time. There is a legend about a drive that walked over to the only door to the computer room and jammed it shut; the staff had to cut a hole in the wall in order to get at it! Walking could also be induced by certain patterns of drive access (a fast seek across the whole width of the disk, followed by a slow seek in the other direction). Some bands of old-time hackers figured out how to induce disk-accessing patterns that would do this to particular drive models and held disk-drive races.

10.7 Sector Queueing

If the hardware is clever enough to determine which sector is passing under the head, the operating system can order requests on that cylinder to minimise latency. For example, if we have requests for sector 3, 8 and 11, and the head is passing over sector 5, we can schedule 8 and 11 first. The disk hardware that supports this is generally very expensive, and is only found on mainframe or high-end server computers.

10.8 Interleaving

Textbook reference: Tanenbaum & Woodhull ppg 158 – 159

In many cases where the operating system is slow, it must spend time processing a block read in from the disk before it can read in another one. For example, the number of DMA buffers may be limited, and the operating system must move out a block to free up a DMA buffer for another transfer. Thus, if the operating system wants to read sectors 0, 1 and 2 from a particular track, it may miss sector 1 after reading 0, and have to wait an entire revolution before it can read sector 1.

If the sectors are **interleaved**, then there will be a gap to give the operating system time to process before its next read.

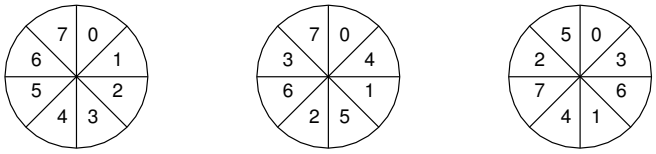


Figure 3-4. (a) No interleaving. (b) Single interleaving. (c) Double interleaving.

Note that interleaving can either be done in hardware (i.e within the disk controller logic) or in the software: for example, on a disk with eight sectors per track, the operating system can treat physical sectors 0,1,2,3,4,5,6,7 as 0,2,4,6,1,3,5,7; in other words, the operating system can itself perform a logical to physical mapping.

10.9 Error Handling

Textbook reference: Tanenbaum & Woodhull ppg 205 – 206

Disks are subject to a wide variety of errors:

a) programming error: e.g request for non-existent sector. Hopefully the operating system is written to ensure this does not happen. If it does, halt the system?

b) transient error: e.g dust on the head. The best option is to retry the operation; if errors persist, tell the upper layers the sector is **bad**.

c) permanent error: e.g a physically bad sector. This is a problem as some application programs read the entire disk (e.g backup programs). Some intelligent drives keep a spare cylinder, and when permanent errors occur, internally map the bad sector to one on the spare cylinder. This can erode the arm scheduling algorithms used.

d) seek error: e.g arm went to track 7, not 6. Some drives fix these errors automatically. Others just inform the operating system. Here the operating system must **recalibrate** the head by bringing it back to cylinder 0 and retrying the seek.

e) controller error: e.g it refuses to accept commands. The operating system can attempt to reset the controller. If the problem persists, give up.

disk crash: n. A sudden, usually drastic failure that involves the read/write heads dropping onto the surface of the disks and scraping off the oxide; may also be referred to as a 'head crash'.

farming: [Adelaide University, Australia] n. What the heads of a disk drive are said to do when they plow little furrows in the magnetic media. Typically used as follows: "Oh no, the machine has just crashed; I hope the hard drive hasn't gone farming again."

10.10 Recent Disk Advances

Recent advances in disk systems are *disk striping* and *RAID*. In disk striping, a group of disks is treated as a single unit, and each block is composed of subblocks stored on each disk. Transfer time is reduced as the subblocks can be transferred in parallel, fully utilising the available I/O bandwidth. This also allows a large 'virtual' disk to be composed of several cheap disk drives.

Disk striping is extended with RAID, a redundant array of disks. Data is duplicated across several physical disks. Each block is checksummed, to ensure the data is not corrupted. RAID improves transfer time and access time, as per disk striping. In the event of bad blocks or disk failure, data can be recovered from the redundant storage. Mean time between failure is significantly improved with RAID.

11 Terminals

Textbook reference: Tanenbaum & Woodhull ppg 235 – 249

Every computer has one or more terminals used to communicate with it. By terminal, I mean an I/O device consisting of a keyboard and a screen. Terminals have a large number of different forms, which we will soon see. The terminal device drivers must hide these differences from the device-independent software, so that I/O on terminals can be done by user processes without any knowledge of the actual hardware involved.

11.1 Terminal Hardware

There are two broad categories: serial interfaced terminals (usually using RS-232) and memory-mapped terminals. Serial terminals are standalone with a keyboard and display. They are attached to the computer usually via an RS-232 interface, which needs at least three wires: ground, data in, data out. Other handshaking wires can also used to control the flow of data.

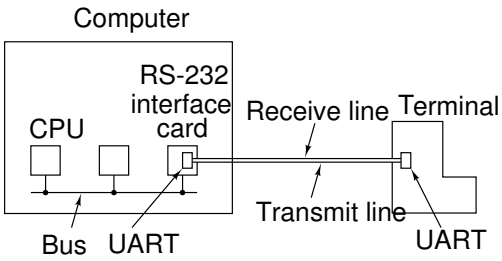
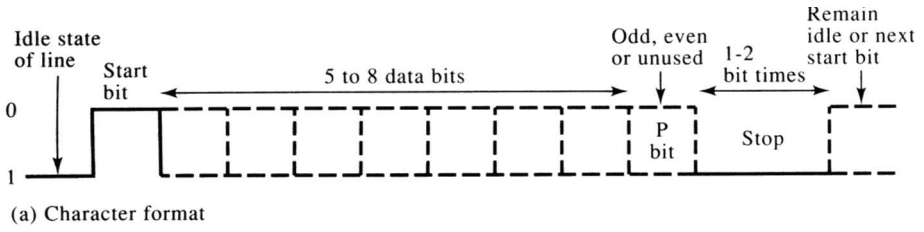


Figure 3-30. An RS-232 terminal communicates with a computer over a communication line, one bit at a time. The computer and the terminal are completely independent.

Characters to/from the terminal are sent in a serial fashion, e.g 7 bits per character, one **start** bit and one or more **stop** bits. The start/stop bits are used to delimit the characters.



Characters are transmitted **asynchronously** over the serial line: that is, the computer has no idea when the next character will arrive. Common data speeds are (in bits per second): 300, 1200, 2400, 9600 and 19200. The terminal and the computer both use chips called **UART**s to do the character-to-serial and serial-to-character conversion.

At 9600 bps, with 7 data bits, one start bit and two stop bits (i.e 10 overall), we get 960 characters per second, or around 1 ms per character. This is a long time for an operating system. Usually the operating system asks the UART to return an interrupt after sending/receiving a character. Some UARTs have small buffers (2,4,16 characters), and are able to send less interrupts to the operating system.

11.2 Serial Terminal Types

Hard-copy terminals just print the characters they receive to paper. Dumb terminals just pretend they are hard-copy, but without any paper. Intelligent terminals can move the cursor, change fonts, clear the screen, scroll backwards, bold characters etc.

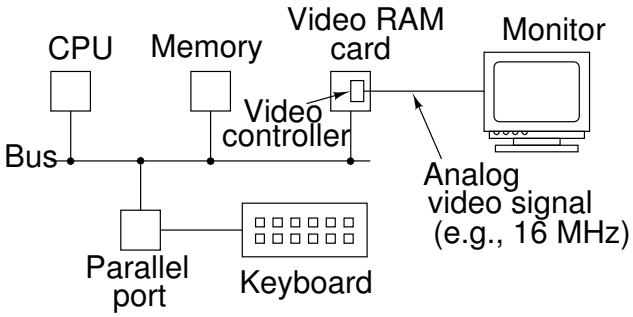
tty: /T-T-Y/ n. A terminal of the teletype variety, characterized by a noisy mechanical printer, a very limited character set, and poor print quality. Usage: antiquated (like the TTYs themselves).

glass tty: /glass T-T-Y/ n. A terminal that has a display screen but which, because of hardware or software limitations, behaves like a teletype or some other printing terminal, thereby combining the disadvantages of both: like a printing terminal, it can't do fancy display hacks, and like a display terminal, it doesn't produce hard copy. An example is the early 'dumb' version of Lear-Siegler ADM 3 (without cursor control).

smart terminal: n. A terminal that has enough computing capability to render graphics or to offload some kind of front-end processing from the computer it talks to. The development of workstations and personal computers has made this term and the product it describes semi-obsolescent, but one may still hear variants of the phrase 'act like a smart terminal' used to describe the behavior of workstations or PCs with respect to programs that execute almost entirely out of a remote server's storage, using said devices as displays.

11.3 Memory-Mapped Terminals

These terminals have their display memory-mapped into the computer. A good example are the video displays on most microcomputers.



With a **character-mapped** display, writing a character in a memory location causes the character to be displayed. With a **bit-mapped** display, every bit in the video memory controls one pixel on the screen. The operating system must 'paint' the characters on the screen. In both cases, scrolling involves copying every byte in video memory from one address to another.

The keyboard is completely decoupled from the display. It is usually **parallel** connected to one memory address, which is where the operating system received the characters. With many keyboards, the actual character is not exchanged. Instead a **key code** is transmitted, indicating which key was pressed. For example, different key codes will be generated for 'left shift', 'right shift', 'caps lock', 'control', 'A' etc. The operating system must convert these key codes into the appropriate characters.

11.4 Terminal Software

The device driver must present the device-independent software with a flow of characters in/out. The terminal independent software must also present an abstract device to the user, one where characters can be read/written.

Input: Many programs just want lines of characters to arrive. They don't want to be bothered with line editing. Some programs, however, want to receive one character at a time, including the user's mistyped characters. The latter mode is known as **raw mode**, as the characters are passed raw. The former is known as **cooked mode**, and the terminal independent software performs the editing.

Thus, the terminal independent software must buffer a partial line while the user is editing it. In fact, the software must buffer characters until the running programs request the characters. There are two buffering methods: a central buffer pool, or a buffer per input terminal. The first is more complicated, but saves a lot of memory (especially if there are 100 terminals connected), and can also prevent individual buffers from overflowing.

In cooked mode, the user needs several characters in order to perform the line editing. These can usually be chosen by the user, but the standard Unix ones are:

^H	Erase last character
^C	Interrupt process/kill line
\	Escape next character
tab	Expand to spaces on output device
^S	Stop output
^Q	Start output
^D	End of terminal input
CR	End line

Most users expect to see the characters they type on the screen. However, in some situations (e.g changing passwords), this needs to be disabled. The terminal independent software thus must also perform **echoing**, and must provide an interface so that programs can turn it on/off. Echoing presents problems:

- How to erase the last character when the user types backspace?
- What about lines longer than the screen width?
- Does the terminal understand about tabs on output?
- Conversion of operating system-specific end of line to that used by the terminal. Unix uses LF, MS-DOS uses CR-LF, Macs use LF-CR.

11.5 Output

Terminal output is simpler than input. However, serial terminal present problems that memory-mapped ones do not. With serial output around 1ms per character, processes can output data faster than it can be transmitted down the wire. The operating system must buffer output or it will be lost. It will also need to block the transmitting process if the buffer threatens to overflow.

Memory-mapped terminals on the other hand are as fast as memory, with 1 to 100 microseconds per character. They have their own problems: how to output the BELL (^G) character on memory-mapped terminals? The operating system should toggle the speaker to simulate the bell. The output driver may need to keep track of where the cursor is on memory-mapped displays. It also must perform scrolling.

To take advantage of the capabilities of smart serial terminals, the software needs to know the special command sequences to user them. These capabilities also need to be simulated on memory-mapped displays by the output software.

The sorts of capabilities are:

- Move cursor up, down, left, right.
- Move cursor to (x,y).
- Insert line or character at cursor.
- Delete line or character at cursor.
- Scroll screen up/down n lines.
- Clear entire screen.
- Clear from cursor to end of line/screen.
- Go to bold/blinking/reverse/normal mode.

A similar situation occurs in GUI environments which have to provide drivers for different mice, video cards and keyboards, while still presenting the same API to the programmer.

12 Introduction to Memory Management

Textbook reference: Stallings ppg 299 – 322; Tanenbaum & Woodhull ppg 309 – 343

12.1 What is Memory & Why Manage It?

Every **process** needs some memory to store its variables and code. But if there is more than one process in memory at any one time, then the operating system must manage memory (as a resource) to prevent processes from reading/damaging each other's memory, and to ensure that each process has enough memory (not too much, not too little). The latter is most difficult, as a process' memory requirements may vary with time, and users schedule processes unpredictably.

One thing to remember is that memory is device-like, and has an address decoder.

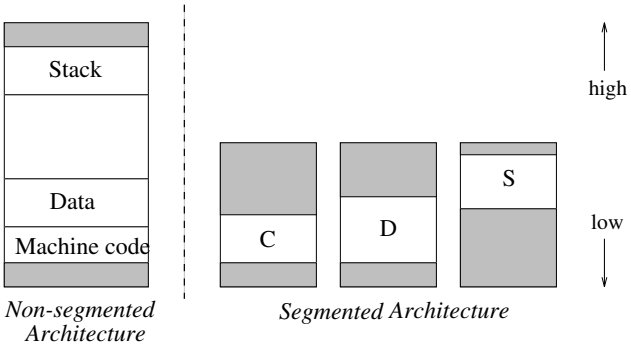
12.2 Process Compilation & Memory Locations

High level languages are converted to machine code in several steps: compilation, linking to form an executable file, and at a later time loading of the executable into main memory to run.

If the **linker** determines which variables get which addresses when running, then the program must always be loaded into the same location in memory every time it is run. This is because the addresses of variables and functions are hard-coded into the executable file.

If the **loader** determines which variables get which addresses when running, then the program can be loaded into different locations in memory each time it is run. This dynamic loading adds overhead to the start-up of a new process.

A generic memory map of a process looks like the following:

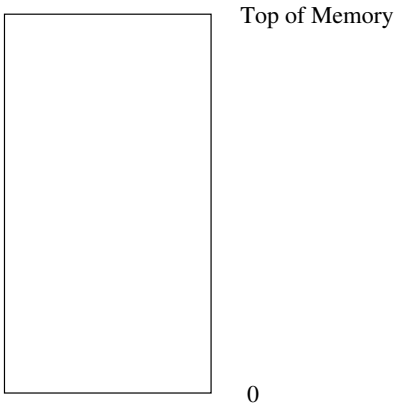


The **code** section (also called the **text**) holds the program's instructions. This usually only needs to be read-only. The **data** section holds the process' global data and variables. The **stack** holds the local variables and the arguments to each routine.

The grey areas are invalid, as the process initially doesn't use these locations. But the stack may grow down as the process calls its routines. On most operating systems the process can also ask for an increased data space. Invalid areas outside of the process remain invalid: the process cannot read from or write to these locations.

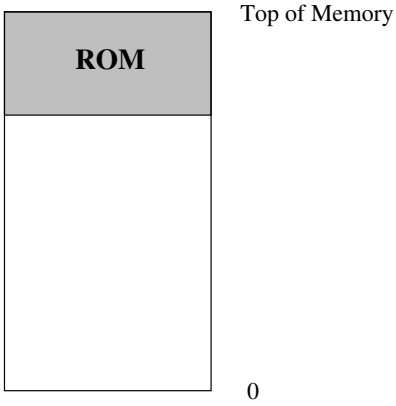
Historically, memory management has evolved from none at all to being very sophisticated. Let's quickly cover the history of memory management.

12.3 Bare Machine



Here, there is no memory management. We give the program all of the memory, with no limitation. This provides maximum flexibility to the user, and minimum hardware cost. There is no special memory hardware, and no need for any operating system software. However, there are no operating system services; the user must provide these.

12.4 Operating System in ROM – Resident Monitor



One way to protect the operating system itself is to put the operating system into ROM, thus it is hardware-protected. The operating system, unfortunately, still needs some RAM memory for its own operations, and this is unprotected from access or modification by any running program. Device addresses are not protected either.

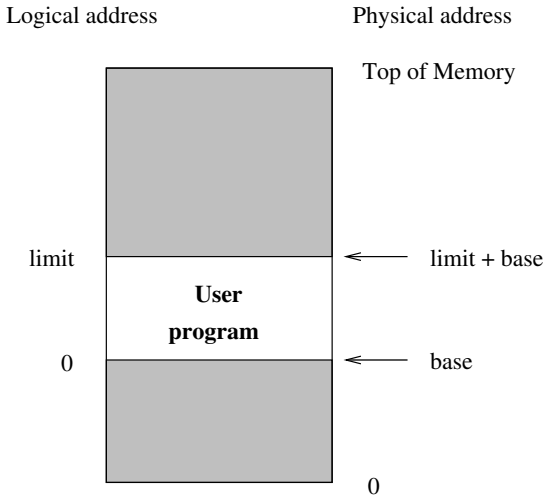
In this environment, it is impossible to protect processes from other processes. This sort of environment was used in the early minicomputer and microcomputer systems, e.g CP/M and the Apple][. We still have a hangover from these days with the BIOS in PC clones.

A variation is to load an extended operating system into RAM. In this situation the operating system is totally unprotected. I have one word for this situation: MS-DOS.

12.5 Partitions

Textbook reference: Tanenbaum & Woodhull ppg 311 – 313

One of the first mechanisms used to protect the operating system, and to protect processes from each other was **partitions**. Here, we add two hardware registers to the memory address decoder: the **base** and **limit** registers. When a process reads from or writes to address 'X', the memory decoder adds on the value of the base register, so the actual operation become a read or write to address 'base + X'.



If the input address is lower than '0' or higher than 'limit', the memory hardware considers this an error, and informs the operating system of a memory access error (usually via an interrupt). Thus, processes can only access memory within these limits.

This addition of hardware allows multiple processes to be loaded into memory and to run without interference from each other. When the operating system performs a context switch, it must remember to switch the *memory maps* of two processes. This is done by changing the values of the two registers. Each process has its own individual pair of base/limit registers, and the operating system chooses these pairs so that process' memory maps never overlap, and each process has enough memory.

On some systems, there is only a base register, and the limit is a constant. And on some systems have two register pairs, one for data and one for machine code. N.B The latter allows two memory address 0s! This is ok, because most processes never read their machine code themselves; the CPU reads and executes the code itself.

One problem with partitions is how much memory to allocate initially? If too little, the process may run out of memory when data and stack collide. If too much, then memory is unused and wasted. It is usually impossible to change the base/limit registers once set, as there are other processes are usually immediately above/below.

At this point, let us define two new terms:

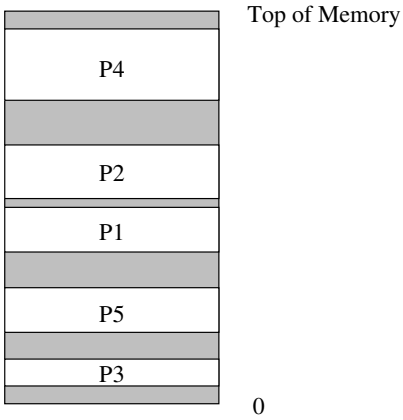
Logical Memory is the memory and its location as seen by the process. In the partition system, all processes see memory as starting at location 0, and going up to the location defined by the limit register. But because the process (running in user mode) cannot modify the limit register, the process sees its logical memory as fixed in size.

Physical Memory is the actual main memory and its location as seen by the operating system. This depends on the physical system, but in general main memory starts at location 0, and goes up to a top location set by the amount of RAM in the computer.

Note well: it's unlikely that any process has its base register set to the value 0. Therefore, physical location 0 is unlikely to ever be logical location 0 for any process.

12.6 Allocating & Placing Partitions in Memory

Partitions were used mainly on batch systems where there were: programs were waiting to be started (not in memory as yet), several processes ready to run, one running process, and zero or more blocked processes. To the operating system, the available **physical** memory looks like a number of **holes**:



As new processes are chosen from the pool of programs waiting to be started, the operating system has to choose a partition size and physical location for this partition. We need a partition allocation algorithm. Here are some possible algorithms:

First fit: Find the first hole where the waiting program will fit. This is fast algorithm, but usually leaves a smaller hole, except where the fit is exact.

Best fit: Find the hole that best fits the job. i.e with the least left over. Surprisingly this is not a good algorithm, as it leaves a lot of tiny, useless holes all over the physical memory.

Worst fit: Find the biggest hole, leaving the biggest remainder. This is usually the partition allocation algorithm chosen by system designers.

When a process exits, **merging** can be done if there is an existing hole above and/or below it.

Fragmentation describes when we have a lot of useless little holes. The system may get to a point when the available memory is enough to start a process, but it is in the form of holes too small to load the process. As the useless holes are outside of any process' memory, this situation is known as **external fragmentation**. This can be solved by **compaction**, by moving existing processes (and their partition registers) to consolidate the holes. The operating system should use an algorithm to minimise the amount of **copying** to make the compaction as fast as possible.

13 Pages

Textbook reference: Stallings ppg 299 – 323; Tanenbaum & Woodhull ppg 319 – 343

13.1 Problems with Partitions

There are several problems with using paritions for memory management. First is the allocation of partition size: if the operating sets the partition to be too big, then the process doesn't use all of the memory and it is wasted memory; on the other hand, if the partition is too small, then there is not enough memory for the process to run. Once a partition size is chosen, it is essentially impossible to change.

The second major problem is fragmentation of physical memory as the number of small holes builds up.

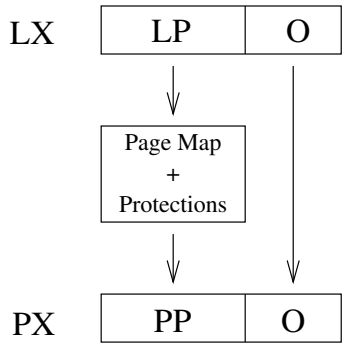
The cause of both problems is the fact that the logical memory map is **contiguous**, i.e for each process, all the machine code is in one lump, all the data is in one lump etc. The process sees a single region of logical memory, and this is mapped to a single region of physical memory. If we could make these lumps *appear* to be contiguous to the process (i.e contiguous logical memory), but actually break the lumps into small physical memory units, then we could fill the unused phsyical holes with these small units.

13.2 Pages

The concept of **pages** attempts to do just this. However, pages introduce their own problems. But first let's examine how the page mechanism performs memory mapping from logical to physical memory.

Here is how page mapping works:

- Memory is broken into lots of **pages**, which are of *fixed size*. The page size is set by the hardware design, but is generally around 1K to 8K in size.
- We use the terminology of a page as seen by the process, and a **page frame** as a page as seen by the operating system in physical memory.
- A Memory Decoder (or **MMU)** maps the memory addresses to pages requested by a process to a set of page frames in physical memory. The decoder can also set protections on eachof the process' page; for example, a process' page may be marked as read-only, read-write, invalid, or privileged-mode access only.
- When a process access address LX, the MMU divides the address by the size of the system's pages. The resulting dividend is the logical page number LP, and the remainder becomes the offset into that page O (i.e $LX = LP + O$).
- The MMU then *maps* the logical page to a physical page frame, by using a lookup table. It then adds on O to get PX, the final physical address of the location in the main memory.



  As an example, consider a system where pages are 2,000 bytes in size. A process tries to read from logical location 37,450. The MMU receives this location number from the address bus. It divides 37,450 by 2,000, obtaining logical page number 18 and offset 1,450.

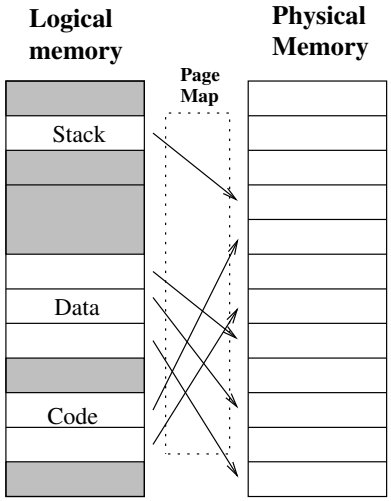
  The MMU consults the current page map. Each process has its own page map, just as with partitions each process had its own base/limit registers. In this page map, logical page 18 maps to physical page frame 115.

  The MMU multiplies page frame 115 by 2,000 to get the bottom address of the page frame, 230,000. It then adds back on the offset, 1,450, to get 231,450. Finally, the MMU performs the requested operation on physical location 231,450.

  From the process' point of view, it has access location 37,450, which is on page 18. But the MMU has mapped this to physical location 231,450 on page frame 115.

- If the original page has a suitable protection, the memory access is permitted. Otherwise, the MMU sends an interrupt to the CPU to inform an appropriate interrupt handler of the protection error.

The page map here is the crucial element that makes the system work. Although processes see their logical memory as being contiguous, their page map can spread their logical memory around as a number of separate page frames in physical memory. For example, a process' memory may actually be placed in physical memory like this:

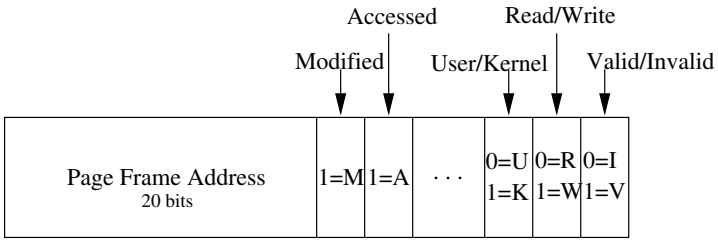


The 'holes' (i.e the available physical memory areas) are now always the same size, that is, the size of the system's pages. So as long as there are enough free page frames, these can be allocated to a new processes as they arrive, or they can be added to the page map of existing process. The latter allows a process' allocated logical memory to grow at any time.

In the partition scheme, each process' size *must* be less than the actual physical amount of memory. With pages, we can make a process be the size of the memory: we just don't allocate all the pages to the process. In other words, the process will occupy the entire address space, but most of that space will be **invalid**. In this situation, the data section and the stack are as far away from each other as they can possibly get, and they can grow much more than with the partition system.

There is one drawback of the page system. When we do a context switch between two processes, we must save the page map for the old process out of the MMU, and load the page map for the new process into the MMU. These operations can be expensive if the page map is big.

13.3 An Example Page Entry



Here is an example page entry (a single page to page frame mapping) from the Intel i386 and up. On this system, pages are 4K in size, and there are 1,048,576 page entries in the page map, numbered from logical page #0 up to logical page #1,048,575.

On the left of the page entry is the matching page frame number. So, if this was page entry #23, and the page frame address was 117, then logical page 23 would be mapped by the MMU to page frame 117.

On the right are the page permissions. If the Valid bit is 0, then no page frame has been mapped to this page, and any access will cause an error. Next is the Read/Write bit: if it is 0, only reads are allowed, if 1, writes are also allowed.

When the User/Kernel bit is 1, access to the page can only be done when the CPU is in kernel mode. Generally, the kernel sets its own pages to have this protection.

Finally, the Access and Modified bits are used by page replacement algorithms, which we will see in the next lecture.

13.4 Pages vs. Paging

Memory management can be a confusing topic, and the terminology used doesn't make it easier. For the rest of these notes, I am using a terminology which is different from the textbook, but I believe will help you grasp the concepts of memory management. Here I will briefly explain my terminology, and also they way in which it differs from the textbook.

A **page system** is a way of mapping from a process' **logical memory** (i.e its address space, or its memory map) to the **physical memory** on the computer. The process' **pages** are mapped to the system's **page frames**.

Paging is a system which copies the contents of unused page frames out to disk, thus making the page frames free for use by other processes. The storage of page frame contents on disk is known as **virtual memory**.

Note the following:

Logical memory: a memory space as seen by a process.

Physical memory: the system's memory space as seen by the operating system.

Virtual memory: the storage of page frame contents on disk.

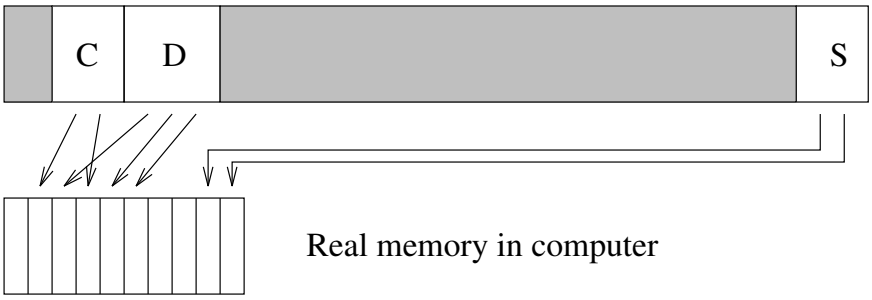
Page system: a form of logical to physical memory mapping which uses a page map.

Paging system: a mechanism which copies the contents of unused page frames out to disk.

The textbook uses the term 'virtual addresses' where I use 'logical addresses', and it uses the term 'paging' to mean both a 'page system' and a 'paging system'.

13.5 Huge Logical Memory Maps

The introduction of 32-bit address spaces (that is, 4 Gbytes of addressable memory) in the early '70s brought a problem: the cost of 4Gbytes of real memory was unimaginable. Page systems were very useful because they allowed a process to occupy all 4Gbytes of logical address space, but in reality it occupied only a small amount of the system's physical memory.



This mapping allowed the data and stack of the process to be placed at opposite ends of this huge address space, thus virtually ensuring that they would never collide. They are then able to *grow*; this allows the process to obtain memory as required, rather than requesting it all when it starts execution.

13.6 Problems of Paged Memory Management

The MMU logical/physical conversion is slow, certainly much slower than the adding on of a base register. This affects the speed at which memory can be read/written.

One optimisation here is to 'cache' the last N logical to physical conversions, as usually the next memory access will be on the same page. This is usually done in the MMU hardware with a **Translation Lookaside Buffer** (TLB).

When context switching between processes, the operating system must 'unmap' all of the pages of the old process, and map in the pages of the next process. If 20 pages have to be unmapped and 30 pages have to be mapped in, the operating system must send 50 commands to the MMU. This can be very slow with processes that have a large number of page map entries.

A page system also suffers from **internal** fragmentation. If a process uses N pages for its code, then $N-1$ will be full, and 1 will be partially full. The same sort of internal fragmentation applies for the data and stack regions in each process.

The number of mappings the MMU must be able to do can be huge. For example, if the page size is 1K, and the address space is 4G, the MMU's page map must hold 4 million page mappings. Thus the MMU's hardware must be very big.

The page size also affects all of the above problems. If it is small, fragmentation is lower, but the number of mappings is larger and context switching slower.

13.7 Sharing Pages

One thing that a paged system can do is to **share** pages between 2 or more processes. A good example is when 10 `vi` editors are running. All have exactly the same code, so the operating system can allow each process to access the same page frames which hold the code. The pages for each process are set to be **read-only**, to prevent one process from altering the code for itself and the other 9 processes.

Sharing can also be done, for example, when a process `fork()`s. The operating system must make copies of the code, data and stack. With page sharing, it can share the page frame that hold the code, and so the code won't need to be copied. Page sharing is also very useful for sharing common libraries between several processes.

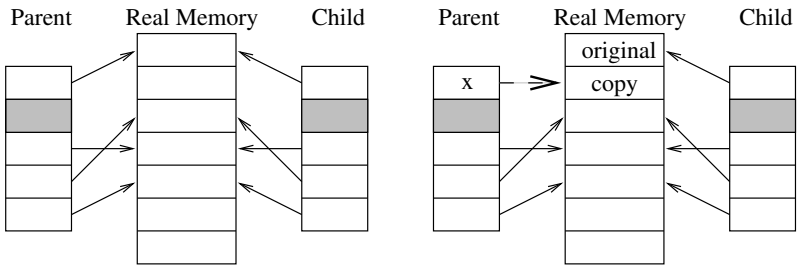
13.8 Copy-on-Write

Copy-on-write is method which can be implemented on a paged system to avoid doing *any* copying on a `fork()` [see ahead to a multi-threaded server].

After a fork, we have two nearly identical processes, the **parent** and the **child**. Note that the contents of their pages are the same, and they will stay the same until one or the other changes a memory value in a page.

Instead of making copies of the pages in the `fork()`, the operating system lets both processes *share* all the pages, but marks every page as **read-only**.

If one process tries to alter a page, a memory error occurs. The operating system receives an interrupt, sees that the page is shared, makes a **copy** of the page by physically copying the contents to another page frame and mapping the 2nd page frame to the current process, and gets the process to retry the memory access.



Not performing the memory copies unless necessary is a big saving under Unix, where a `fork()` is nearly always followed by a `exec()`. This makes the `fork/exec` much faster.

13.9 Operating System Use of Page Entry Protections

We have seen that in the page entries in the MMU, the last three bits set the available protections on each page. Although the bits provide basic protection, the operating system may wish to set similar protections for very different reasons.

The operating system can use the set the basic protections on each process' pages, but it also has to remember *why* each page has this protection. Below is an example table of possible memory areas available to a process, and includes the hardware protections and the operating system reason for setting the permissions that way.

Memory Area	Hardware Protection	OS Protection	Reason
Page 0	Invalid	Invalid	Catches NULL pointer use
Code/Constants	Read-only	Read-only	Unchanging memory, may be shared
Global Data	Read-write	Read-write	Normal variable use
	Read-only	Copy-on-write	Allows untouched pages to be shared
The Heap	Read-write	Read-write	Normal variable use
	Read-only	Copy-on-write	Allows untouched pages to be shared
Invalid	Invalid	Invalid	Pages above heap
Memory Mapped	Read-only	Read-only	Read-only file
File	Read-write	Read-write	Read-write file
	Read-only	Locked region	Record locking on file region
	Read-only	Copy-on-write	Allows unaltered sections to be shared
Shared Memory	Read-only	Read-only	Another process has r-w
Region	Read-write	Read-write	Area is shared read-write
	Read-only	Locked region	Record locking on memory region
	Read-only	Copy-on-write	Allows unaltered sections to be shared
Invalid	Invalid	Fill-on-use	Pages below stack
The Stack	Read-write	Read-write	Normal variable use
	Read-only	Copy-on-write	Allows untouched pages to be shared
Shared Libraries	Read-only	Read-only	Unchanging memory, may be shared
OS Code/Constants	Kernel read-only	Read-only	
OS Global Data	Kernel read-write	Read-write	
Invalid	Invalid	Invalid	
OS Stack	Kernel read-write	Read-write	
Device Pages	Kernel read-write	Read-write	

Observe how part of the process' logical memory map is occupied by the operating system's pages, but these are marked as only accessible in kernel mode. When a process performs a TRAP instruction to do a system call, the CPU switches over to kernel mode, and so the operating system's pages immediately become visible. The TRAP instruction then starts executing the trap handler code at a known location in the memory. The same thing happens when interrupts or exceptions arrive. This is how the operating system makes itself appear when required.

14 Virtual Memory

Textbook reference: Stallings ppg 333 – 382; Tanenbaum & Woodhull ppg 331 – 343

Virtual memory describes methods that give processes more memory than is physically available, or that makes the computer appear to have more memory than is physically available. There are several VM techniques; **paging** is the one most commonly used these days.

14.1 Why Use Virtual Memory?

The memory management methods shown in the last two lectures arise because of one basic requirement: the entire logical address space of a process must be in physical memory before the process can execute and while it is executing. In many cases, the entire process need not be in memory:

- Parts of the process (e.g error handling) get used rarely.
- Often statically declared objects (e.g arrays) are only partially used (e.g a list of records in an array).

If we could get the operating system to have in memory only the needed bits of a process:

- Users could write programs bigger than the size of available memory.
- As each process would use less physical memory while running, the operating system could fit more processes into physical memory.
- Less I/O would be needed to load a process into memory.

The sections of memory currently in use by a process are known as its *working set*, or as its *locality of reference*. The whole point here is to keep the working set in memory (which is fast), and to leave the rest of a process's memory out on disk (which is slow).

14.2 Paging

A paged architecture has a memory granularity less than the process size. Thus, if we can determine what pages are not needed immediately, we can write them out to disk, and release these pages for other pages to use. In other words, we copy to disk the contents of pages which are not part of any process' working set.

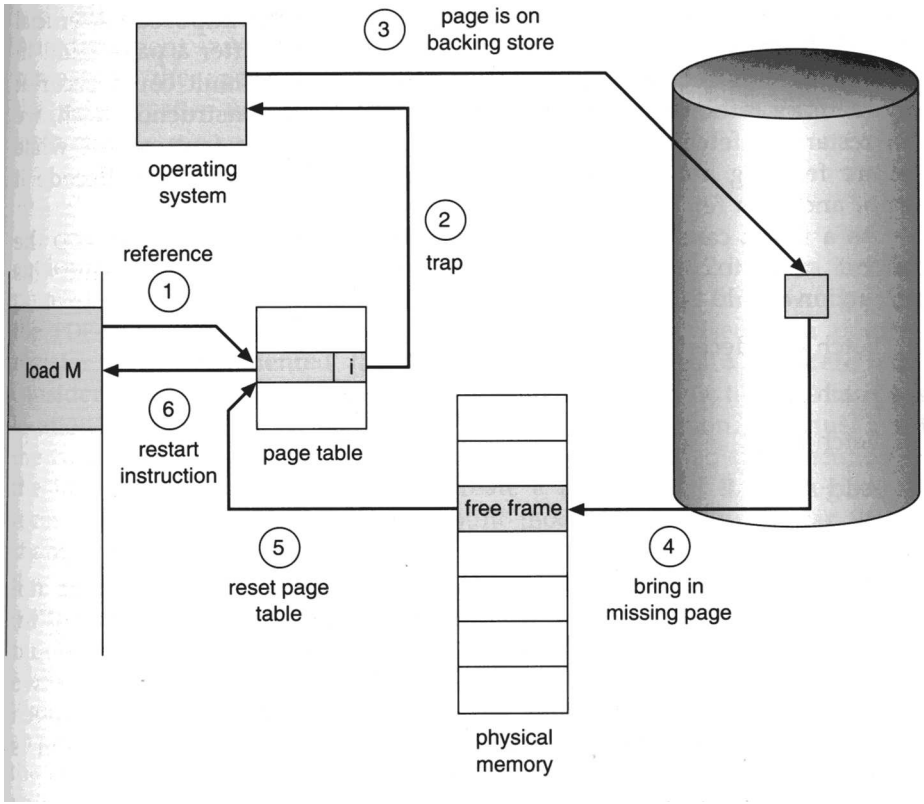
14.3 Paging – How It Works

The operating system either has an abundancy of free pages, or is running short of free pages. As new processes start, or existing processes grow, they request pages from the operating system. If the operating system has spare pages, it allocates them to the requesting process.

However, when the operating system is running short of free pages, the operating system looks through the list of used pages and selects pages that it believes won't be used for a while. It writes these pages to the disk, **scrubs** the pages, and gives them to the process that requested them. If the selection mechanism is good, then eventually only the *working set* of all processes is left in memory.

What happens when a process tries to access a page of memory that has been written to disk? The missing page is marked as **invalid** (it's no longer in main memory), and so a **page fault** occurs when the process tries to access it. The operating system realises that the page is on disk, so it finds a free page frame, and reads the disk copy back into the new page frame.

Note that the operating system must know *why* a page is invalid, and if invalid because it is on the disk, exactly *where* it is on the disk.



After copying out a page to free it, the operating system **scrubs** the page for security reasons – if it didn't do this, a process requesting memory would receive pages with information from another process.

A paging optimisation: if the operating system can tell that the page is **clean**, i.e unchanged since it was last read from disk, there is no need to copy the page out – it is still there.

page out: vi. 1. To become unaware of one's surroundings temporarily, due to daydreaming or preoccupation. "Can you repeat that? I paged out for a minute."

14.4 Hardware Requirements

To provide paging, the operating system needs a method to pick suitable pages to page out. How can it tell if a page is dirty (i.e modified), or if it has been accessed recently? Even better, which pages have been accessed recently?

The MMU on paged systems keeps this information. For each page, it keeps an accessed (A) bit and a modified (M) bit, which are turned on when there is a read or write memory access, respectively. The operating system can look at these bits to help make a decision. It can also turn the bits off as required, e.g when a page frame becomes free.

14.5 Optimal Page Replacement

The best paging algorithm is to choose the page to copy out which is the one that will be used the **furthest** in the future, especially if this period of time is infinity. Obviously, the operating system cannot see into the future, so we can't implement this method.

14.6 Not Recently Used Algorithm

We use the A and M bits in the following manner. When a process starts up, all of its pages have $A = 0$, $M = 0$. Every Nth clock tick, the A bits are set back to 0, to distinguish those pages not recently used. The M bits are left untouched to indicate the **dirty** pages. The hardware sets the A and M bits as described before.

When a page is needed, the operating system categorises the pages into four categories:

- Class 1: not accessed, not modified (clean)
- Class 2: not accessed, modified
- Class 3: accessed, not modified (clean)
- Class 4: accessed, modified

Class 2 indicates that a page was changed a while ago, but not accessed recently (for N clock ticks).

NRU picks a page from the **lowest** non-empty class, i.e. Class 0, or Class 1 if 0 is empty etc. The justification here is that it is better to page out a modified page that hasn't been accessed recently, as against a clean by heavily used page.

The main attraction of NRU is:

- It's easy to understand
- It's fast to implement
- It provides reasonable paging performance, but not optimal

14.7 FIFO Algorithm – First In, First Out

FIFO assumes the oldest page is the one least likely to be needed. The operating system keeps a list of pages: the one at the head is the **oldest**, the tail holds the page most recently allocated by the operating system. When a page must be copied out, the **oldest** is chosen.

This is simple to implement, but it doesn't check page use, so a heavily used page may be paged out.

14.8 Second Chance

Second chance is a variation on FIFO. When a page is needed, look at the oldest page. If it A bit is 0 (i.e it hasn't been accessed recently), use it. Otherwise, set A to 0 and put it on the tail (as if it had just been allocated).

What this is doing is looking for a page that has not been accessed in a long time. If *all* the pages have been referenced, second chance degenerates to FIFO. Both FIFO and second chance are simple, but usually worse than NRU, as an old page is not the same as an unused page.

14.9 Least Recently Used (LRU)

LRU is a good approximation to the optimal algorithm. It assumes that a page heavily used in the recent past will also be heavily used in the future. When a page is needed, pick the page *unused* for the longest time.

This isn't easy to calculate. The operating system needs to keep a list of all used pages, with the most recently used page at the front and the least recently used at the back. The difficulty here is that the page list has to updated after **every** process memory access. This is too expensive.

Instead, the operating system periodically checks for page use (A bit), and reorders the page list. This can still be expensive because the operating system must check every page for recent use. There is a tradeoff here between the frequency of list updates and the accuracy of the result. Fewer list updates is inaccurate but more efficient, more list updates is accurate but expensive CPU-wise.

Although LRU is more expensive to implement than other page choice algorithms, it performs better, and thus is the algorithm most used.

14.10 VM Problems

Obviously, disk I/O is costly. If we page in/out too often, we waste time waiting for the disk.

Optimisation: when a running process needs a **page in**, block it and select another process. Then when the page arrives, make the process ready to run.

Virtual memory makes the machine appear to have more memory than it actually has. However, it's better to have more **real** memory, thus eliminating the need for paging.

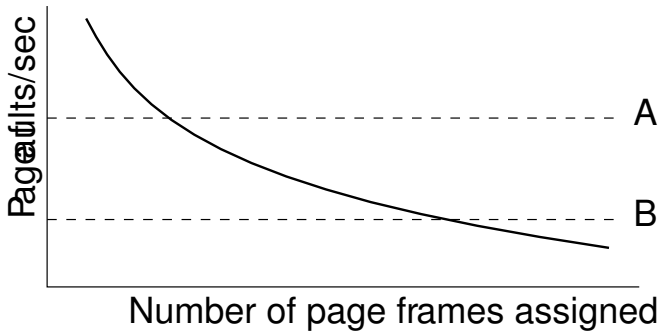
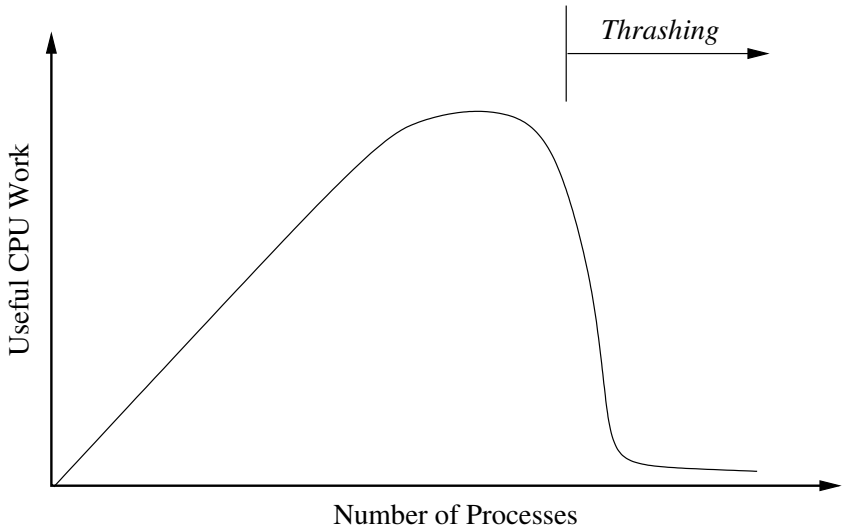


Figure 4-18. Page fault rate as a function of the number of page frames assigned.

Virtual memory increases the CPU utilisation, especially when most processes are I/O bound, because there can be more I/O bound processes in memory, increasing the use of the CPU. But, if all pages are in use, and paging becomes continuous, the machine spends all of its time paging, and no work is done. This is known as **thrashing**.



With an interactive operating system, there is no easy way to limit the number of processes, so you have to live with the possibility of thrashing.

Sharing code pages and other pages *copy-on-write* can help minimise paging.

Instead of waiting for *no* pages to be free, most systems start paging out pages when a *low-water mark* is reached, e.g 5% of total memory. Paging cuts in earlier, but can cope with peaks in memory demands better than 'desperation' paging.

> **thrash**: vi. To move wildly or violently, without accomplishing anything useful. Paging or swapping systems that are overloaded waste most of their time moving data into and out of core (rather than performing useful computation) and are therefore said to thrash. Someone who keeps changing his mind (esp. about what to work on next) is said to be thrashing. A person frantically trying to execute too many tasks at once (and not spending enough time on any single task) may also be described as thrashing.

14.11 Initial Process Memory Allocation

This falls somewhere within the following methods:

Lazy Page Allocation: Mark every page as **invalid**, including all the code pages. Every time a page is **needed**, one is allocated and possibly pages in from disk. This maximises free memory, but can be slow to start up a process. This is also known as **Demand Paging**.

Prepaging: Allocate **every** code and global data page. Only allocate new pages when the global data of the stack grows. This minimises paging but wastes memory.

15 Introduction to File Systems

Textbook reference: Stallings 525 – 554; Tanenbaum & Woodhull ppg 401 – 453

15.1 Introduction

For most users, the file system is the most visible aspect of an operating system, apart from the user interface. Files store programs and data.

The operating system implements the abstract 'file' concept by managing I/O devices, for example, hard disks. Files are usually organised into directories to make them easier to use. Files also usually have some form of protections.

The **file system** provides:

- An interface to the file objects for both programmers and users.
- The policies and mechanisms to store files and their attributes on permanent storage devices.

15.2 What's a File?

A file is a storage area for programs, source code, data, documents etc. that can be accessed by the user through her processes, and are long-term in existence (i.e exist after process-death, logouts and system crashes). There are many different file types, depending on the operating system and the application programs.

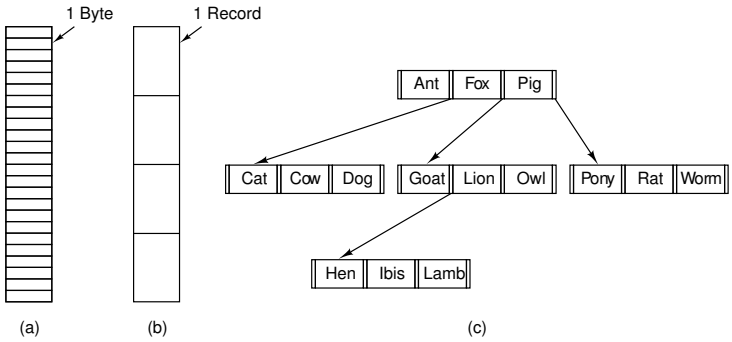


Figure 5-2. Three kinds of files. (a) Byte sequence. (b) Record sequence. (c) Tree.

Examples are byte-structured, record-structures, tree-structured (ISAM). Most systems also give files *attributes*. Example attributes are:

- File's name
- Identification of owner
- Size
- Creation time
- Last access time
- Last modification time
- File type

15.3 File Types

Most operating systems have many different types. Under Unix, all files can be accessed as if they are byte-structured; any other structure is up to the application.

In other operating systems, files are typed according to their content or their name, for example:

- `file.pas`: Pascal source
- `file.ftn`: Fortran source
- `file.obj`: Compiler output
- `file.exe`: Executable
- `file.dat`: Data file
- `file.txt`: Text file

In some systems, the name is just a convention, and you can change the name of a file. In others, the conventions are enforced. You are not allowed to rename files, as the type would then change. This can be a hassle, for example, running `file.pas` through a Pascal source prettifier would produce `file.dat`, which could not be 'converted' back to file.pas.

15.4 File Operations

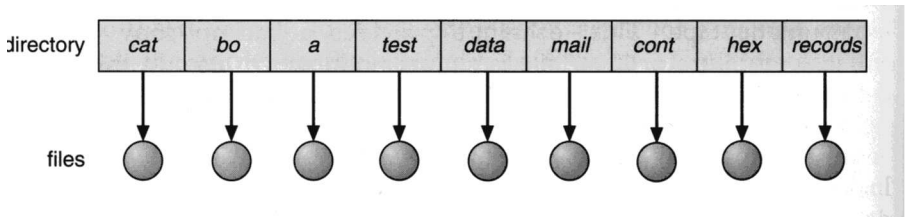
Open, close, read, write (bytes or records) are always provided by every operating system.

Random access is sometimes provided, and usually prevented on special files like terminals, where random access doesn't make sense etc. Record oriented files often have special operations to insert and delete records.

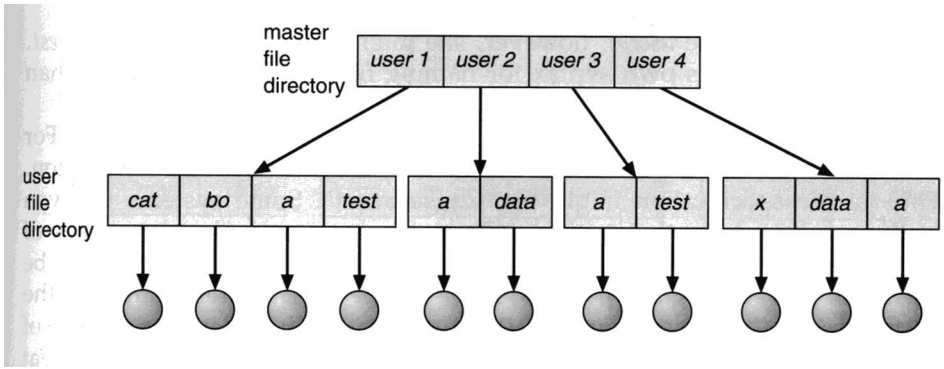
15.5 Directories

Directories are used to help group files logically. They *only* exist to make life easier for humans. There are several types:

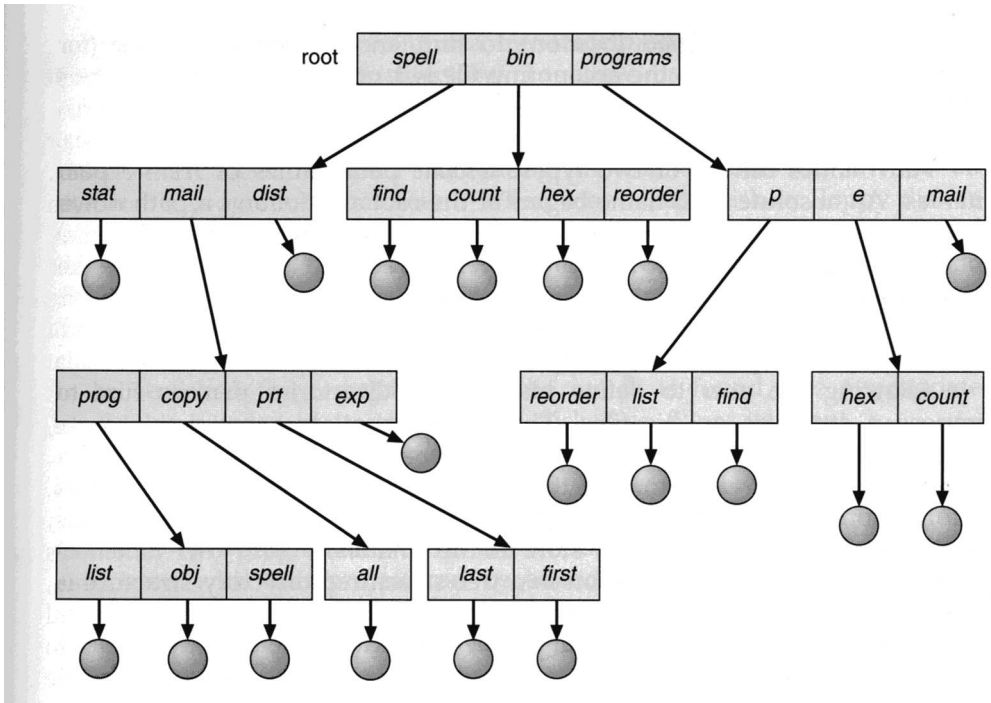
Flat directory (single-level directory).



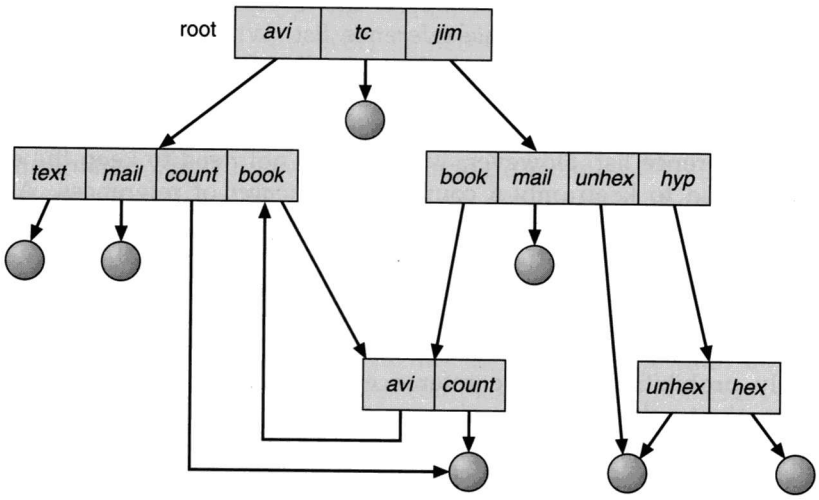
Two-level directory (usually one directory per person).



Tree-structured (hierachial).



Finally, a general graph directory.



The last directory structure can cause problems due to the file duplication. For example, a backup program may back the same file twice, wasting off-line storage.

15.6 Filesystem Metadata

In order to know which blocks a file is composed of, and its attributes, a file system must also store *metatdata* for all files and directories. This metadata occupies some fraction of the disk space, typically 2% to 10%.

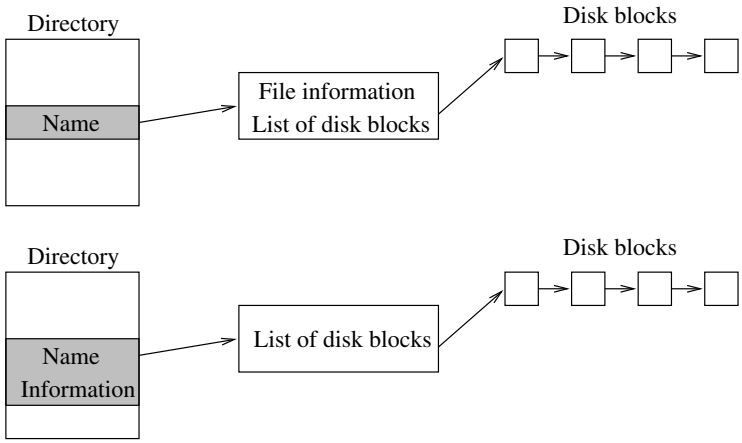
Each file system stores different metadata, but examples are:

- The name and attributes of each file.
- The name and attributes of each directory.
- The list of files and directories in each directory.
- The list of blocks which constitute each file, in order.
- The list of free blocks on the disk.

We will consider the file system metadata in the next few sections.

15.7 Directory Information

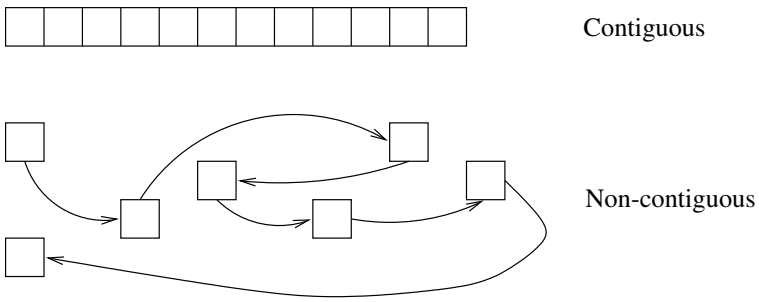
The information about the directory structure (and the list of files in each directory) must be stored by the operating system on disk, so that it is maintained across shutdowns. There are two main methods for storing this information:



The first method allows the acyclic and general directory structure, where a file may have multiple names and multiple attributes.

15.8 File System Design

We now move on to the operating system point of view. The operating system needs to store arbitrarily-sized, often growing, sometimes shrinking, files on block-oriented devices. This can either be done in a **contiguous** fashion, or **non-contiguously**.



A contiguous file layout is fast (less seek time), but it has the same problem as memory partitions: there is often not enough room to grow.

A non-contiguous file layout is slower (we need to find the portion of the file required), and involves keeping a table of the file's portions, but does not suffer from the constraints that contiguous file layout does.

The next problem is to choose a fixed size for the portions of a file: the size of the **blocks**. If the size is too small, we must do more I/O to read the same information, which can slow down the system. If the size is too large, then we get *internal fragmentation* in each block, thus wasting disk space. The average size of the system's files also affects this problem.

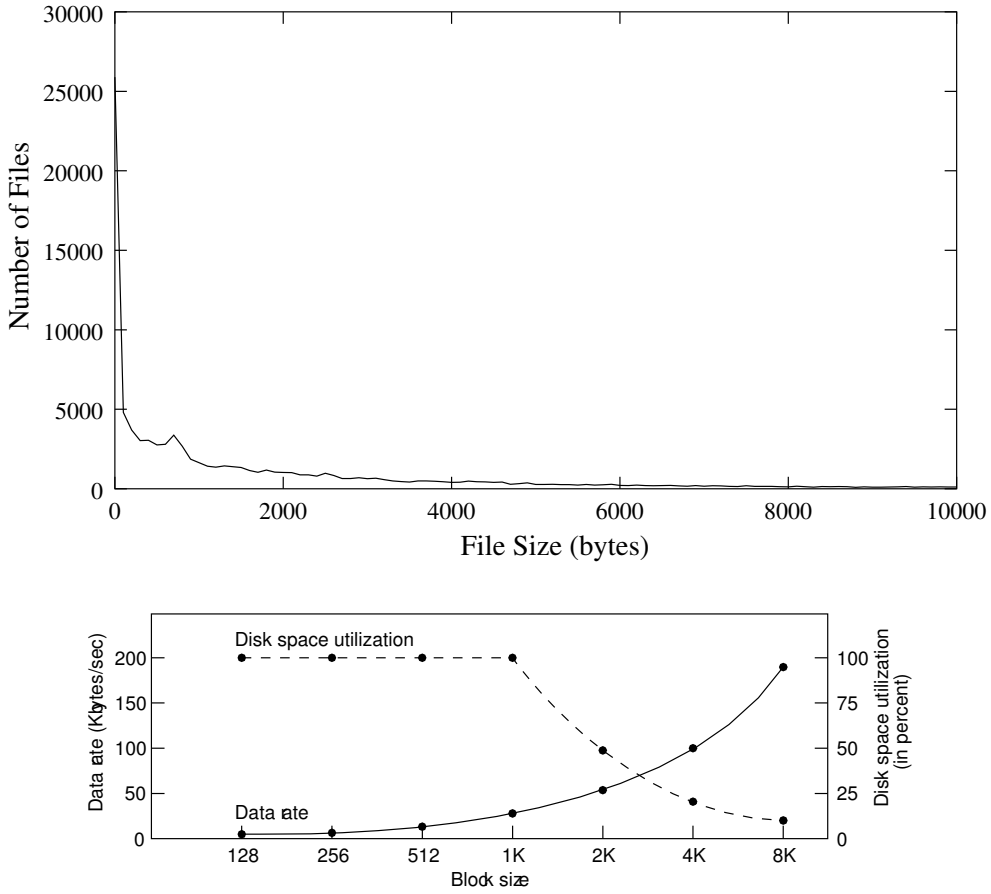


Figure 5-15. The solid curve (left-hand scale) gives the data rate of a disk. The dashed curve (right-hand scale) gives the disk space efficiency. All files are 1K.

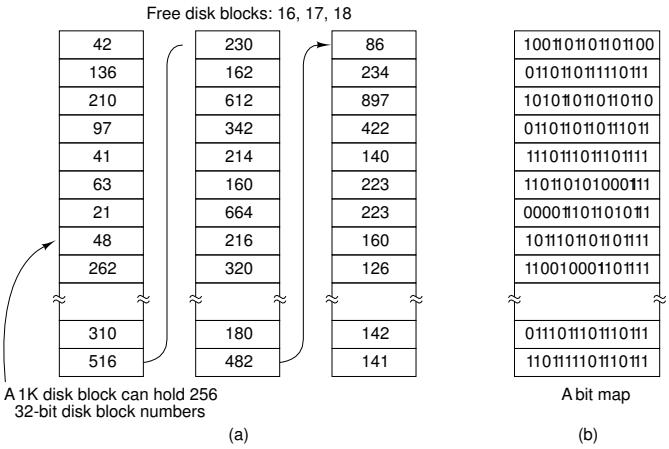
Because of these factors, a block size of 512 bytes, 1K or 2K is usually chosen.

The operating system must know:

- Which blocks on the disk are free (available for use).
- For each file, which blocks it is using.

The first is solved by keeping a list of free disk blocks. This list can often be large. For example, a 20M disk with 1K blocks has 20,480 blocks. If each entry in the list is 2 bytes long, the free list is size 40K. As the number of free blocks becomes smaller, the list size decreases.

Another method of storing the list is with a **bitmap**. Have a table of n bits for a disk with n blocks. If a bit is 1, the corresponding block is *free*; otherwise, the block is in use. The bitmap table here is $1/16$ the size of the free list above (i.e 2560 bytes), but is fixed in size.



Usually the free list resides in physical memory, so that the operating system can quickly find free blocks to allocate. If the free list becomes too big, the operating system may keep a portion of the list in memory, and read in/out the other portions as needed. In any case, a copy of the free list **must** be stored on disk so that the list can be recovered if the machine is shut down.

Thus, as well as the blocks holding file data, the operating system maintains *special* blocks reserved for holding free lists, directory structures etc. For example, a disk under Minix looks like:

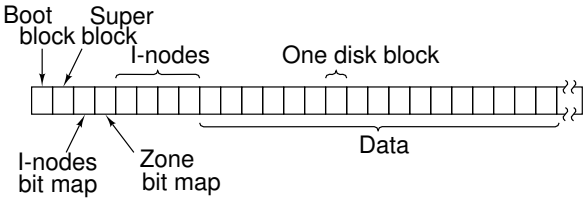


Figure 5-28. Disk layout for the simplest disk: a 360K floppy disk, with 128 i-nodes and a 1K block size (i.e., two consecutive 512-byte sectors are treated as a single block).

Ignore the i-nodes for now. The **boot** block holds the machine code to load the operating system from the disk when the machine is turned on.

The **super** block describes the disk's geometry, and such things as:

- the number of blocks on the disk
- the number of i-node bitmap blocks
- the number of blocks in the free bitmap
- the first data block
- the maximum file size
- the first i-node bitmap block
- the first block in the free bitmap

The **i-nodes** are used to store the directory structure and the attributes of each file. More on these in future lectures.

Note that disks sometimes suffer from physical defects, causing bad blocks. The free list can be used to prevent these bad blocks from being allocated. Mark a bad block as being used; this will prevent it from being allocated in the future.

An alternative is to use a special value to indicate that the block is bad; MS-DOS uses this technique, for example. Bad blocks cannot be marked with a free bitmap, because there are only two values per block: free and in-use.

16 File System Layout

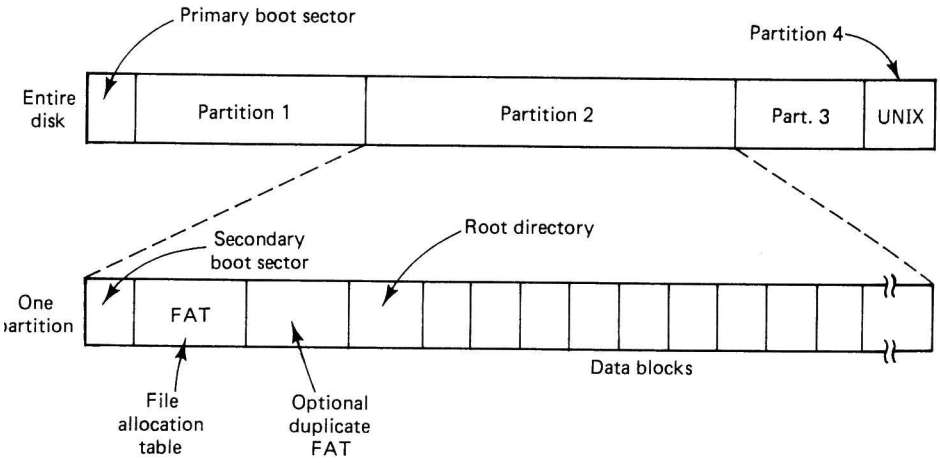
Textbook reference: Stallings 525 – 554; Tanenbaum & Woodhull ppg 415 – 430

16.1 Introduction

The data and attributes of files must be stored on disk to ensure their long-term storage. Different file systems use different layouts of file data and attributes on disk. We will examine the filesystems for MS-DOS and Unix.

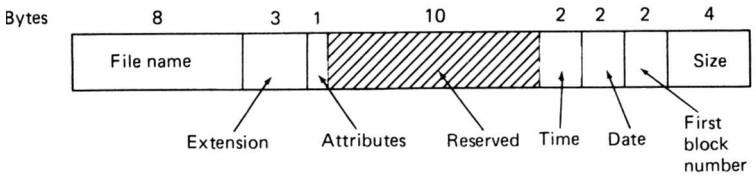
16.2 The MS-DOS Filesystem

MS-DOS breaks disks into up to four sections, known as **partitions**. The first block holds the *primary boot sector*, which describes the types and sizes of each partition.

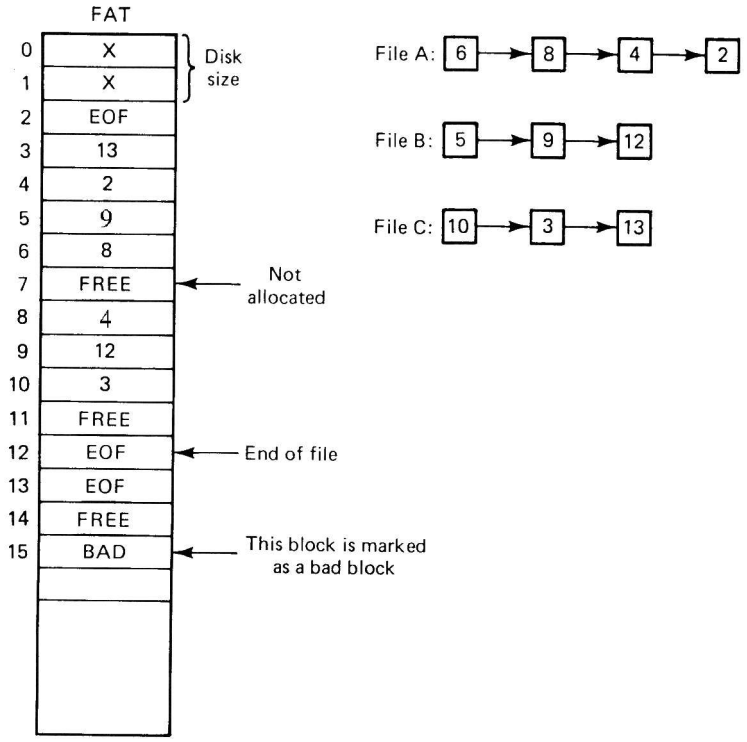


A partition may or may not have an MS-DOS filesystem in it. Within an MS-DOS filesystem is a secondary boot block, a **file allocation table** or **FAT**, a duplicate FAT, a root directory and a number of blocks used for file storage.

Each file has 32 bytes of attributes which are stored in each directory as a *directory entry*. The entry describes the first block used for data storage.



The list of blocks used by the file are kept in the FAT. The FAT lists all disk blocks, and describes if the block is free or bad, or which block comes next in the file.



MS-DOS keeps some of the FAT in memory to speed lookups through the table. For large disks, the FAT may be large, and must be stored in several disk blocks. The size (in bits) of a FAT entry limits the size of the filesystem. For example, MS-DOS originally used a 320K floppy with 1K blocks numbered 0 – 319, using 12 bits to number each block. Thus, the largest FAT (320 blocks) requires 512 bytes, which fits into one disk block.

When hard disks with more than 4096 blocks arrived, the 12-bit block numbers were too small. So MS-DOS had to move to 16-bits, causing the whole directory structure to change.

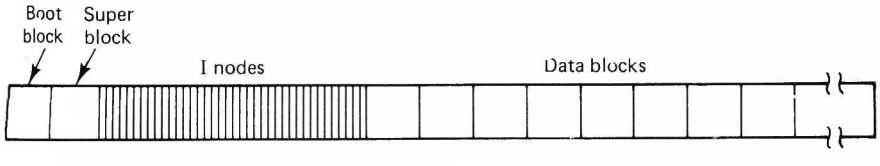
The biggest problem with the FAT scheme is, if the disk is big, the FAT is big. For example, a 64M hard disk, 64,000 1K blocks, thus 2 bytes/block number, thus 128K per FAT. One drawback of the FAT is a search through the FAT to find a file's list of blocks. This is fine for sequential access, but penalises any random access in the file.

MS-DOS performs *first free* block allocation. This may lay a file's data blocks out poorly across the disk. **Defragmentation** can be performed to make files contiguous.

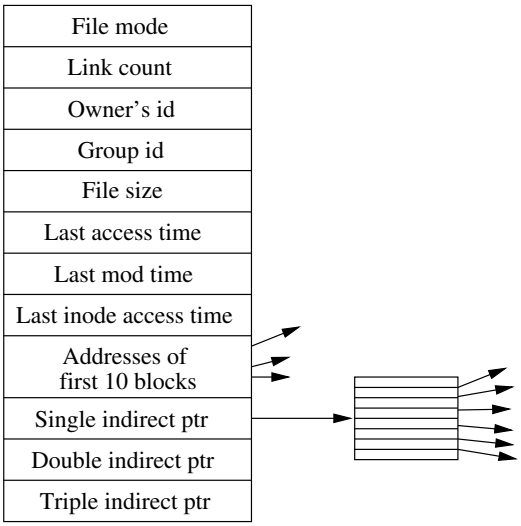
Loss of the FAT makes a filesystem unusable. This is why MS-DOS keeps a duplicate FAT. Viruses, however, usually destroy both FATs.

16.3 The System V Unix Filesystem

The System V filesystem is shown below. The first block is reserved as a boot block. The second block is the **superblock**. It contains information about the layout of the filesystem, such as the number of i-nodes, the number of blocks on the disk, and the start of the list of free disk blocks.



After the superblock are the **i-nodes**. These contain the attributes of files, but not the filenames. Note that the attributes are quite different to MS-DOS. As Unix is a multiuser system, files have ownership and a three-level set of protections (read, write, execute for user, a group of users, and all other users),



Instead of a linear structure for keeping the list of blocks, Unix uses a tree structure which is faster to traverse.

The i-node holds the first 10 block numbers used by the file. If the file grows larger, a disk block is used to store further block numbers; this is a **single indirect block**. Assume the single indirect block can hold 256 block numbers: this allows the file to grow to $10 + 256 = 266$ blocks.

If the single indirect block becomes full, another *two* blocks are used. One becomes the next single indirect block, and the second points to the new single indirect block; this is a **double indirect block**, which can point at 256 single indirect blocks, allowing the file to grow to $10 + 256 + 256 * 256 = 65,802$ blocks.

Sometimes, a file will exceed 65,802 blocks. In this situation, a **triple indirect block** is allocated which points at up to 256 double indirect blocks. There can only be one triple indirect block, but when used, a file can grow to be $10 + 256 + 256^2 + 256^3 = 16,843,018$ blocks, or around 16 gigabytes in size.

One strength of the i-node system is that the indirect blocks are used only as required, and for files less than 10 blocks, none are required. The main advantage is that a tree search can be used to find the block number for any block, and as the tree is never more than three levels deep, it never takes more than three disk accesses to find a block. This also speeds random file accesses.

A System V Unix directory entry looks like:

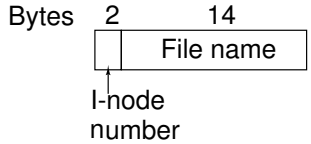


Figure 5-13. A UNIX directory entry.

Note here that Unix only stores the file name and i-node number in each directory entry. The rest of the information about each file is kept in the i-node. This allows files to be **linked**, allowing acyclic and general graph directory structures. This cannot be done with MS-DOS.

592	shared.c in /usr/fred

592	temp_shared.c in /tmp

One problem, if the file `shared.c` is deleted, will the other file still exist? To prevent this, Unix keeps a **link count** in every i-node, which is usually 1. When a file is removed, its directory entry is removed, and the i-node link count decremented; if the link count becomes 0, the i-node and the data blocks are removed.

Linked files have been found to be useful, but there are problems with links. Programs that traverse the directory structure (e.g backup programs) will backup the file multiple times. Even worse, if a directory is a link back to a higher directory (thus making a loop), files in between may be backed up an infinite number of times. Thus, tools must be made clever enough to recognise and keep count of linked files to ensure that the same file isn't encountered twice.

The System V filesystem has several problems. The performance ones are discussed below. The list of i-nodes is fixed, and thus the number of files in each filesystem is fixed, even if there is ample disk space. Unix uses a bitmap to hold the list of free disk blocks, and so bad blocks are not easily catered for.

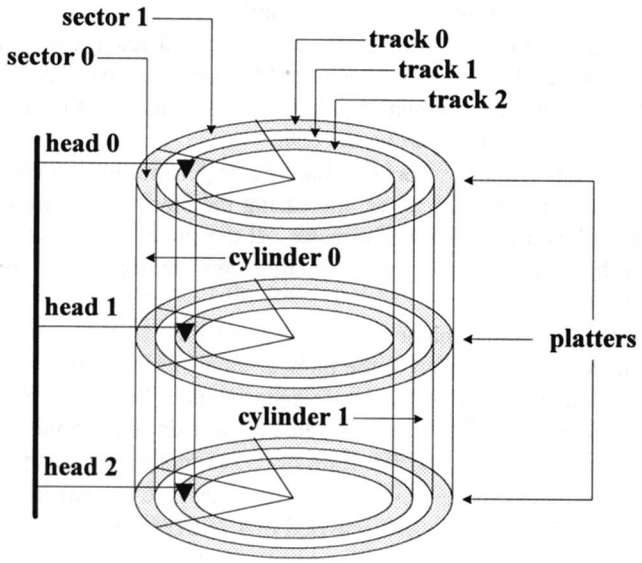
orphaned i-node: n. 1. A file that retains storage but no longer appears in the directories of a filesystem. 2. By extension, a pejorative for any person serving no useful function.

link farm: n. A directory tree that contains many links to files in a master directory tree of files. Link farms save space when (for example) one is maintaining several nearly identical copies of the same source tree, e.g., when the only difference is architecture-dependent object files. "Let's freeze the source and then rebuild the FROBOZZ-3 and FROBOZZ-4 link farms."

16.4 The Berkeley Fast Filesystem

The System V filesystem did not provide good performance. The original block size of 512 bytes gave slow I/O, and the block size was increased to 1,024 bytes. Having all i-nodes at the beginning of the disk caused large head movement as a file's data and attributes were at different ends of the disk. Files that grew slowly ended up with non-contiguous allocation, and the 14 character filename was restrictive.

A new filesystem called the Berkeley Fast Filesystem (FFS) was developed at the University of California, Berkeley, to address these problems. FFS took into consideration the fact that head movement was expensive, but a **cylinder's** worth of data could be accessed without any head movement.



FFS breaks the filesystem up into several *cylinder groups*. Cylinder groups are usually a megabyte or so in size. Each cylinder group has its own free block list and list of i-nodes.

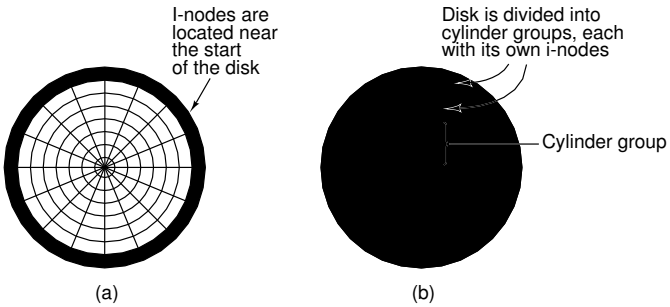


Figure 5-19. (a) I-nodes placed at the start of the disk. (b) Disk divided into cylinder groups, each with its own blocks and i-nodes.

The superblock is replicated in each cylinder group, to minimise the problem of a corrupt filesystem due to loss of the superblock.

To improve I/O speeds, blocks come in two sizes, with the smaller size called a *fragment*. Typical block/fragment sizes are 8K/1K. An FFS file is composed entirely of blocks, except for the last block which may contain one or more consecutive fragments.

Unused fragments may be used by other files, and occasional recopying must be done as files grow in size, to either merge fragments into single blocks, or to keep fragments consecutive within a block.

The Standard I/O library uses the block size to perform file I/O, which helps to maintain I/O performance.

FFS has several allocation policies to improve performance:

- Inodes of files within the same directory are placed in the same cylinder group.
- New directories are in different cylinder groups than their parents, and in the one with the highest free i-node count.
- Data blocks are placed in the same cylinder group as the file's i-node.
- Avoid filling a cylinder group with large files by changing to a new cylinder group at the first indirect block, and at one megabyte thereafter.
- Allocate sequential blocks at rotationally optimal positions.

FFS also increased the filename to 255 characters maximum. FFS provides a significant increase in I/O performance against the System V filesystem (typically several hundred percent improvement).

17 File System Reliability & Performance

Textbook reference: Stallings 525 – 554; Tanenbaum & Woodhull ppg 424 – 432

17.1 File System Reliability

The file system is the repository of user information on a computer system. If a CPU or memory is destroyed, another can be bought. But if a disk is damaged, or the files on the disk damaged, the information therein cannot be restored. Note that even if the data is intact, but the FATs, inodes or directory structure is damaged, the data in the files is effectively lost.

For most users, the consequence of data loss is catastrophic. The operating system must provide methods and tools to minimise the possibility of loss, and also minimise the effect if any loss occurs.

17.2 Bad Blocks

Disks come with bad blocks, and they appear as the disk is used. Each time a bad block appears, mark that block as **used** in the free block table, but ensure that no file uses the block. This leaves the problem of fixing any file that was using the bad block.

17.3 Backups

Generally, the best method of ensuring minimal effect after a catastrophic loss is to have a copy of the data on another medium (disk/tapes); this is a **backup**. It is impossible to have a backup completely up to date, therefore even with a backup you may still lose some data.

Backups should be done at regular intervals, and the *entire* contents of the file system is transferred to disk/tape – a **full** backup. Usually weekly or monthly.

If the file system is large (e.g greater than 200M), backups are very big and time consuming. Between full backups, do **incremental** backups i.e. copy only those files that have changed since the last full/incremental backup.

It is also a good idea to keep 3 **full** dumps, and rotate them when doing a full backup. Thus, even when you are doing a full backup, you still have the last two full backups intact.

17.4 File System Consistency

It is important to keep the file system consistent. If the system crashes before all modified blocks have been written out to disk, the file system is inconsistent, and when the system is rebooted, this may produce weird or unpleasant effects; this is especially true if the file system structures (FATs, inodes, directories, free list) are inconsistent.

Most operating systems have a program that checks the file system consistency. This is usually run when the system reboots. It may do the following:

Check that the link count in an inode equals the number of files pointing to that inode.

Check that all file/directory entries are pointing at used inodes.

Block allocation consistency:

- Read in the free list/bitmap
- Build a **used** list by going through all the inodes/FATs and marking the blocks that are used.
- If the file system is consistent, then each block will have a '1' on the free list or a '1' on the used list.

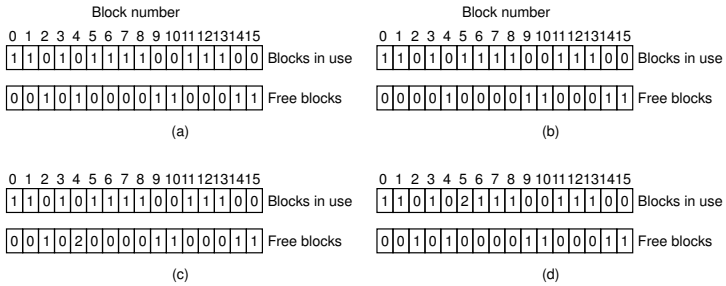


Figure 5-18. File system states. (a) Consistent. (b) Missing block. (c) Duplicate block in free list. (d) Duplicate data block.

- **b)** Missing block # 2. This could be a **bad** block, or a free block that hasn't been marked.
- **c)** Duplicate free block #4. This can be ignored.

- **d)** Duplicate **used** block #5, i.e 2 or more files use this block. This should never happen! If one file is freed, the block is on both the used and the free list! One solution is to make 'n' copies of the block and give each file its own block. Also signal an error to the owners of each file.
- **e)** Block on both free and used lists. We must fix this immediately, as the free block may be allocated and overwritten. Remove the block from the free list.

Some operating systems can protect against user errors. For example, under MS-DOS, you can usually undelete a file that was accidentally deleted, because the directory entry is marked unused, but the remaining information is still intact (i.e attributes, FAT tables). This is technically possible under Unix, but usually not possible because Unix allows multiple processes and users, thus the freed blocks may be reused at any time.

scribble: n. To modify a data structure in a random and unintentionally destructive way. "Somebody's disk-compactor program went berserk and scribbled on the i-node table." Synonymous with **trash**; compare **mung**, which conveys a bit more intention, and **mangle**, which is more violent and final.

17.5 File System Performance – Caching

Disk accesses are much slower than memory, usually at least 10,000 times slower. We therefore need to optimise the file system performance. We have seen that arm and sector scheduling can help in this regard.

Another common technique is a **cache**: a collection of disk blocks that logically belong on disk, but are kept in **memory** to improve performance.

Obviously, we should keep the most recently used or most frequently used disk blocks in memory so that read/writes to these blocks will occur at memory speeds.

Note that we can use the cache to cache **reads** from the disk *and* **writes** to disk. This is known as a **write-through cache**, as writes go through the cache before eventually being written to the disk.

Some operating systems only cache reads, and all writes go directly to disk. This is known as a **write-back cache**. The problem arises as to which block to discard/write back to disk if the cache is full? This is very much like out **paging** problem, and algorithms like FIFO, second chance and LRU can be used here. Note that because block accesses occur much less frequently than page accesses, it is feasible to keep cached blocked in strict LRU order.

Any algorithm that is used should take into account the fact that blocks containing inodes, directories and free lists are special because they are essential to the file system consistency, and are likely to be used frequently. For this reason, some operating systems will write metadata to disk immediately, but writes file data *through* the cache.

One problem with writes *through* the cache is that, if the machine crashes, **dirty** blocks will not be written to the disk, and so data will be lost. This means recent disk writes are not written to disk.

The solution under Unix is to **flush** all dirty blocks to disk every 30 seconds. Caches that write **direct** to disk do not suffer from this problem, but are usually slower because of the I/O delay in writing.

The larger the cache, the more blocks in memory, and thus the better the **hit-rate** and the performance. Disk caches usually range from 512K to 8M of memory.

Finally, it's a bit quirky that disks are used to hold pages from virtual memory, and memory is used to hold recently used disk blocks. It makes sense when you realise that VM is providing more memory with a performance penalty, whereas disk caching is providing some disk with a performance increase.

In fact, newer operating systems (Solaris, FreeBSD) have merged the disk cache into the virtual memory subsystem. Disk blocks and memory pages are kept on the same LRU list, and so the whole of a computer's memory can be used for both working set storage and disk caching.

sync: /sink/ (var. 'synch') n., vi. 1. To synchronize, to bring into synchronization. 2. To force all pending I/O to the disk. 3. More generally, to force a number of competing processes or agents to a state that would be 'safe' if the system were to crash; thus, to checkpoint (in the database-theory sense).

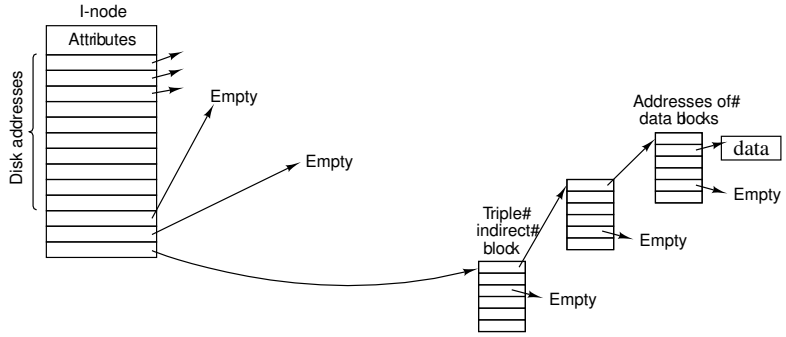
17.6 File Block Allocation

Remember that disk arm motion is slow compared with rotational delay. Therefore the operating system should attempt to allocate blocks to a file contiguously (or with minimal arm movement) where possible. This will lower requested arm motion, and improve disk access.

Some operating systems (notably those for micros) have utilities that take a file system, and rearrange the used blocks to that each file has its blocks arranged in contiguous order. This is really only useful for those files which will not grow. Files that do grow will have some blocks on one area of disk and others on another disk area.

17.7 Holey Files

No, we're not talking about religious files here. Imagine opening a new file, seeking to character 1,000,000 and writing 'Hello' into the file. Technically, the file is 1,000,005 characters long, but it is mostly empty space. A file system that supports **holey** files only allocates blocks that have something in them. For example, in Unix, we would only have the following blocks allocated:



Other data/indirect blocks are allocated only as needed. Reads on unallocated blocks will return 'empty' blocks i.e. all zeroes.

18 Interprocess Communication (IPC)

Textbook reference: Stallings ppg 583 – 586; Tanenbaum & Woodhull ppg 57 – 82

18.1 Why Do Processes Intercommunicate?

If they never did, then all input to a process would have to come from the user! There are several reasons why IPC must be provided. Often a problem is broken into several stages, each handled by a **process** (e.g compilation), so each process passes information to the next stage.

Sometimes a package is broken up into several parts (e.g for an accounting package: inventory, credits, debits, invoicing, payroll). Each part will need to pass/obtain information to/from another part (e.g sales affect inventory etc.).

There are many methods of intercommunicating information between processes. We would also like to have processes on separate machines intercommunicate, too.

18.2 Files

Files are the most obvious way of passing information around. One process writes a file, and another reads it later. This works, but isn't very interactive – you can't use a file to query a database. It can also be very slow, due to disk speeds. However, it is often used for IPC, especially for time-separated files.

Question: what problems do files have as an IPC mechanism for concurrent processes?

18.3 Pipes – Unidirectional Streams

We often need to pass output from one process directly to another process. We could write the output to a file and invoke the next process, but this wastes disk space, especially if the file is discarded after the second process exits.

A classic example is program compilation. In C, the source code is passed through a *preprocessor* before being compiled down to intermediate code by the *compiler front-end*. This is then optimised by the *optimizer*, producing position-independent code. This, finally, has to be linked with any required libraries by the *linker/loader*.

In this situation, there are several intermediate files which will be deleted once the final binary is produced. Many operating systems provide a method of connecting the output **stream** of data from one process to the input of another; this is known as a **pipe** under Unix. A pipe avoids the use of a temporary file. It is unidirectional, so the second process can't talk back to the first.

One pipe problem is the size of the pipe, which is usually limited, e.g. 7K under Unix. If the second process isn't reading as fast as the first is writing, the pipe fills. What should be done?

Unix **blocks** the first process until the second has read some data from the pipe. Similarly, if there is nothing in the pipe, the second process will block reading from the pipe.

Under some systems, the two ends of a pipe are shared between processes that are related (e.g child processes in Unix). In other systems, the pipe ends can be owned by non-related processes. In this latter case, each pipe end needs a 'name' so that processes can find the pipe and connect to it asynchronously.

The naming scheme is usually dependent on the operating system. Pipe ends may be given dummy file names, and can be opened and used just like files. Alternatively, pipe ends may just be given unique numbers.

In any case, how does a process know which pipe to attach itself to? Solutions here are to use a well-known name for certain services, or to have a name lookup service to find the service you want. Obviously, the name service must have a well-known name!

By including the computer's networking address in the pipe's name, IPC via pipes/streams can be performed over networks. This is essentially how most of the Internet's communications works.

18.4 Bidirectional Streams

In this situation, two pipes connect the processes, one in each direction.

This allows replies, so the processes can 'chat'. Two-way IPC is needed for **client/server** interaction. This is the situation when one process is a **client**, and the other is providing a **service**. The first asks for something to be done, and the second performs it and replies with a success/failure message and any associated results.

Bidirectional streams have an inherent **deadlock** problem: Imagine if both pipes fill up and both processes are blocked writing to their pipe. Neither can read any information from their own pipe because they have yet to finish writing into the other pipe. Unidirectional pipes don't suffer from this problem, as there is always one process which isn't writing to a pipe.

Streams are ok if the data really is a stream. But if it is a number of different requests, how does the server

determine where each request begins/ends? Placing markers in the stream is one solution, but then the processes at the end must know how to deal with the markers. We need another approach.

> **deadlock**: n. 1. [techspeak] A situation wherein two or more processes are unable to proceed because each is waiting for one of the others to do something. A common example is a program communicating to a server, which may find itself waiting for output from the server before sending anything more to it, while the server is similarly waiting for more input from the controlling program before outputting anything. (It is reported that this particular flavor of deadlock is sometimes called a 'starvation deadlock', though the term 'starvation' is more properly used for situations where a program can never run simply because it never gets high enough priority. Another common flavor is 'constipation', where each process is trying to send stuff to the other but all buffers are full because nobody is reading anything.) See deadly embrace. 2. Also used of deadlock-like interactions between humans, as when two people meet in a narrow corridor, and each tries to be polite by moving aside to let the other pass, but they end up swaying from side to side without making any progress because they always both move the same way at the same time.

> **deadly embrace**: n. Same as **deadlock**, though usually used only when exactly 2 processes are involved. This is the more popular term in Europe, while **deadlock** predominates in the United States.

18.5 Messages

An alternative IPC is to use messages. Each process can send/receive short lumps of data called **messages**. Each message is independent of all others, and thus is useful for separate requests. A process sends the message to some named destination, either a **process** or an **endpoint**. These may be on the same machine or on remote machines.

- Send(to_destination, from_source, message)
- Receive(&destination, &source, &message)

Each message also holds the addresses for the source and destination process, in a manner similar to e-mail.

Rendezvous Method: The two processes must rendezvous. The sender blocks until the receiver is receiving, and vice versa. Once both are ready, the message is exchanged, and both unblock. This is like passing a letter by hand. Delivery is guaranteed.

Queue Method: The receiver has a **mailbox** (sometimes known as a **port** or a **socket**) where sent messages are delivered. A FIFO queue of messages builds up there. Each `receive()` receives a message. The process blocks if there are no messages to receive. The sender never blocks. This is like sending a letter through Australia Post. There are no guarantees of delivery and, even worse, the receiver's buffer may overflow.

18.6 Remote Procedure Call – RPC

A call operation is basically a send and receive all rolled into one.

```
call(destination, request, &reply)
 {
  send (destination, our_name, request);
  if (error) return(error);

  receive(&our_name, &dummy_buffer, &reply);
  if (error) return(error);
  else return(ok);
 }
```

This can make message passing look like a regular program procedure call, and it is usually known as a **remote procedure call**. For example, a request to read a disk block usually goes directly to the operating system:

```
/* Read block b from the file f, and store it in buf */
err= block_read(block b, file f, buffer *buf)
```

The operating system performs the operation, or returns an error if there is a failure.

The call operation could be used to send the read request to a *remote file server* and get the buffer back from the server. For this to work, we must create the right messages to send the request and receive the reply.

Here's an example subprogram to replace `block_read` with a call to a remote server:

```
block_read(block b, file f, buffer *buf)
 {
  error err;

  struct send_message
   {
    operation o;
    block b;
    file f;
   } out;

  struct recv_message
   {
    error e;
    block b;
    file f;
    char buf[1024];
   } in;

  out.o = READ;
  out.b = b;
  out.f = f;

  err = call(FILE_SERVER, out, &in);
  if (err) return (err);

  err = in.e;
  if (in.b != out.b || in.f != out.f) return(WRONG_ANSWER);
  copy (in.buf, buf);
  return(err);
 }
```

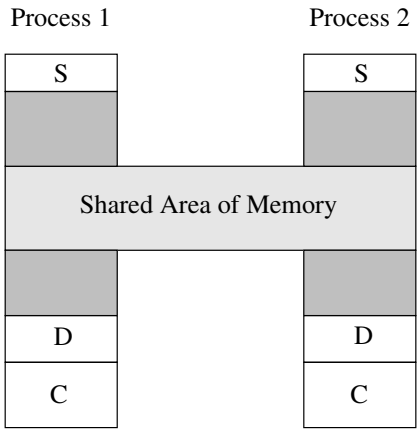
A programmer can use the subprogram given above, and s/he will not be able to tell if the `block_read` is going to the local operating system or to a server.

Actually this is sometimes untrue: the operating system will often timeout on a network send or read, and inform the process of the problem.

Many operating systems provide already-written RPCs to perform operations to remote servers. Note that with uni/bidirectional streams, message and RPCs, the two processes involved do not need to be on the same machine, as the flow of data can travel across network wires.

18.7 Shared Memory

The *fastest* IPC of the lot. Let the operating system map some pages into the same logical locations in two or more processes.



This is easy to do with a paged architecture. The operating system already keeps a list of pages that a process owns; just add a few more to the list. However, the operating system needs to keep a **link count** (like for shared files), so that the page can be freed when the link count becomes zero.

It is not easy to share memory between two or more computers. Several groups are studying how to do this, however.

hot spot: n. 1. It is received wisdom that in most programs, less than 10% of the code eats 90% of the execution time; if one were to graph instruction visits versus code addresses, one would typically see a few huge spikes amidst a lot of low-level noise. Such spikes are called 'hot spots' and are good candidates for heavy optimization or hand-hacking. 2. In a massively parallel computer with shared memory, the one location that all 10,000 processors are trying to read or write at once.

19 Synchronisation

Textbook reference: Stallings ppg 197 – 293; Tanenbaum & Woodhull ppg 57 – 82

19.1 Race Conditions and Critical Sections

We have seen that processes can use shared memory or files for IPC. This can lead to strange effects when there are concurrent processes using the same resource. For example, two processes writing to the same file may cause the file to have unknown contents, as one of the writes will itself be overwritten.

Shared memory is even weirder. Imagine two (or more) accounting processes sharing memory. Each wants to withdraw an amount of money from an account:

```
if (balance - withdrawl >= 0)
   balance = balance - withdrawl;
else error("Can't withdraw that much!");
```

Imagine balance is 800, process A wants to withdraw 500 and process B wants to withdraw 400. If, just after A checks $B - W \geq 0$ and gets 300, it is **pre-empted**, and B is scheduled, B will do the check and withdraw 400, leaving 400. When A is rescheduled, it will already have done the check, and perform the withdrawl, leaving a balance of -100, which is wrong.

This is a **race condition**, where two or more processes are reading or writing some shared data, and the final result depends on who runs precisely when.

The section of code where the race condition occurs is a **critical section**; here it is

```
if (balance - withdrawl >= 0) balance = balance - withdrawl;
```

A critical section happens because it is composed of several steps, and a process can be scheduled out after any of the steps. If there was only one **atomic** step, there would be no critical section, as a process could only be scheduled out after the entire operation.

An operation is atomic if it is guaranteed to be performed all at once, with no interruptions.

19.2 Avoiding a Critical Section

To avoid a critical section, we need the following conditions:

1. No two processes can be inside the critical section simultaneously. As we will see, this isn't enough, so we add three more conditions.
2. No assumptions are made about the relative speeds of each process or the number of CPUs. This disallows solutions based on exact timing.
3. No process stopped outside its critical section should block another process.
4. No process should wait arbitrarily long to enter the critical section. In other words, starvation is not allowed.

Consider a general situation where there is a shared object, e.g the number of stock left for a particular item in a wharehouse, with multiple requests for that stock coming in from various parts of the country. Timing of the requests are unpredictable, and so is the duration of the operations to ship items and update the wharehouse records.

Let us look at some possible solutions for avoiding critical sections.

19.3 Infinite Timeslices

Remember, a process is scheduled out when running if its timeslice expires. If the process could obtain an infinite timeslice, there would be no pre-emption. Therefore, it would complete the critical section, and satisfy condition 1.

However, this is not a good solution, as there is no guarantee that the process will either die, or relinquish the CPU. Thus, this solution violates condition 4.

19.4 Strict Alternation/Rotation

One solution is, for each process:

```
for (ever)
 {
  loop while (turn != 0); /* Wait */     /* != 1, != 2, != 3 etc */
  critical_section();
  turn= 1;                          /*   =2,   =3,   =0 etc */
  other stuff;
 }
```

Thus, the access to the critical section rotates through each process.

This is a **bad** solution, as each process loops continuously waiting for the value of `turn` to change and thus wasting the CPU. This is known as **busy-waiting**.

Also, the solution relies on rotation through the set of processes. Even if a process doesn't want the critical section, it is given it, and others must wait for it to go through the section, thus violating condition 3. Finally, a slow process slows down the rotation, thus violating condition 2.

busy-wait: vi. Used of human behavior, conveys that the subject is busy waiting for someone or something, intends to move instantly as soon as it shows up, and thus cannot do anything else at the moment. "Can't talk now, I'm busy-waiting till Bill gets off the phone."
Technically, 'busy-wait' means to wait on an event by spinning through a tight or timed-delay loop that polls for the event on each pass, as opposed to setting up an interrupt handler and continuing execution on another part of the task. This is a wasteful technique, best avoided on time-sharing systems where a busy-waiting program may hog the processor.

19.5 Test and Set Lock Instruction

If the CPU provides an atomic way of reading and overwriting an address with a '1' (a **test and set lock** instruction), we can create the following:

```
enter_region:
  tsl register, flag  /* Copy the flag to the register, and set flag to 1 */
  cmp register, 0     /* Was flag zero? */
  jnz enter_region    /* No, loop until it is */


leave_region:
  mov flag, 0;        /* Set the flag to zero */
  ret                 /* and return */
```

Now we can protect the critical section with:

```
  enter_section();

      /* Critical section stuff */

  leave_region();
```

A process can only enter the critical section if the `flag` is zero, and in checking the flag, it is set to one, thus preventing anybody else from entering the critical section. This satisfies condition 1.

This also avoids infinite timeslices and the rotation problem. However, we still have busy-waiting, as we loop until we have the `flag`, which wastes the CPU. At the same time, all four conditions are satisfied.

To prevent busywaiting, we need a way of **blocking**/**unblocking** a process if it wants to obtain access to a critical section, but can't get it yet. **Hint:** What normally performs process blocking?

block: 1. vi. To delay or sit idle while waiting for something. "We're blocking until everyone gets here." Compare busy-wait. 2. 'block on' vt. To block, waiting for (something). "Lunch is blocked on Phil's arrival."

19.6 Semaphores

Semaphores were invented by Edgar Dijkstra in 1965. The operating system provides new objects called **semaphores**, each with integer values. The operating system also provides two *system call* operations on

semaphores:

```
acquire(sem)
 {
  if (sem.count == 0) block process;
  sem.count=0;     /* When reawakened, lower count back to 0 */
 }

release(sem)
 {
  sem.count=1;     /* Raise semaphore's value to 1 */
  if (any process blocked waiting for sem) unblock one;
 }
```

The operating system performs both operations in kernel mode, and guarantees that both operations are *atomic*. Now, with the semaphore count initialised by the operating system to 1, we can do:

```
acquire(sem);

    /* Critical section stuff */

release(sem);
```

The first process to acquire the semaphore sets the count to zero. All other processes that try to access the semaphore are blocked. When the process with the semaphore releases it, it sets the count to one,and another process is unblocked. As soon as it is unblocked, it lowers the count to zero, and thus acquires the semaphore.

This solution satisfies all four conditions, and also avoid busy waiting. Usually, the operating system keeps a queue for the set of processes blocked on a semaphore, but this is not strictly necessary.

19.7 Monitors

Of course, if a process goes ahead and enters a critical section without using any synchronisation method, problems will occur. We have to trust that all programmers will do the right thing, and also that the code they produce is correct.

Hoare and Hansen in 1975 suggested building synchronisation into the language so that it is invoked without conscious work by the programmers. The **monitor** is a collection of **code** and condition variables which describe the critical section. The compiler wraps the synchronisation code around the critical section transparently. The synchronisation code can be semaphores, or whatever.

Not many languages provide monitors. The only one that I can think of off-hand is Java.

19.8 Message Passing

Another method of avoiding critical section relies on the fact that in message passing the receiver blocks if there are no message available. This allows processes to exchange a **token** (in the form of a message). Possession of the token allows the process to enter the critical section.

```
#define N 100                       /* number of slots in the buffer */

void producer(void)
{
 int item;
 message m;                         /* message buffer */

 while (TRUE) {
       produce_item(&item);         /* generate something to put in buffer */
       receive(consumer, &m);       /* wait for an empty to arrive */
       build_message(&m, item);     /* construct a message to send */
       send(consumer, &m);          /* send item to consumer */
 }
}

void consumer(void)
{
 int item, i;
 message m;

 for (i = 0; i < N; i++) send(producer, &m);/* send N empties */
 while (TRUE) {
       receive(producer, &m);       /* get message containing item */
       extract_item(&m, &item);     /* extract item from message */
       send(producer, &m);          /* send back empty reply */
       consume_item(item);          /* do something with the item */
 }
}
```

Figure 2-15. The producer-consumer problem with N messages.

This only works when there are two processes; if there were more, to which process would the token-holder send the token?

19.9 Synchronisation Within the Operating System

So far we have looked at synchronisation between processes. However, in many operating systems, different sections of the system may share variables (e.g the process which is running, the free block list, the free memory list).

Each of these operating system sections may be invoked due to system calls and interrupts (timers, I/O completion, timeslice expiry), and thus may "pre-empt" another section's execution.

Without protection, the shared variables may be corrupted due to pre-emption in a non-atomic operation (i.e a critical section). However, we can't use semaphores, because the operating system can't block/unblock itself. Fortunately, because the operating system manages the hardware, it can use this to protect the critical sections.

To protect a critical section, the operating system can *disable* all interrupts. Any interrupts that arrive will be ignored until the operating system re-enables them. This ensures that the execution of the critical section won't be interrupted, and makes the critical section atomic. This might violate condition 4, but we know that the operating system must perform its tasks quickly, so a critical section will not take arbitrarily long to finish.

It is also a good idea to disable only those interrupts which might cause a critical section; for example, leaving disk interrupts enabled probably won't affect your handling of data delivery from the network.

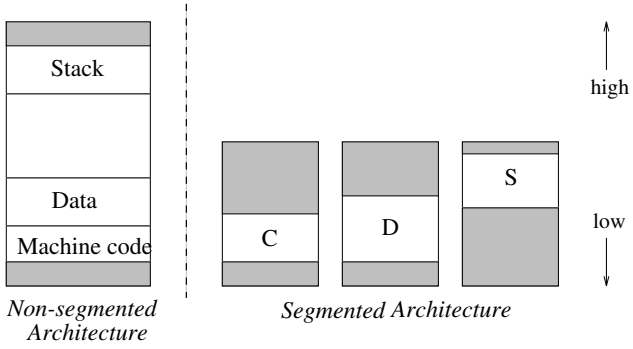
We noted the use of interrupt disabling in Section 9, in the example disk driver from FreeBSD.

20 Threads

Textbook reference: Stallings ppg 153 – 192; Tanenbaum & Woodhull ppg 53 – 56

20.1 Introduction

A process is a sequence of instructions executing in an *address space*, with access to the operating system's services. The process consists of: machine instructions, a data area, a stack, and the machine's registers it is using.



Switching between processes (a **context switch**) is expensive, as the operating system must save/reload the processes' registers and change memory protections.

In many instances, a process would like to be able to perform several independent tasks that can be performed concurrently. Examples of this are database and other servers, and network protocol implementations.

A specific example, a Web server:

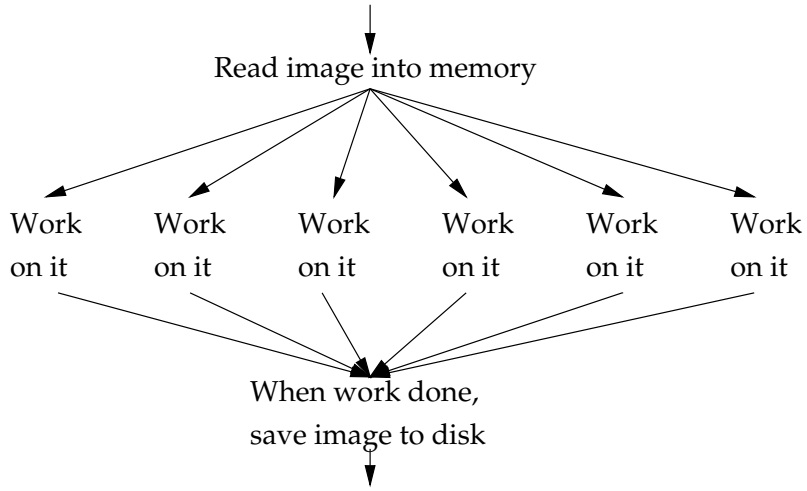
```
loop forever {
   get web page request from client
   check page exists and client has permissions
   transmit web page back to the client
}
```

If the transmission takes a very long time, the server is not able to answer other clients' requests. The server could create a *clone* server to handle the transmission:

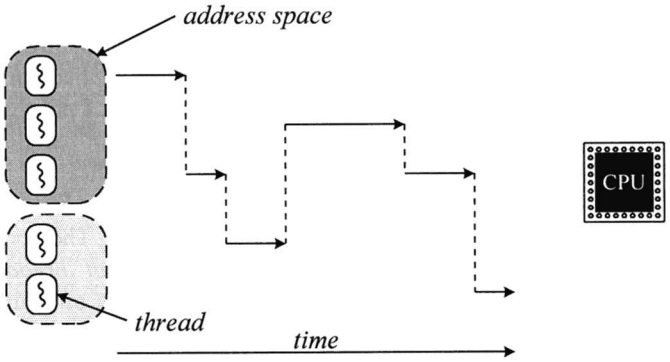
```
loop forever {
   get web page request from client
   check page exists and client has permissions
   make a clone of the server
       original server goes back to 'get web page'
       clone server transmits web page back to the client
}
```

However, if the new server is another process, there is extra context switching overhead. Also, the original server might cache pages in memory, so it would be useful for the two processes to share memory.

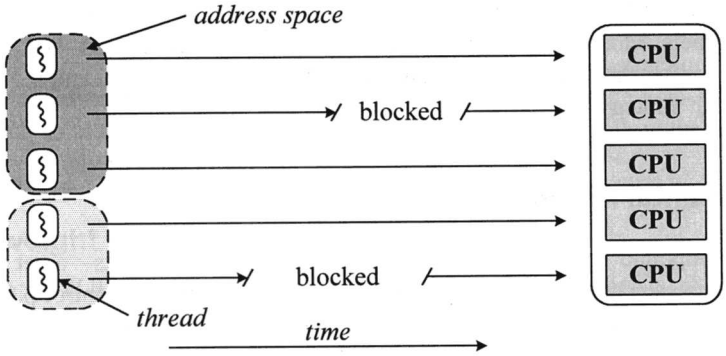
In other situations, some of the tasks to be performed can be done concurrently, but for one stage there is only one task to do, e.g an image manipulation program:



A **thread** is a computational unit within a process. Each thread is relatively independent, but may sometimes need to synchronise with other threads. All threads share a common logical address space. A process, therefore, consists of one or more threads.



Advantages of threads: context switching between threads has less overhead because memory maps do not need to be changed. Switching between threads in two *different* processes has normal overhead. Threads share memory, and so can share information to perform their tasks. When running on a multiprocessor machine, each thread can be scheduled to run on a separate CPU, thus increasing performance.



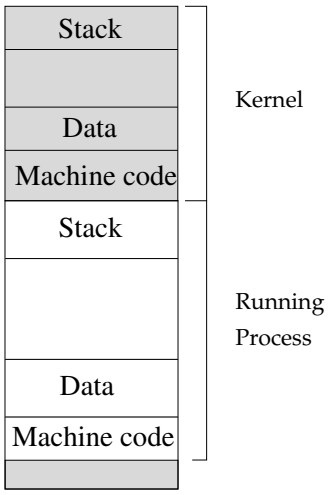
Disadvantages of threads: threads need to have synchronisation primitives available to prevent deadlocks and other problems. Threads have read/write access to other threads' memory, so a badly-behaved thread can damage other threads.

There are several ways of implementing threads. Here are some that are currently in use.

20.2 Kernel Threads

The operating system can make use of threads to perform tasks such as asynchronous I/O. Instead of providing special mechanisms to do the I/O, the kernel can start a **kernel thread** to perform the work. A good example task that can be handled by kernel threads is to perform network transmissions.

There is a kernel-mode process (the **kernel process**) which has several kernel threads. Each thread has as it address space all of kernel memory, and all of the running process' memory.



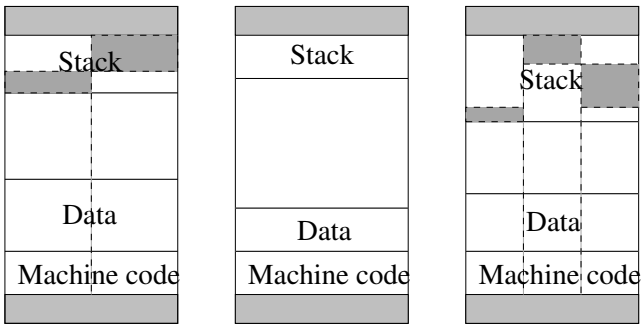
A kernel thread, therefore, doesn't really have its own memory address space; it borrows the running process' and the kernel's. It does have registers and a stack as its context. Context switching of kernel threads is fast.

Disadvantages: only the operating system can use kernel threads, as each runs in kernel-mode and the address space is not tied to a particular process.

20.3 Lightweight Processes

A **lightweight process** is a kernel-supported user-mode thread. Each LWP has its own context; it does not borrow address spaces. Threads within a process have the same address space, and so context switching between them is fast.

Each thread needs its own stack for local variables, but the entire address space is shared between the threads, giving fast context switches but no inter-stack protection.



2 Threads in a Process **Single-threaded Process** **3 Threads in a Process**

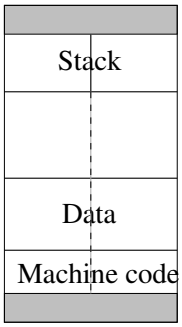
Each thread can perform normal operations such as read/write memory, make systems calls. A thread is blocked just like a normal process. Other threads within the process can continue execution.

LWPs need synchronisation operations to protect the shared memory. The operating system provides these operations via system calls. The disadvantage here is that a system call adds a lot of overhead to any operation, and so LWPs that must do frequent synchronisations suffer poor performance. If the critical section is only a few instructions, *busy-waiting* may be preferable than blocking. Similarly, LWP creation/destruction operations are system calls and are expensive.

As each LWP has a context, the operating system must save this state. The state information is the same size as for a normal process. LWPs are what most people mean when they say 'threads'.

20.4 Mediumweight Processes

A **mediumweight process** is a lightweight process but with a separate stack from the other MWPs. Machine code and global data is still shared.



The advantage is inter-stack protection, but a MWP context switch must perform more memory readdressing, so it is slower. Traditional processes are often known as **heavyweight processes**.

20.5 User Threads

It is possible to provide threads on a system where the kernel knows only about traditional processes. This is accomplished through library packages such as Mach's *C-threads* and POSIX *pthreads*. The libraries provide the functions for thread creation/destruction and synchronisation, with no help required from the kernel.

The library takes responsibility for saving the registers when performing 'internal' context switches between threads in a process. The kernel only performs context switches between normal processes.

Because the kernel is not involved, thread context switching and synchronisation is very fast. Also, there are no extra resources required from the operating system to support user threads. However, if one thread in a process is blocked by the operating system, all the threads in the process are blocked. If the system has multiple processors, threads cannot be executing on more than one CPU.

20.6 Performance Figures

Here are some performance figures for user threads, LWPs and normal processes on a SPARCstation 2 running Solaris:

	Creation Time (microseconds)	Synchronisation Time using semaphores (microseconds)
User thread	52	66
LWP	350	390
Process	1700	200

21 Windows NT

This is a selective look at aspects of Windows NT. It is not a complete tour of NT's functionality. This section is derived from Helen Custer's book on NT and Stephen Ellicott's & Khanh Bui's essays on NT.

Windows NT is an operating system designed by Microsoft. It is pre-emptive, multitasking, multiuser and fully 32-bit. Symmetric multiprocessing, security and networking are built-in. NT also provides several process environments for compatibility with other operating systems, most notably Windows 3.1.

The design of NT was guided by the following goals:

Extensibility: The system must be able to grow and change as market requirements change.

Portability: The system must be moved easily between different hardware platforms.

Reliability: The system should be robust, and protect itself from internal errors and external tampering.

Compatibility: The system should be able to run applications from previous Microsoft operating systems.

Performance: The system should be as fast and responsive as possible on all hardware platforms.

21.1 Overall Design

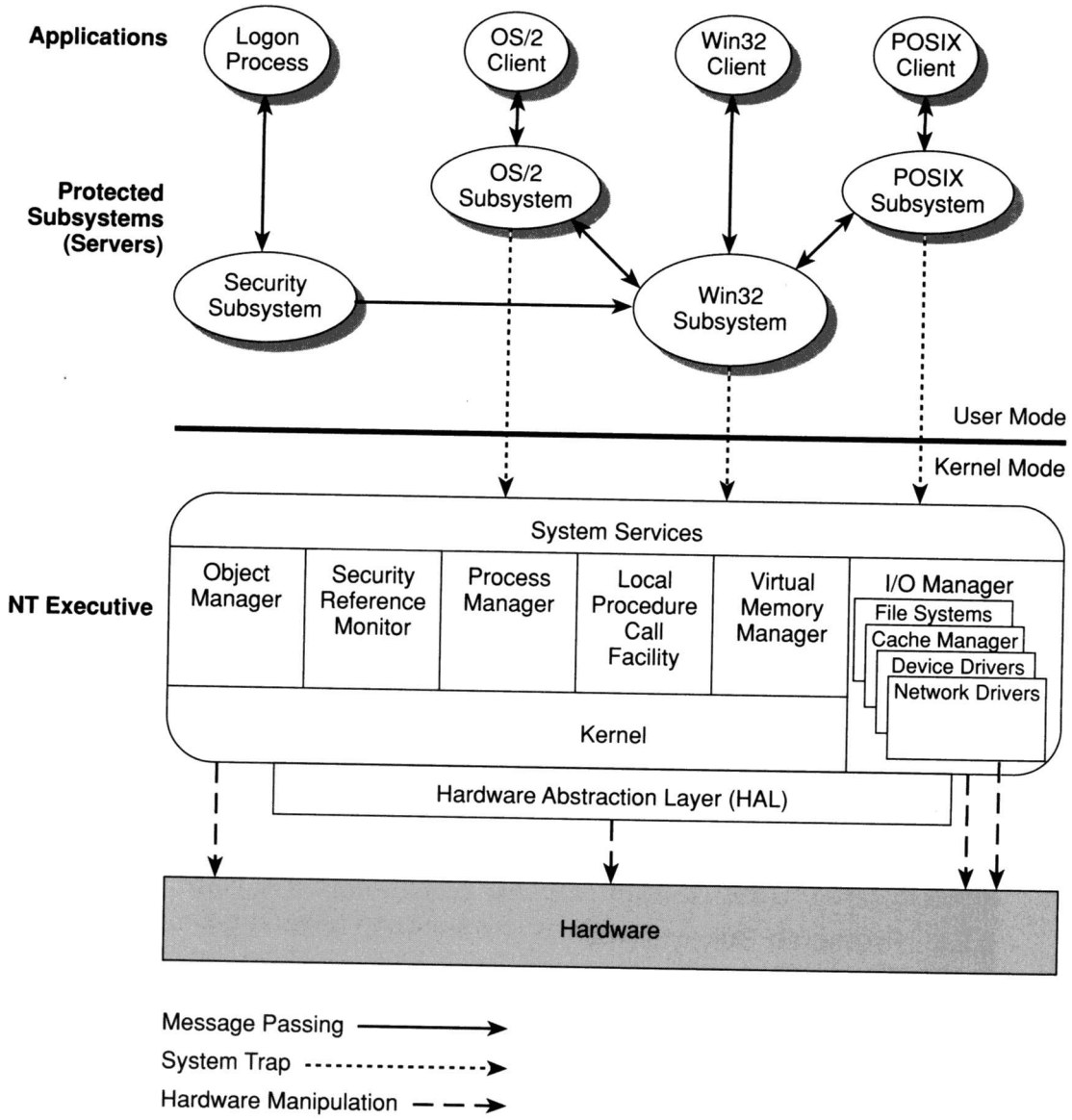


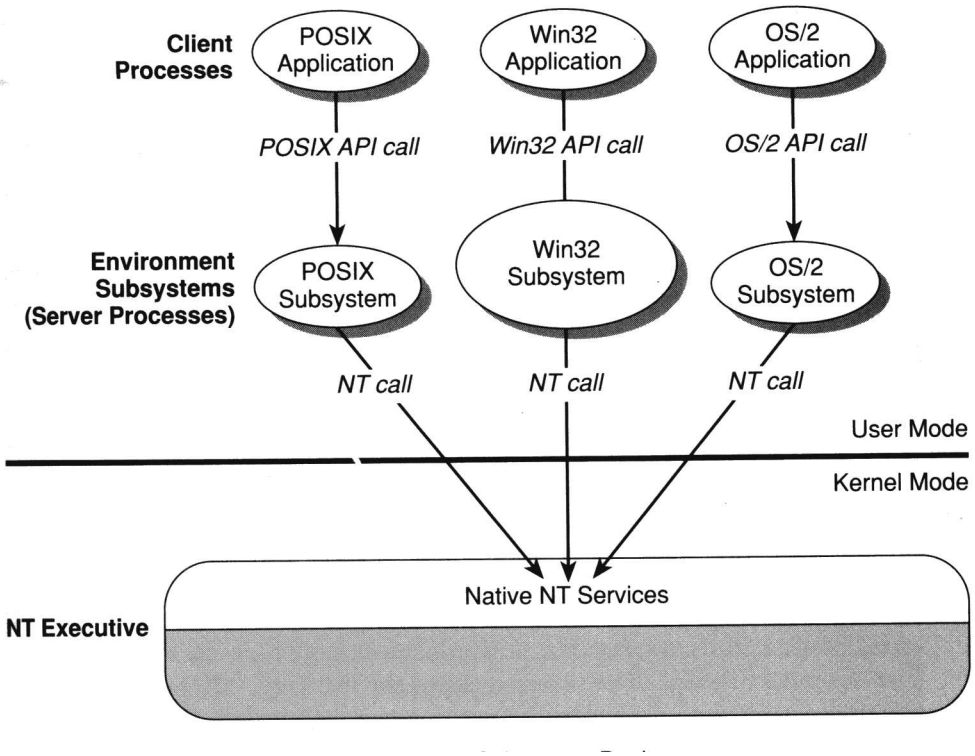
Figure 2-6. Windows NT Block Diagram

NT is a system which uses a micro-kernel approach and a client-server approach in its design. NT is broken into several sections. The **subsystems** run as user-mode processes and provide other processes with certain services. The subsystems are **servers**, and have the same protection as other processes. Clients access their services via message passing.

The **executive** runs in kernel-mode and performs system calls as required by the processes; it also performs message-passing. Below the executive is the **kernel**, which handles thread scheduling, multiprocessor synchronisation, interrupt handling and dispatch, and system recovery on power failure. The **hardware abstraction layer** hides the hardware's complexity from the rest of the executive. The kernel and HAL effectively form the micro-kernel of the system.

NT also uses the 'object' concept to provide access to things in the system: files, memory regions, etc. Processes get 'handles' to object, and objects can have access control lists to give/deny access rights.

21.2 Environment Subsystems



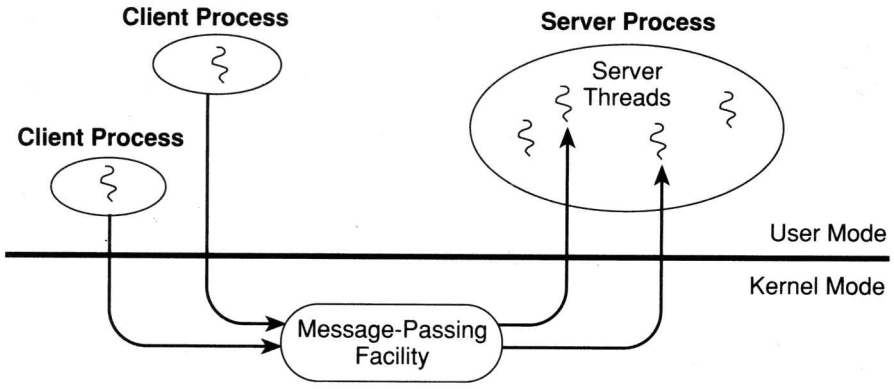
Instead of performing true system calls, applications under NT obtain services from the user-mode environment subsystems.

This allows NT to emulate any number of operating system environments. A subsystem, such as the POSIX subsystem, receives the original request from a POSIX applications, translates the request into an NT system call, and passes the request to the NT executive for servicing. The reply comes back to the POSIX subsystem, and is translated into a reply fit for the POSIX application.

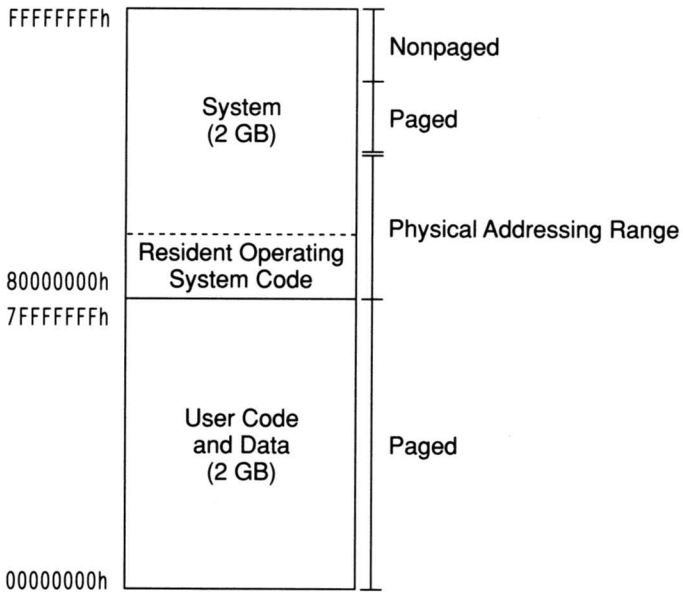
In this way, the original application is unaware that it is running on an emulated environment. Currently, NT supports native NT applications, and has environments for POSIX, Win16, Win32, DOS and OS/2 applications.

21.3 Processes and Threads

NT has both processes and threads; the latter is required to make the subsystems perform efficiently.

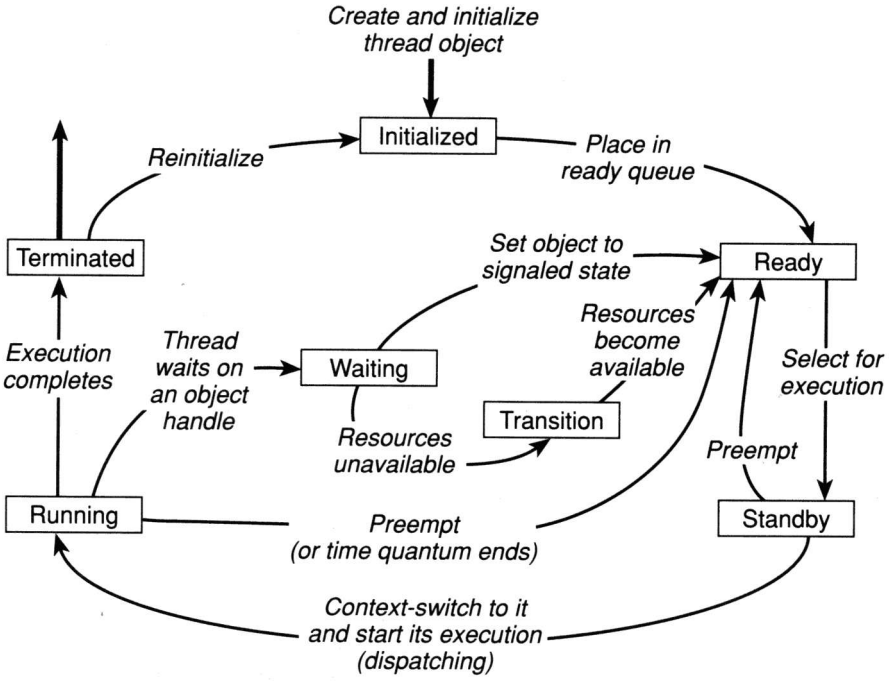


Processes are protected and have their own logical address space. In a 32-bit address space, a process has 2G of the address space, and the remaining 2G is reserved for the protected-mode kernel. When a TRAP is done, the upper 2G becomes valid and the CPU jumps to the kernel's code.



NT uses pre-emtive thread scheduling, with a priority scheme having 32 priority levels. The upper 16 levels are reserved for real-time threads, which have fixed priorities. The lower levels are for normal threads, which start with a particular priority, but move up/down in priority according to their amount of CPU usage.

Threads can be in the following states:



As well as syscalls to create and destroy threads, NT has operations to synchronise threads; these can be used to protect critical sections, or for threads to wait until other threads have performed certain tasks.

Because context switching is expensive, using user-mode processes to emulate environments causes a performance penalty. The implementation of NT has minimised the cost of context switches, improved the speed of message passing, and made other optimisations to help performance.

21.4 Memory Management

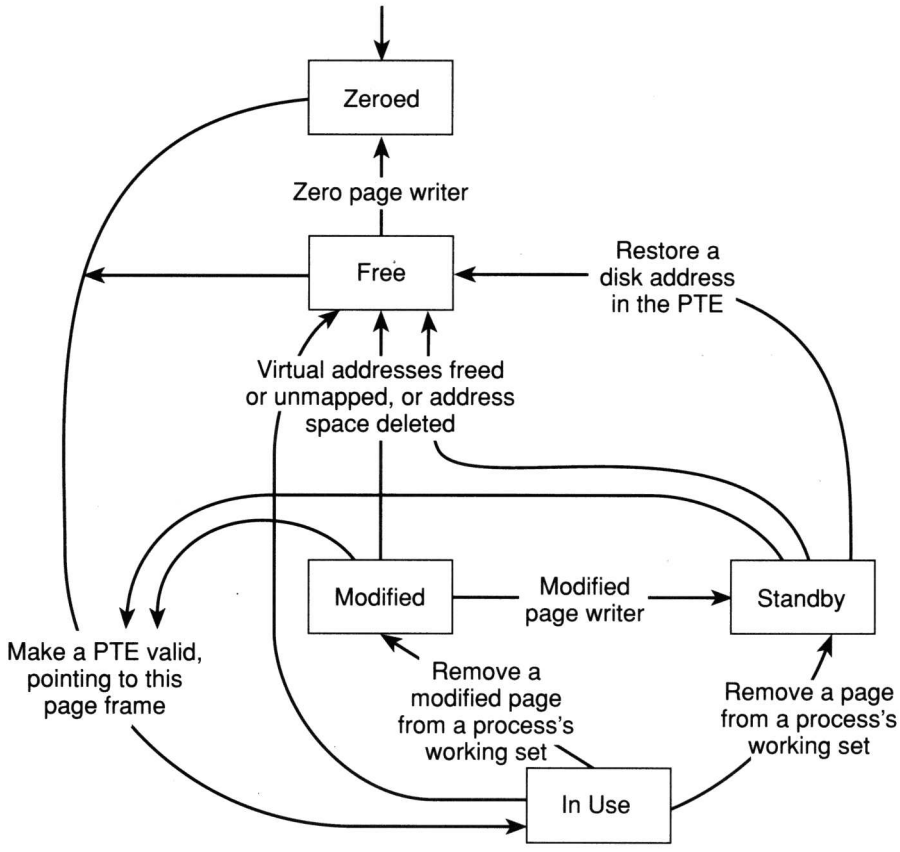
Unlike previous Microsoft operating systems, NT provides a flat, protected address space for each process. NT also provides virtual memory.

Demand paging is used, so that memory is not allocated to a process until it requires it; this helps to keep a process' working set small. NT demand pages 'clusters' of memory; pages near the requested page are loaded in as well as the requested page.

Processes can reserve memory, indicating possible future memory requirements to the system. Pages which go unused are removed from a process' working set. However, a process can lock pages in memory if so required (e.g for real-time processes).

Threads share memory by their very nature. NT allows processes to map files into memory, and to have regions of memory shared between unrelated processes. Copy-on-write is also available to help minimise memory usage.

NT uses a modified FIFO scheme for page replacement, but chooses victim pages well before main memory is exhausted. The victims are placed in a 'standby' list for re-use, or are returned to the original process if required. In this way, NT continually trims the pages in each process so as to maintain the minimum working set. Pages, therefore, can be in one of several states.



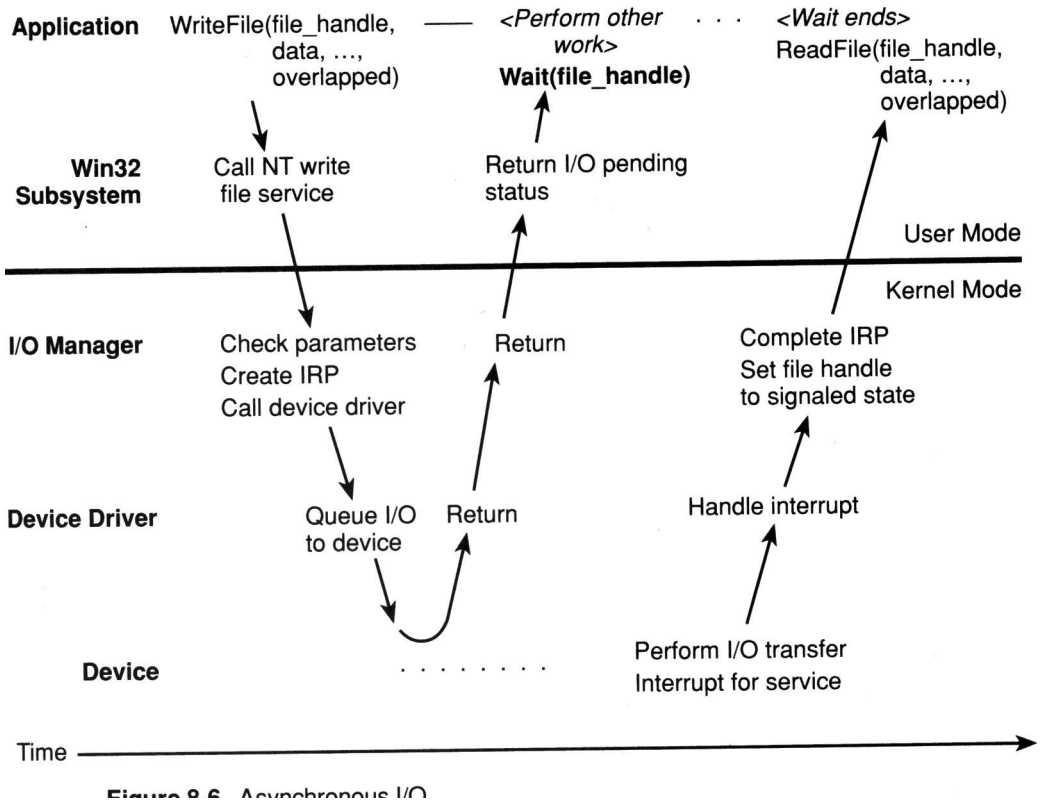
Interestingly enough, some of the executive's pages can be paged in/out of main memory. This helps to keep the working set of the operating system small as well.

21.5 Input/Output

As with most systems, NT uses a layered approach to I/O. For each device, there is a device driver; some drivers handle a number of devices. Above each driver, there is often some device-independent code, such as a filesystem of a network stack.

I/O requests are sent via *I/O request packets* to the I/O manager, which passes them on to the appropriate part of the executive/kernel. I/O can be done directly to a device driver, bypassing the device-independent code.

Unlike most other systems, NT allows an application to perform asynchronous I/O. Instead of blocking on I/O, the process continues execution and, at a later date, the completed I/O causes an exceptional event which is handled by the application.



21.6 The NT Filesystem

NT supports several filesystems: the DOS FAT filesystem, the OS/2 filesystem and a new filesystem native to NT, the NTFS. I don't know if VFAT support is currently available.

The design of NTFS was prompted by the performance, security and attribute deficiencies in the FAT and OS/2 filesystems. Unfortunately, I haven't had enough time to write a discussion on the NTFS, so I might get someone else in the class to describe it.