EDAF35: Operating Systems — Reference Sheet
Lund University

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1 Operating System Introduction

A computer system can be roughly divided into 4 parts.

- The Hardware
- The Operating System
- The Application Programs
- The Users

Defn 1 (Hardware)**.** *Hardware* is the physical components of the system and provide the basic computing resources for the system.. Hardware includes the Central Processing Unit, Memory, and all I/O devices (monitor, keyboard, mouse, etc.).

Remark 1.1 (How to Differentiate). If you are finding it difficult to tell Hardware, Software, and Firmware apart, answer this simple question. Can you hit it with a hammer and break the thing?

Yes Then it is Hardware.
No Then it is Software.
Yes and No Then it is Firmware.

Defn 2 (Software)**.** *Software* is the code that is used to build the system and make it perform operations. Technically, it is the electrical signals that represent `0` or `1` and makes the Hardware act in a specific, desired fashion to produce some result.

On a higher level, this can be though of as computer code.

Remark 2.1 (How to Differentiate). If you are finding it difficult to tell Hardware, Software, and Firmware apart, answer this simple question. Can you hit it with a hammer and break the thing?

Yes Then it is Hardware.
No Then it is Software.
Yes and No Then it is Firmware.

Defn 3 (Operating System)**.** An *operating system* is a large piece of software that controls the Hardware and coordinates the many Application Programs various numbers of Users may use. It provides the means for proper use of these resources to allow the computer to run.

By itself, an operating system does nothing useful. It simply provides an **environment** within which other programs can perform useful work.

The fundamental goal of computer systems is to execute user programs and to make solving user problems easier. These programs require certain common operations, such as those controlling the I/O devices.

In addition, there is no universally accepted definition of what is part of the operating system. A simple definition is that it includes everything a vendor ships when you order "the operating system." The features included, however, vary greatly across systems. Some systems take up less than a megabyte of space and lack even a full-screen editor, whereas others require gigabytes of space and are based entirely on graphical windowing systems. A more common definition, and the one that we usually follow, is that the operating system is the one program running at all times on the computer—usually called the Kernel.

Remark 3.1 (Kernel-Level Non-Kernel Programs). Along with the Kernel, there are two other types of programs:

1. System Programs,
    - Associated with the Operating System but are not necessarily part of the Kernel.
2. Application Programs
    - Includes all programs not associated with the operation of the system

The operating system runs in Kernel-mode, meaning it is allowed to interact with every part of the system, without protection. This allows the OS:

- Load User programs into User-memory
- To dump for errors
- To perform I/O
- To Context Switch and store the information required for such a thing
- In general, to function.

Defn 4 (Kernel)**.** The kernel is a computer program at the core of a computer's operating system with complete control over everything in the system. It is the "portion of the operating system code that is always resident in memory". It facilitates interactions between hardware and software components. On most systems, it is one of the first programs loaded on startup (after the bootloader). It handles input/output requests from software, translating them into data-processing instructions for the central processing unit. It handles memory and its mapping, peripherals like: keyboards, monitors, printers, and speakers. A kernel connects the application software to the hardware of a computer.

The critical code of the kernel is usually loaded into a separate area of memory, which is protected from access by application programs or other, less critical parts of the operating system. The kernel performs its tasks, such as running processes, managing hardware devices such as the hard disk, and handling interrupts, in this protected kernel space.

In modern systems, we tend to have much more than a single Central Processing Unit core. In these multicore/multiprocessor systems, there are 2 ways to organize the way jobs and cores are handled.

1. Symmetric Multiprocessor System
2. Asymmetric Multiprocessor System

Defn 5 (Symmetric Multiprocessor System)**.** In a *symmetric multiprocessor system*, there are multiple Central Processing Units working together. What makes this symmetric is that all CPUs are equal, **there is no single coordinating CPU**. This means that in a 4 CPU system, all 4 CPUs are peers and can work together.

Any CPU can do anything at any time, no matter what any other core is doing.

This is in contrast to an Asymmetric Multiprocessor System.

Defn 6 (Asymmetric Multiprocessor System)**.** An *asymmetric multiprocessor system* has multiple Central Processing Units working together. However, to coordinate all the calculations and operations, **a single CPU is designated the master CPU**. Then, all the other CPUs are slave/worker CPUs.

This is in contrast to an Symmetric Multiprocessor System.

Defn 7 (Application Program)**.** An *application program* is a tool used by a User to solve some problem. This is the main thing a normal person will interact with. These pieces of software can include:

- Text editors
- Compilers
- Web browsers
- Word Processors
- Spreadsheets
- etc.

Additionally, we can have multiple ways of working with system Memory. The 2 main ways are:

1. Uniform Memory Access
2. Non-Uniform Memory Access

Defn 8 (Uniform Memory Access)**.** In *Uniform Memory Access* (*UMA*), **ALL** system Memory is accessed the same way by **ALL** cores.

Defn 9 (Non-Uniform Memory Access)**.** In *Non-Uniform Memory Access* (*NUMA*), some cores have to behave differently to access some Memory.

Defn 10 (User)**.** A *user* is the person and/or thing that is running some Application Programs.

Processes that the user starts run under the user-mode or user-level permissions. This are significantly reduced permissions compared to the Kernel-mode permissions the Operating System has.

Remark 10.1 (Thing Users). Not all Users are required to be people. The automated tasks a computer may do to provide a seamless experience for the person may be done by other users in the system.

1.1 User View

The user's view of the computer varies according to the interface they are using.

In modern times, most people are using computers with a monitor that provides a GUI, a keyboard, mouse, and the physical system itself. These are designed for one user to use the system at a time, allowing that user to monopolize the system's resources. The Operating System is designed for **ease of use** in this case, with relatively little attention paid to performance and resource utilization.

More old-school, but stil in use, a User sits at a terminal connected to a mainframe or a minicomputer. Other users are accessing the same computer through other terminals. These users share resources and may exchange information. The operating system in such cases is designed to maximize resource utilization, to assure that all available CPU time, memory, and I/O are used efficiently and that no individual user takes more than their fair share.

In still other cases, Users sit at workstations connected to networks of other workstations and servers. These users have dedicated resources at their disposal, but they also share resources such as networking and servers, including file, compute, and print servers. Therefore, their operating system is designed to compromise between individual usability and resource utilization.

Lastly, there are Operating Systems that are designed to have little to no User view. These are typically embedded systems with very limited input/output.

1.2 System View

From the computer's point of view, the Operating System is the program that interacts the most with the hardware. A computer system has many resources that can be used to solve a problem:

- CPU time
- Memory space
- File-storage space
- I/O devices
- etc.

The operating system acts as the manager of these resources. Facing numerous and possibly conflicting requests for resources, the operating system must decide how to allocate them so that it can operate the computer system efficiently and fairly. As we have seen, resource allocation is especially important where many Users access the same system.

Another, slightly different, view of an operating system emphasizes the need to control the various I/O devices and user programs. An operating system is a control program. A control program manages the execution of user programs to prevent errors and improper use of the computer. It is especially concerned with the operation and control of I/O devices.

1.3 Computer Organization

The initial program, run ***RIGHT*** when the computer starts is typically kept onboard the computer Hardware, on ROMs or EEPROMs.

Defn 11 (Firmware)**.** *Firmware* is software that is written for a specific piece of hardware in mind. Its characteristics fall somewhere between those of Hardware and those of software. It is almost always stored in the Hardware's onboard storage. Typically it is stored in ROM (Read-Only Memory) or EEPROM (Electrically Erasable Programmable Read-Only Memory). It initializes all aspects of the system, from Central Processing Unit Registers to device controllers, to memory contents.

Remark 11.1 (How to Differentiate). If you are finding it difficult to tell Hardware, Software, and Firmware apart, answer this simple question. Can you hit it with a hammer and break the thing?

Yes Then it is Hardware.
No Then it is Software.
Yes and No Then it is Firmware.

A Central Processing Unit will continue its boot process, until it reaches the `init` phase, where many other system processes or Daemons start. Once the computer finishes going through all its `init` phases, it is ready for use, waiting for some event to occur. These events can be a Hardware Interrupt or a software System Call.

Defn 12 (Daemon)**.** In UNIX and UNIX-like Operating Systems, a *daemon* is a System Program process that runs in the "background", is started, stopped, and handled by the system, rather than the User. Daemons run constantly, from the time they are started (potentially the computer's boot) to the time they are killed (potentially when the computer shuts down). Typical systems are running dozens, possibly hundreds, of daemons constantly.

Some examples of daemons are:

- Network daemons to listen for network connections to connect those requests to the correct processes.
- Process schedulers that start processes according to a specified schedule
- System error monitoring services
- Print servers

Remark 12.1 (Other Names). On other, non-UNIX systems, Daemons are called other names. They can be called *services*, *subsystems*, or anything of that nature.

Defn 13 (Interrupt)**.** An *interrupt* is a special event that the Central Processing Unit **MUST** handle. These could be system errors, or just a button on the keyboard was pressed. Hardware may trigger an interrupt at any time by sending a signal to the CPU, usually by way of the system Bus.

When a CPU receives an interrupt, it may immediately stop what it is doing and transfer execution to some fixed address. To ensure that this happens as quickly as possible, an Interrupt Vector is created.

Defn 14 (Trap)**.** A *trap* or *exception* is a software-generated Interrupt caused by:

- A program execution error (Division-by-zero or Invalid Memory Access).
- A specific request from a user program that an operating-system service be performed (Print to screen).

Defn 15 (Interrupt Vector)**.** The *interrupt vector* is a table/list of addresses that redirect the Central Processing Unit to the location of the instructions for how to handle that particular Interrupt, the Interrupt Handler. Only a predefined number of interrupts is possible, a table of pointers to interrupt routines is used to provide the necessary speed. These locations hold the addresses of the Interrupt Handler routines for the various devices. This array of addresses is indexed by a unique device number, given with the interrupt request, to provide the address of the interrupt service routine for the interrupting device. The interrupt routine is called indirectly through the table, with no intermediate routine needed. Generally, this is stored in low memory (the first hundred or so locations).

1.4 Storage Management

Defn 16 (File)**.** The Operating System abstracts from the physical properties of its storage devices to define a logical storage unit, the *file*. A file is a named collection of related information that is recorded on secondary storage. In general, a file is a sequence of bits, bytes, lines, or records, the meaning of which is defined by the file's creator and user. The operating system maps files onto physical media and accesses these files via the storage devices.

From a user's perspective, a file is the smallest allotment of logical secondary storage; meaning, data cannot be written to secondary storage unless it is within a file.

1.5 System Programs

Another aspect of a modern system is its collection of system programs.

Defn 17 (System Program)**.** *System programs*, also known as *system utilities*, provide a convenient environment for program development and execution. Some of them are simply user interfaces to system calls. Others are considerably more complex. They can be divided into these categories:

File Management These programs create, delete, copy, rename, print, dump, list, and generally manipulate files and directories.

Status Information Some programs simply ask the system for the date, time, amount of available memory or disk space, number of users, or similar status information. Others are more complex, providing detailed performance, logging, and debugging information. Typically, these programs format and print the output to the terminal or other output devices or files or display it in a window of the GUI. Some systems also support a registry, which is used to store and retrieve configuration information.

File Modification Several text editors may be available to create and modify the content of files stored on disk or other storage devices. There may also be special commands to search contents of files or perform transformations of the text.

Programming-Language Support Compilers, assemblers, debuggers, and interpreters for common programming languages (such as C, C++, Java, and PERL) are often provided with the operating system or available as a separate download.

Program Loading and Execution Once a program is assembled or compiled, it must be loaded into memory to be executed. Debugging systems for either higher-level languages or machine language are needed as well.

Communications These programs provide the mechanism for creating virtual connections among processes, users, and computer systems. They allow users to send messages to one another's screens, to browse Web pages, to send e-mail messages, to log in remotely, or to transfer files from one machine to another.

Background Services All general-purpose systems have methods for launching certain System Program processes at boot time. Some of these processes terminate after completing their tasks, while others continue to run until the system is halted. These are typically called Daemons, and systems have dozens of them. In addition, operating systems that run important activities in user context rather than in kernel context may use Daemons to run these activities.

1.6 Operating System Design and Implementation

One important principle is the separation of Policy from Mechanism.

Defn 18 (Mechanism)**.** A *mechanism* determines how to do something.

Defn 19 (Policy)**.** A *policy* determines **what** will be done given the Mechanism works correctly.

The separation of Policy and Mechanism is important for system flexibility. Policies are likely to change across places or over time. In the worst case, each change in policy would require a change in the underlying mechanism. A general mechanism insensitive to changes in policy would be more desirable. A change in policy would then require redefinition of only certain parameters of the system. For instance, consider a mechanism for giving priority to certain types of programs over others. If the mechanism is properly separated from policy, it can be used either to support a policy decision that I/O-intensive programs should have priority over CPU-intensive ones or to support the opposite policy.

Most Operating Systems were built with assembly. However, in recent times (since the invention of C), they have been built with higher-level languages. The advantages of using a higher-level language, or at least a systems-implementation language, for implementing operating systems are the same as those gained when the language is used for application programs:

- The code can be written faster
- Is more compact
- Is easier to understand and debug

In addition, improvements in compiler technology will improve the generated code for the entire operating system by simple recompilation. Finally, an Operating System is far easier to port—to move to some other hardware — if it is written in a higher-level language.

Defn 20 (Port)**.** A *port* is the process of moving a piece of software that was written for one piece of Hardware to another. In some cases, this only requires a recompilation of the higher-level software. In others, it may require completely rewriting the program.

Remark 20.1 (Port Confusion)*.* It is important to note that the Port is ***NOT*** the same thing as a Port.

1.7 Operating System Structure

A system as large and complex as a modern operating system must be engineered carefully if it is to function properly and be modified easily.

1.7.1 Monolithic Approach

Many operating systems do not have well-defined structures. Frequently, such systems started as small, simple, and limited systems and then grew beyond their original scope. MS-DOS is an example of such a system. It was originally designed and implemented by a few people who had no idea that it would become so popular. It was written to provide the most functionality in the least space, so it was not carefully divided into modules.

Defn 21 (Monolithic Kernel)**.** A *monolithic kernel* is an Operating System architecture where the entire operating system is working in Kernel space, and typically uses only its own memory space to run. The monolithic model differs from other operating system architectures (such as the Microkernel) in that it alone defines a high-level virtual interface over computer hardware. A set of System Calls implement all Operating System services such as process management, concurrency, and memory management.

Device drivers can be added to the Kernel as Kernel Modules.

In MS-DOS, the interfaces and levels of functionality are not well separated. For instance, application programs are able to access the basic I/O routines to write directly to the display and disk drives. Such freedom leaves MS-DOS vulnerable to errant (or malicious) programs, causing entire system crashes when user programs fail.

However, this was partly because MS-DOS was also limited by the hardware of its era. Because the Intel 8088 for which it was written provides no dual mode and no hardware protection, the designers of MS-DOS had no choice but to leave the base hardware accessible.

1.7.2 Layered Approach

With proper hardware support, Operating Systems can be broken into pieces that are smaller and more appropriate than those allowed by the original MS-DOS and UNIX systems. The Operating System can then retain much greater control over the computer and over the applications that make use of that computer. Implementers have more freedom in changing the inner workings of the system and in creating modular Operating Systems. Under a top-down approach, the overall functionality and features are determined and are separated into components. Information hiding is also important, because it leaves programmers free to implement the low-level routines as they see fit, provided that the external interface of the routine stays unchanged and that the routine itself performs the advertised task.

1.7.2.1 How to Make Modular Kernels A system can be made modular in many ways. One method is the layered approach, in which the Operating System is broken into a number of layers. The bottom layer (layer 0) is the hardware; the highest (layer N) is the user interface.

1.7.2.2 How to Use Modular Kernels A typical operating-system layer, layer M consists of data structures and a set of routines that can be invoked by higher-level layers. Layer M, in turn, can ***ONLY*** invoke operations on lower-level layers and itself.

1.7.2.3 Advantages of Modular Kernels The main advantage of the layered approach is simplicity of construction and debugging. The layers are selected so that each uses functions and services of only lower-level layers. This approach simplifies debugging and system verification. The first layer can be debugged without any concern for the rest of the system. Once the first layer is debugged, its correct functioning can be assumed while the second layer is debugged, and so on. If an error is found during the debugging of a particular layer, the error must be on that layer, because the layers below it are already debugged. Thus, the design and implementation of the system are simplified. Each layer is implemented only with operations provided by lower-level layers. A layer does not need to know how these operations are implemented; it needs to know only what these operations do.

1.7.2.4 Disadvantages of Modular Kernels The major difficulty with the layered approach involves appropriately defining the various layers. Because a layer can use only lower-level layers, careful planning is necessary. Even with planning, there can be circular dependencies created between layers. For example, the backing-store driver would normally be above the CPU scheduler, because the driver may need to wait for I/O and the CPU can be rescheduled during this time. However, the CPU scheduler may have more information about all the active processes than can fit in memory. Therefore, this information may need to be swapped in and out of memory, requiring the backing-store driver routine to be below the CPU scheduler.

A final problem with layered implementations is that they tend to be less efficient than other types.

1.7.3 Microkernels

This method structures the Operating System by removing all nonessential components from the Kernel and implementing them as system and user-level programs, resulting in a smaller Kernel. There is little consensus regarding which services should remain in the kernel and which should be implemented in user space. Typically, however, microkernels provide minimal process and memory management, in addition to a communication facility.

Defn 22 (Microkernel)**.** A *microkernel* (often abbreviated as μ-kernel) is the near-minimum amount of software that can provide the mechanisms needed to implement an Operating System. These mechanisms include:

- Low-level address space management
- Thread management
- Inter-Process Communication (IPC)

If the hardware provides multiple rings or CPU modes, the microkernel may be the only software executing at the most privileged level, which is generally referred to as supervisor or kernel mode. Traditional Operating System functions, such as device drivers, protocol stacks and file systems, are typically removed from the microkernel itself and are instead run in user space.

In terms of the source code size, microkernels are often smaller than monolithic kernels.

The main function of the Microkernel is to provide communication between the client program and the various services that are also running in user space. Communication is provided through Message Passing.

One benefit of the Microkernel approach is that it makes extending the Operating System easier. All new services are added to user space and consequently do not require modification of the Kernel. When the Kernel does have to be modified, the changes tend to be fewer, because the Microkernel is smaller. The resulting Operating System is easier to port from one hardware design to another. The Microkernel also provides more security and reliability, since most services are running as User— rather than Kernel—processes. If a service fails, the rest of the Operating System remains untouched.

Unfortunately, the performance of Microkernels can suffer due to increased system-function overhead.

1.7.4 Kernel Modules

In this architecture, the Kernel has a set of core components and links in additional services via Kernel Modules, either at boot time or during runtime.

Defn 23 (Kernel Module)**.** A *kernel module* is code that can be loaded into the Kernel image at will, without requiring users to rebuild the kernel or reboot their computer. The modular design ensures that you do not have to make and/or compile a complete Monolithic Kernel that contains all code necessary for hardware and situations.

The idea of the design is for the Kernel to provide core services while other services are implemented dynamically, as the Kernel is running. Linking services dynamically is preferable to adding new features directly to the Kernel, which would require recompiling the Kernel every time a change was made. Thus, for example, we might build CPU scheduling and memory management algorithms directly into the Kernel and then add support for different file systems by way of loadable Kernel Modules.

The overall result resembles a Layered Approach in that each Kernel section has defined, protected interfaces. However, it is more flexible than a Layered Approach, because any Kernel Module can call any other Kernel Module. The approach is also similar to the Microkernel approach in that the primary module has only core functions and knowledge of how to load and communicate with other modules. But it is more efficient, because Kernel Modules do not need to invoke Message Passing to communicate.

1.7.5 Hybrid Systems

In practice, very few Operating Systems adopt a single, strictly defined structure. Instead, they combine different structures, resulting in hybrid systems that address performance, security, and usability issues. For example, both Linux and Solaris use Monolithic Kernels, because having the Operating System in a single address space provides very efficient performance. However, they are also modular, so that new functionality can be dynamically added to the Kernel.

Windows uses a Monolithic Kernel as well (again primarily for performance reasons), but it retains some behavior typical of Microkernel systems. It does this by providing support for separate subsystems (known as operating-system personalities) that run as User-mode processes. Windows also provide support for dynamically loadable Kernel Modules.

1.8 Operating System Debugging

1.8.1 Failure Analysis

If a process fails, most Operating Systems write the error information to a log file to alert Users that the problem occurred. The operating system can also take a Core Dump—— and store it in a file for later analysis.

Defn 24 (Core Dump)**.** A *core dump* captures the memory of the process right as it fails and writes it to a disk.

Remark 24.1 (Why Core?). The reason a Core Dump is named the way it is is because memory was referred to as the "core" in the early days of computing.

Running programs and Core Dumps can be probed by a debugger, which allows a programmer to explore the code and memory of a process. Operating-system kernel debugging is more complex than usual because of:

- The size of the Kernel
- The complexity of the Kernel
- The Kernel's control of the hardware
- The lack of user-level debugging tools.

Defn 25 (Crash)**.** A failure in the Kernel is called a *crash*.

When a Crash occurs, error information is saved to a log file, and the memory state is saved to a Crash Dump.

Defn 26 (Crash Dump)**.** When a Crash occurs in the Kernel, a *crash dump* is generated. This is like a Core Dump, in that the entire contents of that process's Memory is written to disk, except the Crashed Kernel process is written, instead of a User program.

Operating-system debugging and process debugging frequently use different tools and techniques due to the very different nature of these two tasks.

1.8.2 Performance Tuning

Performance tuning seeks to improve performance by removing processing bottlenecks. To identify bottlenecks, we must be able to monitor system performance. Thus, the Operating System must have some means of computing and displaying measures of system behavior. In a number of systems, the operating system does this by producing trace listings of system behavior. All interesting events are logged with their time and important parameters and are written to a file. Later, an analysis program can process the log file to determine system performance and to identify bottlenecks and inefficiencies. Traces also can help people to find errors in operating-system behavior.

Another approach to performance tuning uses single-purpose, interactive tools that allow users and administrators to question the state of various system components to look for bottlenecks. One such tool employs the UNIX command `top` to display the resources used on the system, as well as a sorted list of the "top" resource-using processes.

1.9 System Boot

The procedure of starting a computer by loading the Kernel is known as booting the system. On most computer systems, a small piece of code known as the Bootloader is the first thing that runs.

Defn 27 (Bootloader)**.** The *bootloader* (or bootstrap loader) is a bootstrap program that:

1. Locates the Kernel
2. Loads the Kernel into main memory
3. Starts the Kernel's execution

Some computer systems, such as PCs, use a two-step process in which a simple Bootloader fetches a more complex boot program from disk, which in turn loads the Kernel.

When a CPU receives a reset event, the instruction register is loaded with a predefined memory location, and execution starts there. At that location is the initial Bootloader program. This program is in the form of read-only memory (ROM), because the RAM is in an unknown state at system startup. ROM is convenient because it needs no initialization and cannot easily be infected by a computer virus.

Remark. A reset event on the CPU can be the computer having just booted, or it has been restarted, or the reset switched was flipped.

The Bootloader can perform a variety of tasks. Usually, one task is to run diagnostics to determine the state of the machine. If the diagnostics pass, the program can continue with the booting steps. It also initializes all aspects of the system, from CPU registers to device controllers and the contents of main memory. Sooner or later, it starts the Operating System. Cellular phones, tablets, and game consoles store the entire operating system in ROM. Storing the operating system in ROM is suitable only for:

- Small operating systems
- Simple supporting hardware
- Ensuring rugged operation

A problem with this approach is that changing the bootstrap code requires changing the ROM hardware chips.

All forms of ROM are also known as Firmware. A problem with firmware in general is that executing code there is slower than executing code in RAM. Some systems store the Operating System in firmware and copy it to RAM for fast execution.

A final issue with Firmware is that it is relatively expensive, so usually only small amounts are available. For large operating systems, or for systems that change frequently, the Bootloader is stored in Firmware, and the Operating System is on disk. In this case, the bootstrap runs diagnostics and has a bit of code that can read a single block at a fixed location (say block zero) from disk into memory and execute the code from that boot block. The program stored in the boot block may be sophisticated enough to load the entire operating system into memory and begin its execution.

More typically, it is simple code (as it fits in a single disk block) and knows only the address on disk and length of the remainder of the bootstrap program. GRUB is an example of an open-source Bootloader program for Linux systems. All of the disk-bound bootstrap, and the Operating System that is loaded, can be easily changed by writing new versions to disk. A disk that has a boot partition is called a boot disk or system disk. Now that the full bootstrap program has been loaded, it can traverse the file system to find the Operating System's Kernel, load it into Memory, and start its execution. It is only at this point that the system is said to be running.

2 C Programming

C is one of the lowest "high level" languages you can use today. It provides very minimal abstractions from hardware and assembly code, but allows you to relatively good typechecked code.

2.1 Memory Allocation

Because C is a language that does not provide many abstractions, it also requires the programmer to remember and manage their memory usage. So, **YOU** must be the one to manage the memory, there is **NO** built-in garbage collector for you to use.

Memory allocation is done on the heap of the program's execution space in memory. When you allocate memory in your program, you are actually requesting the operating system to give you the memory you want.

2.1.1 `malloc`

This is the simplest function of all possible memory allocation functions. `malloc`:

- Takes one argument:

  1. The number of bytes to allocate.

- Returns a **POINTER** to the front of the allocated memory.

`malloc` ***DOES NOT*** initialize memory, so it will be garbage.

2.1.2 `calloc`

This is quite similar to malloc. `calloc`:

- Takes 2 arguments:
  1. The number of spaces to allocate, for example the number of elements in an array.
  2. The number of bytes to allocate, for the type being stored.
- Returns a **POINTER** to the front of the allocated memory.

`calloc` ***ZEROS*** memory, so this does have a slight performance penalty.

2.1.3 `realloc`

`realloc` is used to **REALLOCATE** an existing memory location.

- Takes 2 arguments:
  1. The pointer to the memory location previously allocated with either `malloc` or `calloc`.
  2. The amount of memory to reallocate, in bytes.
- If the `NULL` pointer is passed to `realloc`, it will behave exactly like `malloc`.
- Returns a **POINTER** to the front of the reallocated memory

2.1.4 `free`

`free` is used to free memory that was previously allocated, removing from the programming space entirely.

- Takes 1 argument:
  1. A pointer to the memory to be deallocated.
- Returns `void`.

3 System Calls

Defn 28 (System Call)**.** Software may trigger an interrupt by executing a special operation called a *system call.* This can also be called a monitor call. A system call is a messaging interface between applications and the Kernel, with the applications issuing various requests and the Kernel fulfilling them or returning an error.

System calls provide an interface to the services made available by an Operating System. These services are a set of interfaces by which Processes running in User-space can interact with the system. These interfaces give User-level applications:

- Controlled access to hardware
- A mechanism with which to create new Processes
- A mechanism to communicate with existing ones
- The capability to request other Operating System resources

These calls are generally available as routines written in C and C++. Some of the lowest-level tasks (for example, tasks where hardware must be accessed directly) may be written using assembly.

Remark 28.1 (Syscall). In UNIX and UNIX-like systems, System Call is usually shortened to *syscall.*

There are roughly 6 different types of system calls:

1. Process Control
   - End, Abort
   - Load, Execute
   - Create Process, Terminate Process
   - Get process attributes, Set process attributes
   - Wait for time
   - Wait event, Signal event
   - Allocate and Free memory
2. File Manipulation

- Create file, Delete file
- Open, Close
- Read, Write, Reposition
- Get file attributes, Set file attributes

3. Device Manipulation
   - Request device, Release device
   - Read, Write, Reposition
   - Get device attributes, Set device attributes
   - Logically attach or detach devices
4. Information Maintenance
   - Get time or date, Set time or date
   - Get system data, Set system data
   - Get Process, File, or Device attributes
   - Set Process, File, or Device attributes
5. Communications
   - Create, Delete communication connection
   - Send, Receive messages
   - Transfer status information
   - Attach or Detach remote devices
6. Protection

System Calls provide a layer between the hardware and User-space Processes. This layer serves three primary purposes.

1. It provides an abstracted hardware interface for User-space programs. When reading or writing from a file, applications do not have to be concerned with the type of disk, media, or even the type of filesystem on which the file resides.
2. System Calls ensure system security and stability. With the Kernel acting as a middle-man between system resources and User-space, the Kernel can arbitrate access based on permissions, Users, and other criteria. This arbitration prevents applications from incorrectly using hardware, stealing other Processes' resources, or otherwise doing harm to the system.
3. There is a single common layer between User-space and the rest of the system allows for the virtualized system provided to Processes.

System Calls are exposed to the programmer by an Application Programming Interface.

Defn 29 (Application Programming Interface)**.** An *Application Programming Interface* (*API*) specifies a set of functions that are available to an application programmer. They specify the parameters that are passed to each function and the return values the programmer can expect.

Typically, API calls perform System Calls in the background, without the programmer knowing about them.

The system call interface in Linux, as with most UNIX systems, is provided in part by the C library. The C library implements the main Application Programming Interface on UNIX systems, including the standard C library and the system call interface. The C library is used by all C programs and is easily wrapped by other programming languages for use in their programs. POSIX is composed of a series of standards from the IEEE that aim to provide a portable Operating System standard roughly based on UNIX.

3.1 How to Use Syscalls

System Calls (often called Syscalls in Linux) are typically accessed via functionsdefined in the standard C library. These functions can define an arbitrary number of arguments and might[1] result in one or more side effects, for example writing to a file or copying some data into a provided pointer.

System Calls also provide a return value of type `long` that signifies success or error. Usually, though not always, a negative return value denotes an error. A return value of zero is usually (but again, not always) a sign of success.

The C library, when a System Call returns an error, writes a special error code into the global `errno` variable. This variable can be translated into human-readable errors via library functions such as `perror()`.

Finally, System Calls have well-defined behavior. For example, the System Call `getpid()` is defined to return an integer that is the current Process's PID. However, the definition of behavior says nothing of the implementation to achieve this behavior. The Kernel must provide the intended behavior of the System Call but is free to do so with whatever implementation it wants as long as the result is correct.

[1] Nearly all system calls have a side effect (they result in some change of the system's state). A few syscalls, such as `getpid()`, do not have side effects and just return data from the Kernel.

	Windows	UNIX
Process Control	`CreateProcess()`	`fork()`
	`ExitProcess()`	`exit()`
	`WaitForSingleObject()`	`wait()`
File Manipulation	`CreateFile()`	`open()`
	`ReadFile()`	`read()`
	`WriteFile()`	`write()`
	`CloseHandle()`	`close()`
Device Manipulation	`SetConsoleMode()`	`ioctl()`
	`ReadConsole()`	`read()`
	`WriteConsole()`	`write()`
Information Maintenance	`GetCurrentProcessID()`	`getpid()`
	`SetTimer()`	`alarm()`
	`Sleep()`	`sleep()`
Communications	`CreatePipe()`	`pipe()`
	`CreateFileMapping()`	`shm_open()`
	`MapViewOfFile()`	`mmap()`
Protection	`SetFileSecurity()`	`chmod()`
	`InitializeSecurityDescriptor()`	`umask()`
	`SetSecurityDescriptorGroup()`	`chown()`

Table 3.1: System Calls in UNIX and Windows

3.2 How are Syscalls Defined?

In this section, we will be analyzing the `getpid()` System Call. It is defined to return an **integer** (to the User-space) that represents the current Process's PID. The implementation of `getpid()` is shown below.

```
SYSCALL_DEFINE0(getpid) {
        return task_tgid_vnr(current); // returns current->tgid
}
```

`SYSCALL_DEFINE0` is a macro that defines a system call with no parameters (hence the 0). The expanded code looks like this:

```
asmlinkage long sys_getpid(void)
```

System Calls have a strict definition.

1. The `asm` linkage modifier on the function definition is a directive to tell the compiler to look only on the stack for this function's arguments. **This is a required modifier for all system calls.**
2. The function returns a `long`. For compatibility between 32- and 64-bit systems, system calls defined to return an `int` in User-space return a `long` in the Kernel.
3. The `getpid()` System Call is defined as `sys_getpid()` in the Kernel.
    - This is the naming convention taken with all System Calls in Linux.
    - System Call `bar()` is implemented in the Kernel as function `sys_bar()`.

3.2.1 Syscall Numbers

Defn 30 (Syscall Number)**.** Each system call is assigned a unique *syscall number*. This number is used to reference a specific System Call. When a User-space process executes a System Call, the syscall number identifies which syscall was executed;

the Process does not refer to the syscall by name.

After a Syscall Number has been assigned, it cannot change, or already-compiled applications will break. Likewise, if a System Call is removed, its syscall number cannot be recycled, or previously compiled code would aim to invoke one System Call but would invoke another. Linux does provide a "not implemented" System Call, `sys_ni_syscall()` , which does nothing except `return -ENOSYS` , the error corresponding to an invalid System Call. This function is used in the rare event that a syscall is removed or otherwise made unavailable.

The Kernel keeps a mapping of all registered System Calls in the *system call table*, stored in `sys_call_table` . **This table is architecture-dependent.** This table assigns each valid syscall to a unique syscall number.

3.2.2 Syscall Performance

System calls in Linux are very fast. This is because of:

- Linux's fast context switch times; entering and exiting the kernel is a streamlined and simple affair
- The simplicity of the system call handler
- The simplicity of the individual system calls themselves

3.3 Syscall Handler

It is not possible for User-space applications to simply execute a Kernel-function call to a function existing in Kernel-space because the Kernel exists in a protected memory space. If applications could directly read and write to the Kernel's address space, system security and stability would be nonexistent.

Instead, User-space applications must somehow signal to the Kernel that they want to execute a System Call and have the system switch to Kernel mode, where the System Call can be executed in Kernel-space by the Kernel on behalf of the application. The mechanism to signal the Kernel is a Trap, a software interrupt. Incur a Trap, and the system will switch to Kernel-mode and execute the exception handler. However, in this case, the exception handler is actually the system call handler

The important thing to note is that, somehow, User-space causes an exception or trap to enter the Kernel.

3.3.1 Denoting Correct Syscall

Simply entering Kernel-space alone is not sufficient because multiple System Calls exist, all of which enter the Kernel in the same manner. Thus, the Syscall Number must be passed into the Kernel, usually through a Register.

3.3.2 Parameter Passing

In addition to the Syscall Number, most System Calls require that one or more parameters be passed to them. Somehow, User-space must relay the parameters to the Kernel during the trap. There are 2 main ways to do this.

1. The easiest way is to store the parameters in registers
2. If there are not enough registers, or the parameter will not fit in a single register, one is filled with a pointer to User-space memory where all the parameters are stored.

The return value is sent back to User-space also by a register.

3.4 Syscall Functions

3.4.1 Process Control

A running program needs to be able to halt its own execution, either normally or abnormally. If a System Call is made to terminate the currently running program abnormally, or if the program runs into a problem and causes an error Trap, a dump of memory is sometimes taken and an error message generated. The dump is written to disk and may be examined by a debugger—a system program designed to aid the programmer in finding and correcting errors, or bugs—to determine the cause of the problem.

Under either normal or abnormal circumstances, the Operating System must transfer control to the invoking command interpreter. The command interpreter then reads the next command.

To determine how bad the execution halt was, when the program ceases execution, it will return an exit code. By convention, and for no other reason, an exit code of `0` is considered to be the program completed execution successfully. Otherwise, the greater the return value, the greater the severity of the error.

3.4.2 File Manipulation

We first need to be able to `create()` and `delete()` files. Either System Call requires the name of the file and perhaps some of the file's attributes. Once the file is created, we need to `open()` it and to use it. We may then `read()` , `write()` , or perform any other Application Programming Interface-defined action(s). Finally, we need to `close()` the file, indicating that we are no longer using it.

We may need these same sets of operations for directories if we have a directory structure for organizing files in the file system. In addition, for either files or directories, we need to be able to determine the values of various attributes and perhaps to reset them if necessary.

Defn 31 (File Attribute)**.** A *file attribute* contains metadata about the file. This includes the file's name, type, protection codes, accounting information, and so on.

Remark. If the system programs are callable by other programs, then each can be considered an Application Programming Interface by other system programs.

3.4.3 Device Manipulation

Defn 32 (Device)**.** A *device* in an Operating System is a resource that must be controlled. Some of these devices are physical devices (for example, disk drives), while others can be thought of as abstract or virtual devices (for example, files).

A system with multiple Users may require us to first `request()` a device, to ensure exclusive use of it. After we are finished with the device, we `release()` it. These functions are similar to the `open()` and `close()` System Calls for files. Other Operating Systems allow unmanaged access to devices. The hazard then is the potential for device contention and perhaps Deadlock.

Once the device has been requested (and allocated to us), we can `read()` , `write()` , just as we can with files. In fact, the similarity between I/O devices and files is so great that many Operating Systems, including UNIX, merge the two into a combined file–device structure. In this case, a set of System Calls can be shared between both files and Devices. Sometimes, I/O devices are identified by special file names, directory placement, or file attributes.

3.4.4 Information Maintenance

Many System Calls exist simply for the purpose of transferring information between the User program and the Operating System. For example, most systems have a System Call to return the current `time()` and `date()` . Other System Calls may return information about the system, such as the number of current Users, the version number of the Operating System, the amount of free memory or disk space, and so on.

Another set of System Calls is helpful in debugging a program. Many systems provide System Calls to `dump()` memory. A program `trace` lists each System Call as it is executed. In addition, the Operating System keeps information about all its Processes, and System Calls are used to access this information.

3.4.5 Communications

Both of the models discussed are common in Operating Systems, and most systems implement both. Message Passing is useful for exchanging smaller amounts of data, because no conflicts need to be avoided. It is also easier to implement than is shared memory for intercomputer communication. Shared-Memory allows maximum speed and convenience of communication, since it can be done at memory transfer speeds when it takes place within a computer. Problems exist, however, in the areas of protection and synchronization between the Processes sharing memory.

3.4.5.1 Message Passing Messages can be exchanged between the Processes either directly or indirectly through a common mailbox. Before communication can take place, a connection must be opened. The name of the other communicator must be known. Each Process has a *process name*, and this name is translated into an identifier, PID, by which the Operating System can refer to the Process. The `get_processid()` System Call does this translation. The identifiers are then passed to general-purpose `open()` and `close()` calls provided by the file system or to specific `open_connection()` and `close_connection()` System Calls, depending on the model of communication. The recipient Process usually must give its permission for communication to take place with an `accept_connection()` call.

Most Processes that will be receiving connections are special-purpose Daemons. They execute a `wait_for_connection()` call and are awakened when a connection is made. The source of the communication, known as the client, and the receiving Daemon, known as a server, then exchange messages by using `read_message()` and `write_message()` System Calls. The `close_connection()` call terminates the communication.

3.4.5.2 Shared-Memory

In the shared-memory model, `shared_memory_create()` and `shared_memory_attach()` System Calls are used by Processes to create and gain access to regions of memory owned by other Processes. The Operating System tries to prevent one Process from accessing another Process's memory, so shared memory requires that two or more Processes agree to remove this restriction. They can then exchange information by reading and writing data in the shared areas. The form of the data is determined by the Processes and is not under the Operating System's control. The Processes are also responsible for ensuring that they are not writing to the same location simultaneously.

3.4.6 Protection

Protection provides a mechanism for controlling access to the resources provided by a computer system. Historically, protection was a concern only on multiprogrammed computer systems with several Users. However, with the advent of networking and the Internet, all computer systems, from servers to mobile handheld devices, must be concerned with protection.

3.5 Syscall Implementation

The actual implementation of a system call in Linux does not need to be concerned with the behavior of the system call handler. The hard work lies in designing and implementing the system call; registering it with the kernel is simple.

3.5.1 Implementing Syscalls

The first step in implementing a system call is defining its purpose.

- What will it do?
  - The syscall should have exactly one purpose.
  - Multiplexing syscalls (a single system call that does wildly different things depending on a flag argument) is discouraged in Linux.
- What are the new system call's arguments, return value, and error codes?
  - The system call should have a clean and simple interface with the smallest number of arguments possible.
  - The semantics and behavior of a system call are important; they must not change, because existing applications will come to rely on them.
- Be forward thinking; consider how the function might change over time.
- Can new functionality be added to your system call or will any change require an entirely new function?
- Can you easily fix bugs without breaking backward compatibility?
- Will you need to add a flag to address forward compatibility?
  - Many system calls provide a flag argument to address forward compatibility.
  - The flag is not used to multiplex different behavior across a single system call—as mentioned, but to **enable new** functionality and options without breaking backward compatibility or needing to add a new system call.
- Design the system call to be as general as possible.
  - Do not assume its use today will be the same as its use tomorrow.
  - The purpose of the system call will remain constant but its uses may change.
- Is the system call portable?
  - Do not make assumptions about an architecture's word size or endianness.

3.5.2 Parameter Verification

System calls must carefully verify all their parameters to ensure that they are valid and legal. The system call runs in kernel-space, and if the user can pass invalid input into the kernel without restraint, the system's security and stability can suffer.

For example, file I/O syscalls must check whether the file descriptor is valid. Process-related functions must check whether the provided PID is valid. Every parameter must be checked to ensure it is not just valid and legal, but correct. Processes must not ask the kernel to access resources to which the process does not have access.

One of the most important checks is the validity of any pointers that the user provides. Imagine if a process could pass any pointer into the kernel, unchecked, even passing a pointer to which the kernel-calling process did not have read access! Processes could then trick the kernel into copying data for which they did not have access permission, such as data belonging to another process or data mapped unreadable. Before following a pointer into user-space, the system must ensure that:

- The pointer points to a region of memory in user-space. Processes must not be able to trick the kernel into reading data in kernel-space on their behalf.

- The pointer points to a region of memory in the process's address space. The process must not be able to trick the kernel into reading someone else's data.
- The process must not be able to bypass memory access restrictions. If reading, the memory is marked readable. If writing, the memory is marked writable. If executing, the memory is marked executable.

Kernel code must never blindly follow a pointer into user-space!

The kernel provides two methods for performing the requisite checks and the desired copy to and from user-space. One of these two methods must always be used.

1. For writing **to** user-space, the function `copy_to_user()` is provided. It takes three parameters.
   (a) The first is a pointer to the destination memory address in the process's address space.
   (b) The second is a pointer to the source pointer in kernel-space.
   (c) The third is the size, in bytes, of the data to copy.
2. For reading **from** user-space, the method `copy_from_user()` is analogous to `copy_to_user()`. It also takes 3 parameters.
   (a) The first is a pointer to the destination memory address in Kernel-space.
   (b) The second is a pointer to the source memory address in the Process's address space.
   (c) The third is the size, in bytes, of the data to read.

Both of these functions return the number of bytes they failed to copy on error. On success, they return zero. It is standard for the syscall to return `-EFAULT` in the case of such an error.

Both `copy_to_user()` and `copy_from_user()` may block. This occurs if the page containing the user data is not in physical memory but is swapped to disk. In that case, the process sleeps until the page fault handler can bring the page from the swap file on disk into physical memory.

A final possible check is for valid permission. In older versions of Linux, it only `root` could perform these actions. Now, a finer-grained "capabilities" system is in place.

The new system enables specific access checks on specific resources. A call to `capable()` with a valid capabilities flag returns nonzero if the caller holds the specified capability and zero otherwise. See `<linux/capability.h>` for a list of all capabilities and what rights they entail. For example, `capable(CAP_SYS_NICE)` checks whether the **caller** has the ability to modify nice values of other processes.

By default, the superuser possesses all capabilities and nonroot possesses none.

3.5.3 Final Steps in Binding a Syscall

After the System Call is written, it is trivial to register it as an official System Call:

1. 1. Add an entry to the end of the system call table. This needs to be done for each architecture that supports the System Call (which, for most calls, is all the architectures). The position of the syscall in the table, starting at zero, is its Syscall Number. For example, the tenth entry in the list is assigned syscall number nine.
2. For each supported architecture, define the syscall number in `<asm/unistd.h>`.
3. Compile the syscall into the Kernel image (as opposed to compiling as a module). This can be as simple as putting the System Call in a relevant file in `kernel/`.

Look at these steps in more detail with a fictional System Call, `foo()`. First, we want to append `sys_foo()` to the system call table, and record its Syscall Number. This number is the zero-indexed location of the new `sys_foo()` function. For most architectures, the table is located in `entry.S`. Although it is not explicitly specified, the System Call is implicitly given the next subsequent syscall number.

For each architecture you want to support, the System Call must be added to the architecture's system call table. Usually you would want to make the System Call available to each architecture, so it must be placed in each architecture's system call table. The System Call does not need to receive the same syscall number under each architecture. Then, the Syscall Number is added to `<asm/unistd.h>`.

Because the System Call must be compiled into the core Kernel image in all configurations, so the `sys_foo()` function must be placed somewhere in `kernel/*.c`. You should put it wherever the function is most relevant. For example, if the function is related to scheduling, you could define it in `kernel/sched.c`.

3.5.4 Why NOT Implement a Syscall

The previous sections have shown that it is easy to implement a new System Call, but that in no way should encourage you to do so. Often, much more viable alternatives to providing a new System Call are available.

Let's look at the pros, cons, and alternatives. The pros of implementing a new interface as a syscall are:

- They are simple to implement and easy to use.
- Their performance on Linux is fast.

The cons:

- You need a syscall number, which needs to be officially assigned to you.
- After the System Call is in a stable series Kernel, it is written in stone. The interface cannot change without breaking user-space applications, which Linux explicitly disallows.
- Each architecture needs to separately register the System Call and support it.
- System Calls are not easily used from scripts and cannot be accessed directly from the filesystem.
- Because you need an assigned syscall number, it is hard to maintain and use a System Call outside of the master Kernel tree.
- For simple exchanges of information, a System Call is overkill.

The alternatives:

- Implement a device node and `read()` and `write()` to it. Use `ioctl()` to manipulate specific settings or retrieve specific information.
- Certain interfaces, such as semaphores, can be represented as file descriptors and manipulated as such.
- Add the information as a file to the appropriate location in `sysfs`.

3.6 Syscall Context

The Kernel is in Process-context during the execution of a System Call. The current pointer points to the current task, which is the Process that issued the System Call.

In Process-context, the Kernel is capable of sleeping (for example, if the system call blocks on a call or explicitly calls `schedule()`) and is fully preemptible. The capability to sleep means that system calls can make use of the majority of the Kernel's functionality to simplify its own programming. The fact that Process context is preemptible implies that, like User-space, the current task may be preempted by another task. Because the new task may then execute the same System Call, care must be exercised to ensure that the calls are reentrant. Of course, this is the same concern that Symmetric Multiprocessor Systems introduce.

When the System Call returns, control continues in `system_call()` , which ultimately switches to User-space and continues the execution of the User process.

4 Process Management

Defn 33 (Process)**.** A *process* is a Program in the midst of execution, and all its related resources. In fact, two or more processes can exist that are executing the same program. Processes are, however, more than just the executing program code (often called the text section in UNIX). They also include a set of resources such as open files and pending signals, internal Kernel data, processor state, a memory address space with one or more memory mappings, one or more Threads of execution, and a data section containing global variables.

Processes, in effect, are the living result of running program code.

Defn 34 (Program)**.** A *program* is object code stored on some media, typically as a File. These contain the instructions that the processor will execute when the program is running as a Process. These instructions are stored in what is called the *text section* of the program. It also contains statically allocated information, such as `static` variables.

Occassionally, Threads can be subject to Preemption.

Defn 35 (Preemption)**.** *Preemption* is the act of temporarily interrupting a task being carried out by a computer system, without requiring its cooperation, and with the intention of resuming the task at a later time. Such changes of the executed task are known as context switches. It is normally carried out by a privileged task or part of the system known as a preemptive scheduler, which has the power to preempt, or interrupt, and later resume, other tasks in the system.

In any given system design, some operations performed by the system may not be preemptible. This usually applies to Kernel functions and service interrupts which, if not permitted to run to completion, would tend to produce race conditions resulting in deadlock.

On modern Operating Systems, Processes provide two virtualizations:

1. a virtualized processor
    - The virtual processor gives *this* Process the illusion that it alone monopolizes the system, despite possibly sharing the processor among hundreds of other processes.
2. Virtual memory lets the process allocate and manage memory as if it alone owned all the memory in the system.
    - Threads share the virtual memory abstraction, whereas each receives its own virtualized processor.

4.1 The Process Life Cycle

A Process begins its life when, the `fork()` System Call is called. This creates a new Process by duplicating an existing one. The Process that calls `fork()` is the **parent**, whereas the new Process is the **child**. The `fork()` System Call returns from the kernel twice: once in the **parent** and once in the newborn **child**. The parent resumes execution and the child starts execution at the same place, where the call to `fork()` returns.

Often, immediately after a `fork` it is desirable to execute a new, different Program. The `exec()` family of function calls creates a new address space and loads a new program into it.

Finally, a program exits via the `exit()` System Call. This function terminates the Process and frees all its resources. A parent Process can inquire about the status of a terminated child via the `wait4()` System Call, which enables a Process to wait for the termination of a specific Process. When a Process exits, it is placed into a special zombie state that represents terminated Processes until the parent calls `wait()` or `waitpid()` .

4.1.1 Process States

Every Process exists in a state that describes how the process can and will behave.

- **New**: The process is in the stage of being created.
- **Ready**: The process has all the resources available that it needs to run, but the CPU is not currently working on this process's instructions.
- **Running**: The CPU is working on this process's instructions.
- **Waiting**: The process cannot run at the moment, because it is waiting for some resource to become available or for some event to occur.
- **Terminated**: The process has completed.

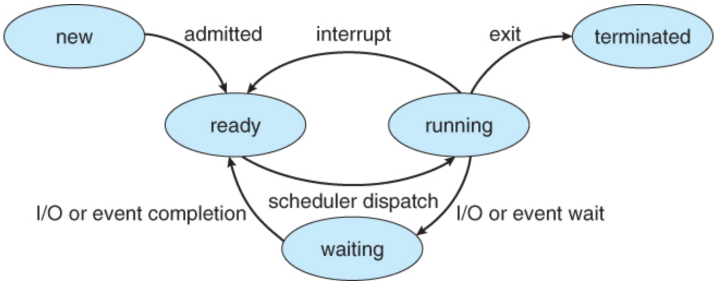


Figure 4.1: Process Life Cycle

4.1.2 Process Control Blocks and Context Switching

The information that is saved during a Context Switch (An example is shown in Figure 4.2) is saved in the Process Control Block.

Defn 36 (Context Switch)**.** A *context switch* is performed when a computer is performing several different Processes in sequence. A context switch involves saving the state of the currently running Process into a Process Control Block, and then loading a waiting process from its Process Control Block. After saving the information, every register in the CPU has its values changes to the new control blocks values, and the CPU continues execution.

A visualization of a context switch is shown in Figure 4.2.

Defn 37 (Process Control Block)**.** The *process control block* (*PCB*) contains **ALL** the state information (the processor's context) needed for a CPU to perform a context switch, either because of Preemption or because the process terminated. The information that the PCB contains includes:

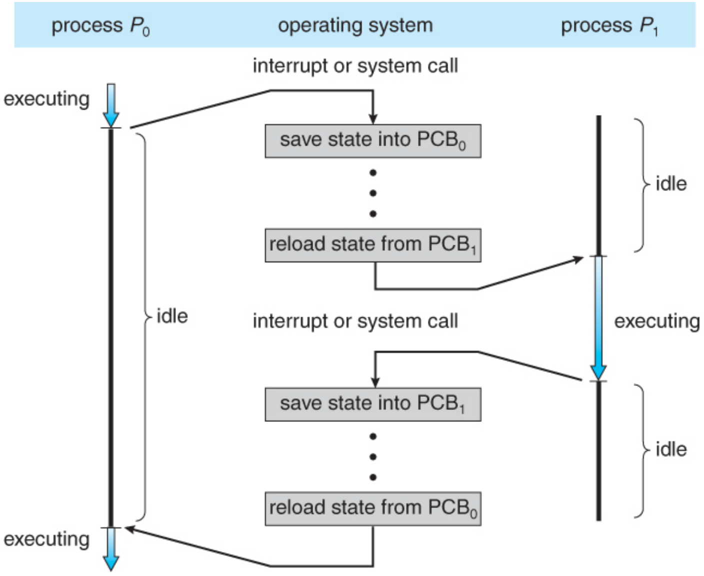


Figure 4.2: Diagram of a Context Switch

- Process State: Running, waiting, etc., as discussed in Section 4.1.1
- Process ID (PID), and parent process ID (PPID).
- CPU registers and Program Counter: Saved and restored when swapping processes in and out of the CPU.
- CPU-Scheduling information: Priority information and pointers to scheduling queues.
- Memory-Management information: Page tables or segment tables.
- Accounting information: User and Kernel CPU time consumed, account numbers, limits, etc.
- I/O Status information: Devices allocated, open file tables, etc.

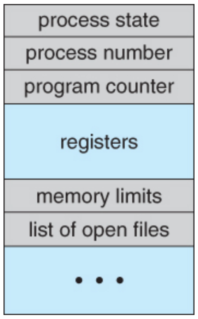


Figure 4.3: Process Control Block

Remark. In Figure 4.3, the Process Number field is the PID of the Process.

The time spent performing a context-switch is pure overhead, because the system does no useful work while switching. Switching speed varies from machine to machine, depending on the memory speed, the number of registers that must be copied, and the existence of special instructions (a single instruction to load or store all registers). A typical speed is a few milliseconds. Context-switch times are also highly dependent on hardware support.

The more complex the operating system, the greater the amount of work that must be done during a context switch. In addition, advanced memory-management techniques may require that extra data be switched with each context. For instance, the address space of the current process must be preserved as the space of the next task is prepared for use.

4.2 Process Creation

Most operating systems implement a `spawn` mechanism to create a new process in a new address space, read in an executable, and begin executing it. UNIX takes the unusual approach of separating these steps into two distinct functions: `fork()` and `exec()` . The first, `fork()` , creates a child process that is a copy of the current task. It differs from the parent only in:

- Its PID (which is unique)
- Its PPID (parent's PID, which is set to the original process)

- Certain resources and statistics, such as pending signals, which are not inherited

The second function, `exec()` , loads a new executable into the address space and begins executing it.

4.2.1 Copy-on-Write

In Linux, `fork()` is implemented through the use of copy-on-write pages. Copy-on-write (or CoW) is a technique to delay or altogether prevent copying of the data. Rather than duplicate the process address space, the parent and the child can share a single read-only copy.

The data, however, is marked in such a way that if it is written to, a duplicate is made and each Process receives their own unique copy. Consequently, the duplication of resources occurs only when they are written; until then, they are shared read-only. This technique delays the copying of each page in the address space until it is actually written to. In the case that the pages are never written—for example, if `exec()` is called immediately after `fork()` —they never need to be copied.

The only overhead incurred by `fork()` is the duplication of the parent's page tables and the creation of a unique Process Descriptor for the child. In the common case that a Process executes a new executable image immediately after forking, this optimization prevents the wasted copying of large amounts of data.

4.2.2 Forking

The bulk of the work in forking is handled by `do_fork()` , which is defined in `kernel/fork.c` , by calling `copy_process()` and then starting the process. The interesting work is done by `copy_process()` :

1. It calls `dup_task_struct()` , which creates a new kernel stack, `thread_info` structure, and `task_struct` for the new process. The new values are identical to those of the current task. At this point, the child and parent Process Descriptors are identical.

2. It then checks that the new child will not exceed the resource limits on the number of processes for the current user.

3. The child needs to differentiate itself from its parent. Various members of the Process Descriptor are cleared or set to initial values. Members of the Process Descriptor not inherited are primarily statistical information. The bulk of the values in `task_struct` remain unchanged.

4. The child's state is set to `TASK_UNINTERRUPTIBLE` to ensure that it does not yet run.

5. `copy_process()` calls `copy_flags()` to update the flags member of the `task_struct` . The `PF_SUPERPRIV` flag, which denotes whether a task used superuser privileges, is cleared. The `PF_FORKNOEXEC` flag, which denotes a process that has not called `exec()` , is set.

6. It calls `alloc_pid()` to assign an available PID to the new task.

7. Depending on the flags passed to `clone()` , `copy_process()` either duplicates or shares open Files, filesystem information, signal handlers, process address space, and namespace. These resources are typically shared between Threads in a given Process; otherwise they are unique and copied here.

8. Finally, `copy_process()` cleans up and returns to the caller a pointer to the new child.

Back in `do_fork()` , if `copy_process()` returns successfully, the new child is woken up and run. Deliberately, the kernel runs the child process first.

`fork()` returns `0` in the newly created child process, and the PID of the child in the parent. Then, `exec()` **COMPLETELY REPLACES THE PROCESS' MEMORY**, meaning that after an `exec()` , the child is not executing the same program anymore.

4.3 Process Scheduling

With multiprogramming, the objective is to have **some** Process running at all times. Note that we are discussing a computer with a single CPU, and likely a single Thread here. Time sharing makes the CPU Context Switch so frequently that users can interact with each program and it seems like they are all running concurrently.

Defn 38 (Process Scheduler)**.** The *process scheduler* is responsible for selecting an available process (one in the New, Ready, or Running states discussed in Section 4.1.1) from one of possibly many queues to run next.

4.3.1 Scheduling Queues

When a Process enters the system, it is put in the **Job Queue**, which consists of **EVERY** process on the system.

The processes that are in main memory, are ready, and waiting to execute are in the **Ready Queue**. The Process Control Blocks are kept in a doubly linked list, with the first and last PCBs explicitly marked by the list itself and a pointer to the next PCB in the ready queue in each PCB.

There are other queues as well:

- **Device Queue**: Completion of I/O Request(s)
  - Each device has its own queue.

These various queues can be represented by Figure 4.4.

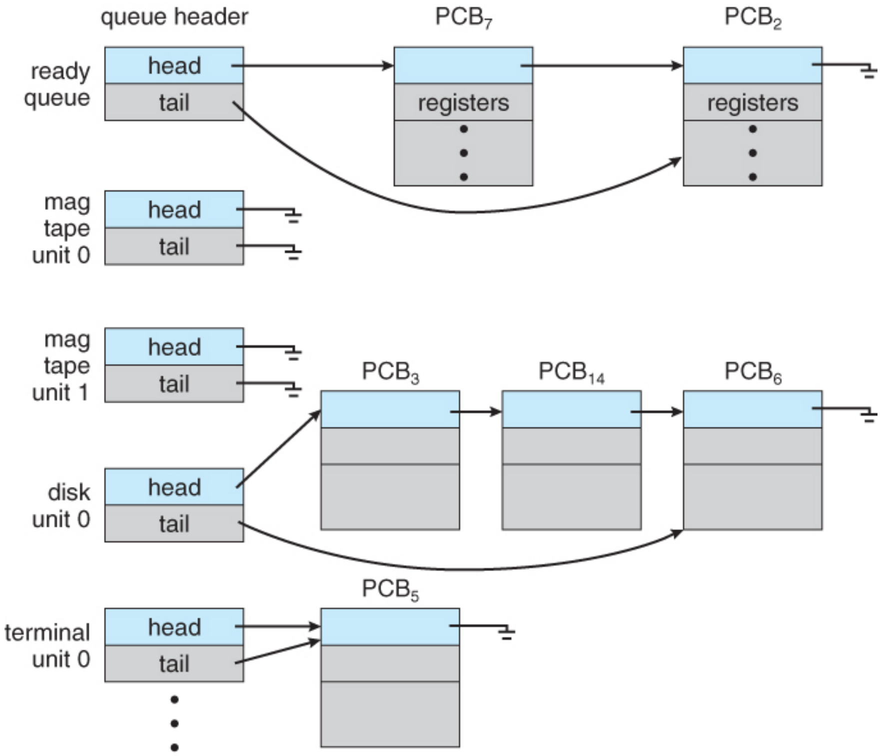


Figure 4.4: Various System Queues

A good visualization of how Processes and their queues work is shown in Figure 4.5.

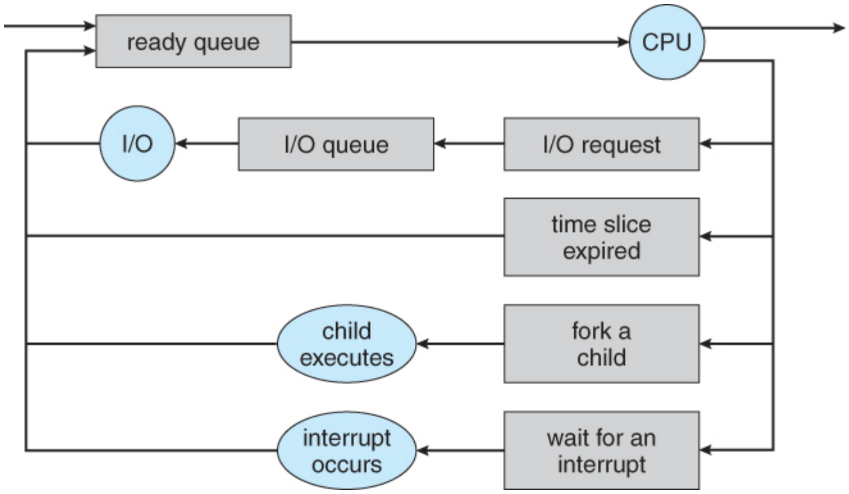


Figure 4.5: Queuing Diagram for Process Scheduling

4.3.2 Schedulers

Defn 39 (Scheduler)**.** A *scheduler* is responsible for selecting the Process from one of the queues to execute next.

Typically, many more Processes are submitted at once than can be handled immediately. So, some are sent to a mass-storage device where they are keyp for later scheduling by the *long-term scheduler* or *job scheduler*. The *short-term scheduler*, or the *CPU scheduler* selects from the Processes that are ready to execute and allocates the CPU to them. The CPU scheduler is run every hundred milliseconds, whereas the job scheduler may be run every few minutes. This allows the job scheduler to run for longer periods of time, because it is active for less time overall.

The job scheduler determines the *degree of multiprogramming*, by determining how many Processes can live in memory at any given time. If the degree of multiprogramming is stable, then the average rate of process creation must be equal to the average departure rate of processes leaving the system. Most desktop Operating Systems do not use the long-term scheduler. Instead they put all tasks into the short-term queue, and rely on human behavior to help control the business of the systems.

Defn 40 (I/O Bound)**.** An *I/O Bound* Process is one where most of the process's time is spent performing I/O rather than computations.

Defn 41 (CPU-Bound)**.** A *CPU-Bound* Process spends most of its time performing computations.

It is important to have a good mix of I/O Bound and CPU-Bound processes, so that no single queue is ever too full, improving overall system throughput.

There are also *medium-term scheduler*s that perform *swapping*. This scheduler removes a Process from memory, store it somewhere, then reintroduce the process to memory again later.

4.4 The Process Descriptor and Task `struct`

Defn 42 (Task List)**.** The Kernel stores the list of Processes in a circular doubly-linked list called the *task list*. Each element in the task list is a Process Descriptor of the type `struct task_struct` .

Defn 43 (Process Descriptor)**.** The *process descriptor* contains all the information about a specific Process, including:

- Open files
- The Process's address space,
- Pending signals,
- The Process's state,
- The Process's priority
- The Process's policy
- The Process's parent
- The Process's id (PID)

In Linux, the process descriptor is of type `struct task_struct` , which is defined in `<linux/sched.h>`.

4.4.1 Allocating the Process Descriptor

Like in any other programming language, the `task_struct` record must be initialized somehow. This is done with the *slab allocator* to provide object reuse and Cache Coloring.

Defn 44 (Cache Coloring)**.** *Cache coloring* (also known as page coloring) is the process of attempting to allocate free pages that are contiguous from the CPU cache's point of view, in order to maximize the total number of pages cached by the processor. Cache coloring is typically employed by low-level dynamic memory allocation code in the operating system, when mapping virtual memory to physical memory. A virtual memory subsystem that lacks cache coloring is less deterministic with regards to cache performance, as differences in page allocation from one program run to the next can lead to large differences in program performance.

4.4.2 Storing the Process Descriptor

The system identifies Processes by a unique Process Identification Value or PID. The PID is a numerical value represented by the opaque type[2] `pid_t` , which is typically an `int` . Because of backward compatibility with earlier UNIX and Linux versions, the default maximum value is only 32,768 (that of a `(short int)`), although the value can be increased as high as four million (this is controlled in `<linux/threads.h>`). The Kernel stores this value as PID inside each Process Descriptor. This maximum value is important because it is essentially the maximum number of Processes that may exist concurrently on the system.

[2] "An opaque type is a data type whose physical representation is unknown or irrelevant" Love 2010, pg. 26.

Inside the Kernel, tasks are typically referenced directly by a pointer to their `task_struct` structure. In fact, most Kernel code that deals with Processes works directly with `struct task_struct`. Consequently, it is useful to be able to quickly look up the Process Descriptor of the currently executing task, which is done via the current macro. This macro must be independently implemented by each architecture. Some architectures save a pointer to the `task_struct` structure of the currently running Process in a register, enabling for efficient access. Other architectures make use of the fact that `struct thread_info` is stored on the Kernel stack to calculate the location of `thread_info` and subsequently the `task_struct`.

4.4.3 Process State

The state field of the process descriptor describes the current condition of the process. Each process on the system is in exactly one of five different states. This value is represented by one of five flags:

1. `TASK_RUNNING`: The process is runnable; it is either currently running or on a runqueue waiting to run. This is the only possible state for a Process executing in User-space; it can also apply to a process in Kernel-space that is actively running.
2. `TASK_INTERRUPTIBLE`: The Process is sleeping (that is, it is blocked), waiting for some condition to exist. When this condition exists, the Kernel sets the Process's state to `TASK_RUNNING`. The Process also awakes prematurely and becomes runnable if it receives a signal.
3. `TASK_UNINTERRUPTIBLE`: This state is identical to `TASK_INTERRUPTIBLE` **except that it does not wake up and become runnable if it receives a signal**. This is used in situations where the Process must wait without interruption or when the event is expected to occur quite quickly. Because the task does not respond to signals in this state, `TASK_UNINTERRUPTIBLE` is less often used than `TASK_INTERRUPTIBLE`.
4. `__TASK_TRACED`: The Process is being traced by another Process, such as a debugger, via `ptrace`.
5. `__TASK_STOPPED`: Process execution has stopped; the task is not running nor is it eligible to run. This occurs if the task receives the `SIGSTOP`, `SIGTSTP`, `SIGTTIN`, or `SIGTTOU` signal or if it receives any signal while it is being debugged.

4.4.4 Manipulating the Current Process's State

Kernel code often needs to change a process's state. The preferred mechanism is using

```
set_task_state(task, state); /* set task ‘task’ to state ‘state’ */
```

This function sets the given `task` to the given `state`. If applicable, it also provides a memory barrier to force ordering on other processors. This is only needed on SMP systems.

4.4.5 Process Context

Normal program execution occurs in User-space. When a program executes a system call or triggers an exception, it enters Kernel-space. At this point, the Kernel is said to be “executing on behalf of the process” and is in Process-context. When in process context, the `current` macro is valid.

Remark. Other than process context there is Interrupt-context. In interrupt context, the system is not running on behalf of a process but is executing an interrupt handler. No Process is tied to interrupt handlers.

Upon exiting the kernel, the Process resumes execution in User-space, unless a higher-priority process has become runnable in the interim. If that happens, the scheduler is invoked to select the higher priority process. System Calls and exception handlers are well-defined interfaces into the kernel. A Process can begin executing in kernel-space only through one of these interfaces. All access to the Kernel is through these interfaces.

4.4.6 Process Family Tree

All processes are descendants of the init Process, whose PID is one. The kernel starts `init` in the last step of the boot process. The `init` process, in turn, reads the system initscripts and executes more programs, eventually completing the boot process.

Every process on the system has exactly one parent. Likewise, every process has zero or more children. Processes that are all direct children of the same parent are called siblings. The relationship between processes is stored in the process descriptor. Each `task_struct` has a pointer to the parent's `task_struct`, named `parent`, and a list of children, named `children`.

4.5 Process Termination

When a process terminates, the Kernel releases the resources owned by the process and notifies the child's parent of its demise. Usually, process destruction is self-induced. It occurs when the process calls the `exit()` System Call. This can be done either explicitly when it is ready to terminate or implicitly on return from the main subroutine of any program (The C compiler places a call to `exit()` after `main()` returns).

A process can also terminate involuntarily. This occurs when the process receives a signal or exception it cannot handle or ignore.

Regardless of how a process terminates, the bulk of the work is handled by `do_exit()` , defined in `kernel/exit.c` , which completes a number of chores:

1. It sets the `PF_EXITING` flag in the flags member of the `task_struct` .
2. It calls `del_timer_sync()` to remove any kernel timers. Upon return, it is guaranteed that no timer is queued and that no timer handler is running.
3. If BSD process accounting is enabled, `do_exit()` calls `acct_update_integrals()` to write out accounting information.
4. It calls `exit_mm()` to release the `mm_struct` held by this process. If no other process is using this address space, i.e. the address space is not shared, the Kernel then destroys it.
5. It calls `exit_sem()` . If the process is queued waiting for an IPC semaphore, it is dequeued here.
6. It then calls `exit_files()` and `exit_fs()` to decrement the usage count of objects related to file descriptors and filesystem data, respectively. If either usage counts reach zero, the object is no longer in use by any process, and it is destroyed.
7. It sets the Process's exit code, stored in the `exit_code` member of the `task_struct` , to the code provided by `exit()` or whatever Kernel mechanism forced the termination. The exit code is stored here for optional retrieval by the parent.
8. It calls `exit_notify()` to send signals to the Process's parent, reparents any of the Process's children to another thread in their thread group or the init process, and sets the Process's exit state, stored in `exit_state` in the `task_struct` structure, to `EXIT_ZOMBIE` .
9. `do_exit()` calls `schedule()` to switch to a new process. Because the process is now not schedulable, this is the last code the Process will ever execute. `do_exit()` never returns.

At this point, we have a Zombie Process.

Defn 45 (Zombie Process)**.** A *zombie process* in Linux is a process that has been completed, but its entry still remains in the process table due to lack of correspondence between the parent and child Processes. This happens when the Process has been terminated, but the Process Descriptor has **not** be deallocated yet.

- All objects associated with the Process are freed.
  - This assumes that this Process was the only one using these objects, i.e. no other Threads/Processes were using them.
- The Process is not runnable and no longer has an address space in which to run.
- The process is in the `EXIT_ZOMBIE` exit state.
- The only memory it occupies is its Kernel stack, the `thread_info` structure, and the `task_struct` structure.
- The Process exists solely to provide information to its parent. After the parent retrieves the information, or notifies the Kernel that it is uninterested, the remaining memory held by the process is freed and returned to the system for use.

4.5.1 Removing a Process Descriptor

After `do_exit()` completes, the Process Descriptor for the terminated Process still exists, but the Process is a Zombie Process and is unable to run. By remaining a Process, albeit a Zombie Process, this enables the system to obtain information about a child Process after it has terminated.

Consequently, the acts of cleaning up after a Process and removing its Process Descriptor are separate.

After the parent has obtained information on its terminated child, or signified to the Kernel that it does not care, the child's `task_struct` is deallocated. The `wait()` family of functions are implemented via a single System Call, `wait4()`. The standard behavior is to suspend execution of the calling task until one of its children exits, at which time the function returns with the PID of the exited child. Additionally, a pointer is provided to the function that on return holds the exit code of the terminated child.

When it is time to finally deallocate the Process Descriptor, `release_task()` is invoked. It does the following:

1. Calls `__exit_signal()`, which calls `__unhash_process()`, which in turns calls `detach_pid()` to remove the process from the PIDhash and remove the process from the task list.
2. `__exit_signal()` releases any remaining resources used by the now dead process and finalizes statistics and bookkeeping.
3. If the task was the last member of a thread group, and the leader is a zombie, then `release_task()` notifies the zombie leader's parent.
4. `release_task()` calls `put_task_struct()` to free the pages containing the Process's Kernel stack and `thread_info` structure and deallocate the slab cache containing the `task_struct`.

At this point, the Process Descriptor and all resources belonging solely to the process have been freed.

4.5.2 Parentless Tasks

If a parent exits before its children, some mechanism must exist to reparent any child tasks to a new process, or else parentless terminated processes would forever remain Zombie Processes, wasting system memory. The solution is to reparent a task's children on exit to either another Process in the current Thread group or, if that fails, the `init` process.

When a suitable parent for the child(ren) has been found, each child needs to be located and reparented to this `reaper` parent Process.

With the Process(es) successfully reparented, there is no risk of stray Zombie Processes. The `init` process routinely calls `wait()` on its children, cleaning up any zombies assigned to it.

5 Threads

Defn 46 (Thread)**.** *Threads of execution*, often shortened to *threads*, are the objects of activity within the process. Each thread has a ***thread context*** which includes:

- Thread ID
- A unique program counter
- Process stack
- Set of processor Registers

The Kernel schedules the individual threads, not Processes.

In traditional UNIX systems, each Process consists of one thread. In modern systems, however, multithreaded programs/processes are common. In this case, this Process's threads share:

- The Code Section
- The Data Section
- Operating System resources, such as files and signals.

Remark 46.1 (Threads in Linux). Linux has a unique implementation of threads; it does not differentiate between Threads and Processes. To Linux, a thread is just a special kind of process.

Threads are very useful in modern programming whenever a Process has multiple tasks to perform independently of the others. The use of Threads is even more aparent when the single process/program must perform many similar tasks. This is particularly true when one of the threads may block, and it is desired to allow the other threads to proceed without blocking.

Figure 5.1 illustrates what a multithreaded application roughly looks like, visually.

The biggest benefits of using multiple Threads are:

1. **Responsiveness**. Multithreading an interactive application may allow a program to continue running even if part of it is blocked or is performing a lengthy operation, thereby increasing responsiveness to the user. This quality is especially useful in designing user interfaces.

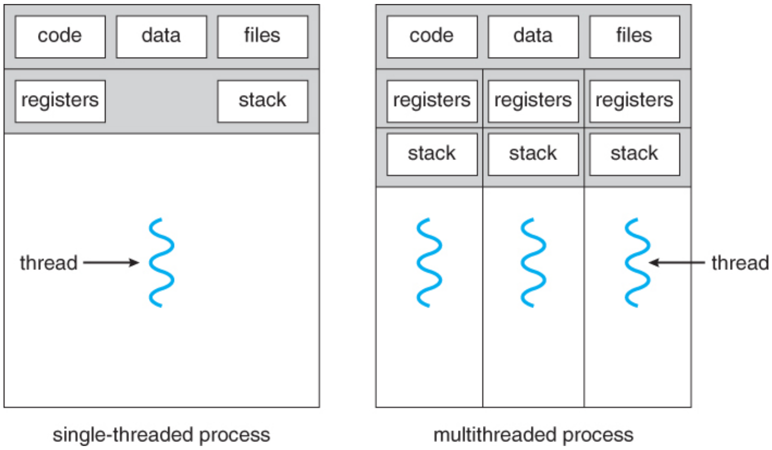


Figure 5.1: Single- vs. Multithread Diagram

2. **Resource sharing**. Processes can only share resources through techniques such as Message Passing and Message Passing. Using these techniques requires explicit arrangement by the programmer. However, threads share the memory and the resources of the process to which they belong, allowing an application to have several different threads of activity within the same address space.
3. **Economy**. Allocating memory and resources for process creation is costly. Because threads share the resources of the process to which they belong, it is more economical to create and context-switch threads.
4. **Scalability**. The benefits of multithreading can be even greater in a multiprocessor architecture, where threads may be running in parallel on different processing cores. A single-threaded process can run on only one processor, regardless how many are available.

Defn 47 (Parallelism)**.** *Parallelism* is where a system can perform more than one task simultaneously.

Defn 48 (Concurrency)**.** *Concurrency* supports more than one task executing simulataneiously, and allows all the tasks to make progress. Thus, it is possible to have concurrency without Parallelism.

To handle the increase in Process Thread counts, many CPUs support more than one thread per core. This means multiple threads can be loaded into the CPU for faster switching. On desktop Intel CPUs, this is called **hyperthreading**.

The biggest difficulties in using multiple Threads are:

1. **Identifying tasks**. Examine applications to find areas that can be divided into independent tasks that can be run concurrently on individual cores.
2. **Balance**. While identifying tasks that can run in parallel, programmers must also ensure that the tasks perform equal work of equal value. In some instances, a certain task may not contribute as much value to the overall process as other tasks.
3. **Data splitting**. Just as applications are divided into separate tasks, the data accessed and manipulated by the tasks must be divided to run on separate cores.
4. **Data dependency**. The data accessed by the tasks must be examined for dependencies between two or more tasks. When one task depends on data from another, the tasks must be synchronized to accommodate the data dependency.
5. **Testing and debugging**. When a program is running in parallel on multiple cores, many different execution paths are possible, making testing and debugging much harder.

There are 2 distinct types of Parallelism, though many applications use both of them.

1. Data Parallelism
2. Task Parallelism

Defn 49 (Data Parallelism)**.** *Data parallelism* focuses on distributing subsets of the same data across multiple computing cores and performing the same operation on each core. For example, summing the contents of an array of size N. On a single-core system, one thread would simply sum the elements $[0] \dots [N-1]$. On a dual-core system, however, thread A, running on core 0, could sum the elements $[0] \dots [\frac{N}{2}-1]$ while thread B, running on core 1, could sum the rest of the elements $[\frac{N}{2}] \dots [N-1]$.

Defn 50 (Task Parallelism)**.** *Task parallelism* involves distributing tasks/Threads across multiple computing cores. Each thread is performing a unique operation. Different threads may be operating on the same data, or they may be operating on different data.

5.1 User and Kernel Threads

A relationship must exist between User Threads and Kernel Threads. There are three common ways of establishing such a relationship:

1. The Many-To-One Model
2. The One-To-One Model
3. The Many-To-Many Model

Defn 51 (User Thread)**.** *User thread*s are Threads created by a User Process. They are supported above the kernel and are managed without kernel support.

Defn 52 (Kernel Thread)**.** *Kernel thread*s are like regular Threads, except that they can only be started by the Kernel and its previous kernel threads. Additionally, they do not have an address space (Their `mm` pointer, which points at their address space, is `NULL` .). They operate only in the Kernel-space and do not context switch into User-space. Kernel threads are schedulable and preemptable, the same as normal Processes.

5.1.1 Many-To-One Model

This model maps many user-level threads to a single Kernel Thread. Thread management is done by the thread library in user space, so it is efficient. However, the entire process will block if a thread makes a blocking system call. Also, because only one thread can access the kernel at a time, multiple threads are unable to run in parallel on multicore systems.

5.1.2 One-To-One Model

This model maps each user thread to an individual kernel thread. It provides more concurrency than the many-to-one model by allowing another thread to run when a thread makes a blocking system call. It also allows multiple threads to run in parallel on multiprocessors.

The only drawback to this model is that creating a user thread requires creating the corresponding kernel thread, which is quite expensive. The overhead of creating kernel threads can hurt the performance of an application. To combat this, most implementations of this model restrict the number of threads supported by the system. Most desktop operating systems use this model.

5.1.3 Many-To-Many Model

The many-to-many model multiplexes many user-level threads to a smaller or equal number of kernel threads. The number of kernel threads may be specific to either a particular application or a particular machine (an application may be allocated more kernel threads on a multiprocessor than on a single processor).

Whereas the Many-To-One Model allows the developer to create as many User Threads as they wishes, it does not result in true concurrency, because the kernel can schedule only one thread at a time. The One-To-One Model allows greater concurrency, but the developer must be mindful of the number of threads within an application.

The many-to-many model suffers from neither of these shortcomings:

- Developers can create as many user threads as necessary, and the corresponding kernel threads can run in parallel on a multiprocessor.
- When a thread performs a blocking system call, the kernel can schedule another thread for execution.

5.2 Thread Libraries

Defn 53 (Thread Library)**.** A *thread library* is an Application Programming Interface that allows a programmer to create and manage Threads.

There are 2 main ways to implement a Thread Library:

1. Provide a library entirely in user space with no kernel support. All code and data structures for the library exist in **user-space**. This means that invoking a library function results in a function call in user space and not a system call.
2. Implement a kernel-level library supported directly by the operating system. All code and data structures for the library exist in **kernel-space**. Invoking a library function results in a System Call to the Kernel.

There are 3 different libraries that are used frequently.

1. POSIX Pthreads.
    - This provides a standard interface for **how the threads should behave**.
    - The actual implementation details are left for the implementor to decide.

    - Global variables are shared between threads.
    - Brought in by the standard library's `pthread.h` header.

2. Windows' Threads.
    - Global variables are shared between threads.
    - Must include the `windows.h` header.

3. Java's Threads.

Although there are these different libraries, all of them provide similar functionality. So, throughout this section (unless otherwise specified), all information will be general.

5.2.1 Synchronous/Asynchronous Threading

There are 2 main ways to create multiple threads.

1. Asynchronous
    - Once the parent thread creates a child thread, the parent resumes execution.
    - The parent and child execute concurrently.
    - Each thread is independent.
    - The parent does not need to know if a child terminates.
    - Little data sharing between threads.

2. Synchronous
    - The parent creates one or more children, and then waits for all of them to finish executing.
    - Called the ***fork-join*** strategy.
    - The child threads perform their work concurrently, but the parent **MUST** wait for all children to finish.
    - Typically a lot of data sharing between threads.
    - The program must provide a "`run`"-like function that is the first thing a new thread executes.
        - The actual name of this function varies depending on the Thread Library in use.
    - The programmer must provide a point where the main program waits by having each child thread `join`.
        - In the Pthreads and Java libraries, to wait for multiple threads, a `for` loop is constructed and iterates over all threads, making them `join`.
        - The actual name of this function varies depending on the Thread Library in use.

5.2.2 Thread Attributes

When creating Threads, some information can be passed to the constructing function regarding the attributes for the thread. These attributes include:

- Security Information
- Stack Size
- Flag to indicate if thread starts in a suspended state (Can/cannot be scheduled).

5.3 Implicit Threading

Because programs are starting to use so many Threads that it is becoming hard to manage, the creation and management of threads is moving from developers to compilers/run-time libaries. This way, the computer manages threads rather than the programmer.

Defn 54 (Implicit Threading)**.** *Implicit Threading* is the transfer of Thread creation and management away from the programmer, and to the compiler and/or run-time libaries. This frees the programmer from having to think/worry about the issues that arise because of multithreading, while still allowing programs to take advantage of the benefits of multithreading.

There exist 3 main methods for implementing implicit threading:

1. Thread Pools
2. OpenMP
3. Grand Central Dispatch

5.3.1 Thread Pools

In a Thread Pool system, all (or at least most) of the Threads available for use by a Process are created during startup. They are then placed in a pool, and wait for work to arrive.

Defn 55 (Thread Pool)**.** A *thread pool* system is one where all Threads that can be used by any Process on the system is in a pool, hence the name. When a job comes in that would use one (or more) of these threads, they are pulled out of the pool and allowed to execute. When they finish execution, they return to the pool.

If there are jobs ready, but there are no threads available in the pool, they wait until one is available.

A Thread Pool offers these benefits:

1. Servicing a request with an **existing thread** is faster than waiting **to create a thread**.
2. A thread pool limits the number of threads that exist at any one point, preventing performance degradation. This is particularly important on systems that cannot support a large number of concurrent threads.
3. Separating the task to be performed from the mechanics of creating the task allows us to use different strategies for running the task.

Additionally, the number of Threads available in the Thread Pool can be set dynamically. Some factors that can affect the number of threads in the pool are:

1. Number of CPUs in the system
2. Amount of physical memory
3. Expected number of concurrent job requests

There are more sophisticated architectures that offer varying benefits. Some even allow for the shrinking of the pool as needed, to reduce the footprint of the running Process.

5.3.2 OpenMP

OpenMP is a set of compiler directives as well as an API for programs written in C, C++, or FORTRAN that provides support for parallel programming in shared-memory environments. OpenMP allows for parallel programming by identifying parallel regions as blocks of code that may run in parallel. Application developers insert compiler directives into their code at parallel regions they know can be executed in parallel, and these directives instruct the OpenMP runtime library to execute the region in parallel.

It can create as many threads as are available in a system with the `#pragma omp parallel` directive. There are also directives for parallelizing loops, automatically dividing the work among the spawned threads.

This system also allows developers to choose the way the OpenMP library behaves, allowing for several different levels of parallelism. These include:

- Setting the number of threads manually.
- Allowing developers to identify whether data is shared between threads or are private to a thread.

5.3.3 Grand Central Dispatch

Grand Central Dispatch (*GCD*) is a Thread Pool system developed by Apple for OSX and iOS. If is a combination of C extensions, an Application Programming Interface, and a runtime library. This allows GCD to use POSIX threads and manage the creation/destruction of threads as needed. This allows developers to identify sections of code that may be run in parallel.

Like in OpenMP, blocks of code that may be parallelized must be identified by the programmer with the `^{ code; }` syntax. When executing, GCD will schedule blocks for execution by placing them on a dispatch queue. When an item from the dispatch queue is removed, it is assigned to a Thread from the queue's Thread Pool.

There are 2 types of dispatch queues:

1. Serial (**Cannot** be executed in parallel).
   - Items are removed in a FIFO order.
   - One block **MUST** finish executing before another can be drawn from the dispatch queue.
   - Each process gets its own serial queue, the *main queue*.
   - Additional serial dipatch queues can be made for local for execution.
2. Concurrent (**Can** be executed in parallel).
   - Items in this dispatch queue are also removed in a FIFO order, but multiple may be removed at once.
   - This allows multiple blocks to execute in parallel.
   - There are 3 system-wide dispatch queues, according to priority.

(a) Low
(b) Default
(c) High

- Priority is a relative importance of the blocks.

5.4 Threading Issues

In this section, we will discuss some common issues that arise because of multithreading.

5.4.1 The `fork()` and `exec()` System Calls

Since `fork()` creates a separate, but duplicate, child Process from its parent, what are the semantics when creating a Thread on a UNIX system, since Threads are just another kind of Process?

If one thread in a program calls `fork()` , does the new process duplicate all threads, or is the new process single-threaded? To answer this, there are two versions of `fork()` , one that duplicates all threads and another that duplicates only the thread that invoked the `fork()` system call.

The `exec()` system call is relatively unchanged; if a thread invokes the `exec()` system call, the program specified in the parameter to `exec()` will **replace the entire process**, including all threads.

Which version of `fork()` to use depends on the application. If `exec()` will be called immediately after forking, then duplicating **all** threads is unnecessary, as the program specified in the parameters to `exec()` will replace the process anyways, thus duplicating only the calling thread is appropriate. If, however, the separate process does not call `exec()` after forking, the separate process should duplicate all threads.

5.4.2 Signal Handling

Defn 56 (Signal)**.** A UNIX *signal* is used to notify a Process that an event has occurred. The reception of the signal can be synchronous or asynchronous. Synchronous in this context means that the signal is **delivered to the same proces that caused the signal**. Asynchronous means the signal is generated by an event **external to the running process**, such as keyboard presses or timer expiration.

Which one depends on the source of and the reason for the event to be signaled. However, all signals have the same general pattern:

1. A signal is generated by the occurrence of a particular event.
2. The signal is delivered to a process.
3. Once delivered, the signal must be handled.

When a Signal is delivered, it must be handled by either:

1. The default signal handler
2. The user-defined signal handler

Every Signal has a default handler that the Kernel runs to handle the Signal. However, these actions can be overridden by a user-defined signal handler. How a Process responds to a signal depends on the process and the type of signal that is received.

Signal handling in single-threaded processes is simple, because the only Thread is also the Process. However, multithreaded programs have some complications because there are multiple Threads for the single Process.

1. Deliver the signal to the thread to which the signal applies.
2. Deliver the signal to every thread in the process.
3. Deliver the signal to certain threads in the process.
4. Assign a specific thread to receive all signals for the process.

How a Signal is delivered depends on the type of signal generated. Synchronous signals need to be delivered **to the Thread causing the Signal**. Some asynchronous signals need to be delievered to all threads in a Process.

On UNIX and UNIX-like systems, a Thread can specify what Signals it will accept, and which it will block. Thus, the asynchronous signal may be delievered to only the threads that are not blocking that signal. In addition, since signals need to be handled **only once**, they are typically only delivered to the first non-blocking thread found.

5.4.3 Thread Cancellation

Defn 57 (Thread Cancellation)**.** *Thread cancellation* means terminating a Thread before it has completely finished its execution.

Remark 57.1 (Target Thread)*.* The Thread that is to be cancelled is often called the *target thread.*

There are 2 main ways to cancel a Thread:

1. **Asynchronous cancellation**
   - One thread immediately terminates the Target Thread.
   - Difficult when resources have been allocated to a cancelled Thread.
   - Difficult when a thread is updating data that is shared with other threads.
   - Operating System will reclaim some, but not all resources from a canceled thread, so a necessary system-wide resource may not be freed.
2. **Deferred cancellation**.
   - Target Thread periodically checks whether it should terminate, allowing it an opportunity to terminate itself in an orderly fashion.

To change the way Pthreads handle potential cancellation signals, they can enable and disable various ways to cancel themselves. POSIX Pthreads support 3 different types of modes/states for how a Target Thread will handle a request.

Mode	State	Type
Off	Disabled	—
Deferred	Enabled	Deferred
Asynchronous	Enabled	Asynchronous

Table 5.1: Pthread Cancellation Modes

The default cancellation type is deferred cancellation, when a Thread has reaced a cancellation point. At this point, a *cleanup handler* is invoked, which frees any resources the Thread may have had allocated to it.

5.4.4 Thread-Local Storage

Threads that belong to a Process all share their data. However, sometimes a thread will need its own copy of data, called *thread-local storage.*

> It is easy to confuse TLS with local variables; however, TLS data is visible throughout a Thread's execution. TLS is similar to `static` data, except each piece of TLS data is unique to each thread.

5.4.5 Scheduler Activations

When using the Many-To-Many Model of Kernel-Thread Library communications, there may be some issues. To handle these issues, many systems implement Lightweight Processes as an intermediary between the User and Kernel.

Defn 58 (Lightweight Process)**.** A *lightweight process* (*LWP*) is a virtual processor onto which the application can schedule a User Thread to run. Then, each lightweight process is attached to a Kernel Thread, and those kernel threads are scheduled by the Operating System to run on real, physical processors.

These Lightweight Processes are used for each of the potentially Kernel-block tasks that may occur. When this happens, the Kernel Thread blocks, which blocks the Lightweight Process, which then blocks the User Thread. An application can use as many Lightweight Processes as it wants, but if the Process only has a limited amount, some of the LWPs may need to be queued.

One way to handle these communications is by using *scheduler activation.* The steps for this to work are shown below.

1. The Kernel provides a Process with a set of Lightweight Processes, LWPs, virtual processors.
2. When a User Thread is about to block, the Kernel makes an *upcall* ot the LWP informing it that it is about to block, and identifies the Thread that will block.
3. The Kernel will then allocate a new LWP to the Process to run the *upcall handler* on. This saves the state of the blockeing thread, schedules another thread, and context switches to the other thread.
4. When the blocking event that the Thread was waiting on, the Kernel makes another *upcall* to the LWP informing the blocked thread that it may run and unblocks it.
5. The unblocked User Thread can now be scheduled. It eventually is scheduled to execute and does.

5.5 Linux Implementation of Threads

Threads are a popular modern programming abstraction. They provide multiple executors within the same program in a shared memory address space. They can also share open files and other resources. Threads enable concurrent programming and, on multiple processor systems, true parallelism.

The Linux kernel is unique in that there is no concept of a Thread. Instead, Linux implements all Threads as standard Processes. The Linux kernel does not provide any special scheduling semantics or data structures to represent Threads. Instead, a Thread is merely a Process that shares certain resources with other Processes. Each Thread has a unique `task_struct` and appears to the kernel as a normal Process which just happen to share resources, such as an address space, with other Processes.

For example, assume you have a Process that consists of four Threads. In Linux, there are simply four Processes and thus four normal `task_struct` structures. The four Processes are set up to share certain resources. The result is quite elegant. However, on systems with explicit Thread support, one Process Descriptor might exist that points to the four different Threads. The Process Descriptor describes the shared resources, such as an address space or open files. The Threads then describe the resources they alone possess.

5.5.1 Creating Threads

Threads are created the same as normal Processes, i.e. `fork()` is used. The difference is that the `clone()` System Call is passed flags corresponding to the specific resources to be shared.

```
clone(CLONE_VM | CLONE_FS | CLONE_FILES | CLONE_SIGHAND, 0);
```

The code above results in behavior identical to a normal `fork()` , except that the address space, filesystem resources, file descriptors, and signal handlers are shared. In other words, the new task and its parent are what are popularly called Threads.

The flags provided to `clone()` help specify the behavior of the new process and detail what resources the parent and child will share. Table 5.2 lists the `clone()` flags, which are defined in `<linux/sched.h>` , and their effect.

Flag	Meaning
`CLONE_FILES`	Parent and child share open files.
`CLONE_FS`	Parent and child share filesystem information.
`CLONE_IDLETASK`	Set PID to zero (used only by the idle tasks).
`CLONE_NEWNS`	Create a new namespace for the child.
`CLONE_PARENT`	Child is to have same parent as its parent.
`CLONE_PTRACE`	Continue tracing child.
`CLONE_SETTID`	Write the TID back to user-space.
`CLONE_SETTLS`	Create a new TLS for the child.
`CLONE_SIGHAND`	Parent and child share signal handlers and blocked signals.
`CLONE_SYSVSEM`	Parent and child share SystemV `SEM_UNDO` semantics.
`CLONE_THREAD`	Parent and child are in the same thread group.
`CLONE_VFORK`	`vfork()` was used and the parent will sleep until the child wakes it.
`CLONE_UNTRACED`	Do not let the tracing process force `CLONE_PTRACE` on the child.
`CLONE_STOP`	Start process in the `TASK_STOPPED` state.
`CLONE_SETTLS`	Create a new TLS (thread-local storage) for the child.
`CLONE_CHILD_CLEARTID`	Clear the TID in the child.
`CLONE_CHILD_SETTID`	Set the TID in the child.
`CLONE_PARENT_SETTID`	Set the TID in the parent.
`CLONE_VM`	Parent and child share address space.

Table 5.2: `clone()` Flags

5.5.2 Kernel Threads

It is often useful for the kernel to perform some operations in the background. The kernel accomplishes this via kernel threads, standard processes that exist solely in kernel-space.

Defn 52 (Kernel Thread)**.** *Kernel threads* are like regular Threads, except that they can only be started by the Kernel and its previous kernel threads. Additionally, they do not have an address space (Their `mm` pointer, which points at their address space, is `NULL` .). They operate only in the Kernel-space and do not context switch into User-space. Kernel threads are schedulable and preemptable, the same as normal Processes.

Linux delegates several tasks to kernel threads, most notably the `flush` tasks and the `ksoftirqd` task. Kernel threads are created on system boot by other kernel threads. The kernel handles this automatically by forking all new kernel threads off of the `kthreadd` Kernel process. The interface for Kernel Threads is declared in `<linux/kthread.h>` .

When started, a Kernel Thread continues to exist until it calls `do_exit()` or another part of the kernel calls `kthread_stop()` , passing in the address of the `task_struct` structure returned by `kthread_create()` .

6 CPU Scheduling and Synchronization

The growing importance of multicore systems has brought an increased emphasis on developing multithreaded applications. In such applications, several threads, which may be sharing data, are running in parallel on different processing cores. These Processes are called Cooperating Processes.

Defn 59 (Cooperating Process)**.** A *cooperating process* is one that can affect or be affected by other Processes executing on a system. They can share a logical address space (code and data), **Threads**, or can share data through files and/or messages, **Communications**.

Given the way that multiple Threads can be scheduled, namely in any order (relatively speaking), as programmers, we cannot be certain about which thread will be scheduled first. This leads to all sorts of problems because of sharing information between multiple users. The largest, and likely the most common, error in a multiThreaded program is the Race Condition.

Defn 60 (Race Condition)**.** A *race condition* is when several processes access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place. The only way to prevent a race condition is to ensure that **only one Thread can change the value at a time**.

6.1 Process/Thread Synchronization

The main problem that occurs in multiThreaded programs is that there is a small portion of code that is a Critical Section. This leads to the development of the Critical Section Problem.

Defn 61 (Critical Section)**.** The *critical section* of a Process is a portion where the Thread and/or Process is changing common variables, updating a table, writing a file, or other global state changes.

6.1.1 Critical Section Problem

The *Critical Section Problem* is the issue of coordinating multiple Threads about a Critical Section of the code. The problem is to design a protocol that the Processes/Threads can use to cooperate. Each Process must request permission to enter its critical section. The section of code implementing this request is the Entry Section. The critical section may be followed by an Exit Section. The remaining code is the Remainder Section.

Defn 62 (Entry Section)**.** The *entry section* of a Process is the portion where the request to execute the Critical Section occurs. In the case of a Mutex, this is the process of aquiring the it. For a Semaphore, it is the process of manipulating the value it currently contains.

Defn 63 (Exit Section)**.** In the *exit section*, the constructs used to ensure coordination in the Critical Section are freed. In the case of a Mutex, this is the process of releasing the it. For a Semaphore, it is the process of manipulating the value it currently contains in the opposite direction it was initially manipulated by.

Defn 64 (Remainder Section)**.** The *remainder section* is the rest of the code, after this Critical Section. This code may be parallelized, or not. It could contain further Critical Sections.

Any solution to this problem **MUST** satisfy one of the following 3 requirements:

1. **Mutual Exclusion**. If Process P_i is executing its Critical Section, then **no other** processes can execute their critical sections.
2. **Progress**. If no Process is executing its Critical Section, and some processes wish to enter their critical sections, then only those processes that **are not executing** in their Remainder Sections can decide which will enter the Critical Section next. Essentially, the only way a process gets a voice in the choice is by not having executed the critical section yet.

3. **Bounded Waiting**. There exists a bound on the number of times that other Processes are allowed to enter their Critical Sections after a process has made a request to enter its critical section and before that request is granted.

To handle the Critical Section Problem, there are 2 main types of Kernels that present solutions.

1. Nonpreemptive Kernels. Not used frequently today.
2. Preemptive Kernels. The most common type today.

Defn 65 (Nonpreemptive Kernel)**.** A *nonpreemptive kernel* is a Kernel that does **NOT** use Preemption on Processes or Threads running in kernel-mode.

Defn 66 (Preemptive Kernel)**.** A *preemptive kernel* is a Kernel that uses Preemption on Processes or Threads running in kernel-mode. This means that we cannot say anything definitive about the state of the Kernel's data structures at a given time, because we cannot say which process/thread is running at that time.

6.1.2 Hardware Support for Synchronization

Software-based solutions to handling multithreading and multiprocessing tends to be better than hardware-based solutions, as they are more flexible. Many of the solutions that will be presented here are based on the idea of **Locking**.

Defn 67 (Lock)**.** A *lock* allows **only one** Thread to enter the portion of code that is locked. While a thread holds this lock no other Thread can execute on this code portion.

Remark 67.1 (Binary Semaphore). Locks can be represented as *binary Semaphore*s.

In a single-processor system, we can solve the Critical Section Problem by preventing interrupts from being handled. This would prevent the currently running instruction from being preempted in any way, and allow it to finish. However, this does not really work on a multiprocessor system, because disabling interrupts and their handling on all processors is time consuming.

However, the idea of certain instructions being Atomic is an elegant solution to the Critical Section Problem. So, most computer systems provide special hardware-level instructions that allow us to test and modify the contents of a word, or swap the contents of 2 words Atomically.

Defn 68 (Atomic)**.** An *atomic* operation is one that cannot be interrupted, preempted, or altered in any way. As soon as an atomic operation begins, the system **MUST** finish handling it before it may do anything else.

Some operations on data are possible to do at any given point in time, without affecting the potential outcome. One example of this is **reading** from a location in memory. However, if this location can also be written to, we need to limit the number of writers. Additionally, if someone is waiting to write, they should get some priority over anything waiting to read. Thus, the Read/Write Lock was created.

Defn 69 (Read/Write Lock)**.** *Read/Write Lock*s allow either an unlimited number of readers **OR** 1 writer at any given time. Writers will be scheduled to use the lock sooner than readers, so the value is updated first, before anyone reads it again. But, the writer will have to wait until everyone currently reading the value is done reading, otherwise the value in memory will change underneath the readers.

6.1.3 Mutex Locks

The hardware-based solutions presented in Section 6.1.2 are typically not available to application programmers. Instead, operating system designers build software tools to handle the Critical Section Problem. The simplest tool is that of a Mutex.

Defn 70 (Mutex)**.** A *mutex* (short for ***mut**ual **ex**clusion*) is the same as a Lock, **but it can be system wide (shared by multiple processes)**. A mutex lock protects critical regions and prevents race conditions. That is, a process must acquire the lock before entering a critical section; it releases the lock when it exits the critical section.

The `acquire()` function acquires the lock, preventing any other Thread and/or Process from using the thing the lock protects. Likewise, the `release()` function releases the lock, allowing another Thread and/or Process take acquire the lock and use the resource it protects. To perform its function correctly, the lock's `acquire()` and `release()` functions must be Atomic.

When a Thread and/or Process attempts `acquire()` the lock, while it is already owned by someone else, it is put in a `WAITING` state.

There are a variety of Mutexes, depending on the way the way they are used is implemented. In one variety, the Spinlock, the Process/Thread that is attempting to `acquire` the lock will continuously call the `acquire()` function until it gets the lock.

Defn 71 (Spinlock)**.** A *spinlock* is one way of having a system use a Mutex lock. In this implementation, the Process/Thread that wants to `acquire` the lock loops continuously, calling `acquire()` until it gets it. This means that there is no Context Switch to another task.

This means that while a Process/Thread is not executing anything useful and may be hogging the CPU's cycles, if the lock is freed soon, then no Context Switch back is required.

6.1.4 Semaphores

Semaphores are a more general way of approaching resource allocation and mutual exclusion within a system. Because of this generality, there are 2 kinds of Semaphores:

1. Counting Semaphore
2. Binary Semaphore

Defn 72 (Semaphore)**.** A *semaphore* regulates the number of things (Processes or Threads) performing operations on something (Shared Resource). Functionally, this is the same as a Mutex but allows x Processes/Threads to enter or use the resource at a time. This allows for limits on the number of CPU, I/O or RAM intensive tasks running at the same time.

A semaphore can only be interacted with through 2 operations `wait()` and `signal()` . `wait()` is similar to a Mutex's `acquire()` function and the `signal()` function is similar to the Mutex's `release()` function. Here, if a Process or Thread `wait`s, if there is more of the resource, then the requester gets the resource, and the internal count of the semaphore is decremented. If a Process or Thread `signal`s, then it is done with the resource, and the requester loses access to the resources, and the internal count of the semaphore is incremented. Again, these manipulations **MUST** be Atomic.

Remark 72.1 (Confusion with Mutexes)*.* Technically, you can create a Semaphore that acts like a Mutex by giving it a binary value. However, this is typically in poor programming taste, because while both function similarly, the Semaphore is for signalling the amount of a resource available and the Mutex is for signalling if code is capable of execution.

Remark 72.2 (Correct Use of Semaphores)*.* The correct use of a Semaphore is for signaling from one task to another. A Mutex is meant to be taken and released, always in that order, by each task that uses the shared resource it protects. By contrast, tasks that use Semaphores either signal or wait, not both.

A Semaphore contains not only its integer value, but also a pointer to the list of waiting Threads/Processes. This way the things waiting on the Semaphore's values can be reached. However, we now have issues with Starvation and Deadlock.

Defn 73 (Starvation)**.** *Starvation* is when a thing is waiting for a resource indefinitely. For example, if a Process/Thread is waiting for a Semaphore to become available, and these requesters are services in a Last-In First-Out order, its possible the first requester to enter the queue never leaves.

Semaphores have some additional issues to go with them:

- A process might never release a resource once it has been granted access to the resource.
- A process might attempt to release a resource that it never requested.
- A process might request the same resource twice (without first releasing the resource).

6.1.4.1 Counting Semaphore A *counting Semaphore* allows for the value contained within the Semaphore to range over a domain of integer values. For example, the integers from 0 to 10, allowing for 10 different users to access the same resource at once.

Once the Semaphore count reaches 0, nothing else can use the resource until one of the current users relinquishes control. So, the first Process/Thread that uses `wait()` when the Semaphore's internal value is 0 will be put in either a Spinlock-like state, or will be put into a waiting queue.

Typically, the Processes/Threads that are using the Semaphore will be qusing it for quite some time, new requesters are put into a waiting queue/state. Then, the Scheduler is called, performing a Context Switch to a Thread/Process that is ready to run, and Context Switches.

Thus, whenever another user of the Semaphore `signal`s, one of the Processes/Threads should be awoken from this waiting state, moved to the ready state, and be made schedule-able. Which waiting thing is chosen depends on the way the queue is structured, and how things get scheduled, and many other factors.

> In this system, we don't guarantee immediate execution of the thing requesting the Semaphore, only that it can be scheduled.

How this queue is structured is different between every Kernel, but it is typically constructed out of the Process Control Block or the Thread control block.

Negative Semaphore Values In some implementations of a Semaphore, the internal value can become negative. In the strict, classical definition of a Semaphore, this internal value **CANNOT** be negative. However, if we allow the negative value, and the Semaphore reaches it, it represents the number of things that are waiting on the Semaphore to be freed up.

6.1.4.2 Binary Semaphore A *binary Semaphore* only allows the internal value within the system to be zero or one. This effectively acts as a Mutex.

6.1.5 Priority Inversion

Priority Inversion is a scheduling challenge where a higher-priority process needs to read or modify kernel data that is currently being used by a lower-priority process. Since the kernel data is typically protected with a Lock, the higher-priority process must wait for a lower-priority one to finish with that resource. The situation becomes more complicated if the lower-priority process is preempted in favor of another process with a higher priority.

It occurs only in systems with more than two priorities. Typically these systems solve the problem by implementing a Priority-Inheritance Protocol.

Defn 74 (Priority-Inheritance Protocol)**.** A *priority-inheritance protocol* is one where a lower-priority Process that is using resourced needed by a higher-priority process will inherit the higher priority until it is done with the resource. Then, the lower-priority process is returned to its original priority level.

6.1.6 Monitors

Using Semaphores can be difficult, with some common errors being:

- Using `signal()` before the Critical Section and `wait()` afterwards. This will may allow multiple requesters to execute their critical sections at times when they shouldn't.
- Using `wait()` twice, once before the Critical Section and once after. This will cause a Deadlock to occur.
- Forgetting either the `wait()` before the Critical Section or the `signal()` after it. Forgetting the `wait()` will violate mutual exclusion. Forgetting the `signal()` will cause a Deadlock.

To handle these kinds of issues, the Monitor type was created.

Defn 75 (Monitor)**.** A *monitor* is an abstract data type that includes:

- Programmer-defined operations that must be executed with mutual exclusion.
- The variables whose values define the state of an instance of that type.
- The bodies of functions that operate on those varables.

A monitor ensures that only one Process or Thread can execute any actions in the monitor at any given time. Thus, the programmer **does not** need to code the synchronization explicitly.

The general syntax of a monitor type is shown in Listing 1.

The use of `conditions` in the Monitor allow for operations that require the use of those conditions to `wait()` and `signal()` them. This prevents Processes and/or Threads from performing other actions that require those conditions until they are freed. The difference with `signal()` in a Monitor and a Semaphore is that if that condition is already active, **nothing happens**.

In Monitors, just like with Semaphores, when something `waits` a condition that is already completely used,the requester is put into a queue. How the requester is pulled from the queue depends on the setup of the Monitor

Monitors have some additional issues to go with them:

- A process might never release a resource once it has been granted access to the resource.
- A process might attempt to release a resource that it never requested.
- A process might request the same resource twice (without first releasing the resource).

6.2 Scheduling

CPU scheduling is the basis of multiprogrammed operating systems. In a single-processor system, only one process can run at a time. Others must wait until the CPU is free and can be rescheduled. By switching the CPU among processes, the operating system can maximize CPU utilization.

For example, a Process is executed until it must wait. Typically the process waits for the completion of some I/O request. In a simple computer system, the CPU then just sits idle. All this waiting time is wasted; no useful work is accomplished.

Scheduling of this kind is a fundamental operating-system function. Almost all computer resources are scheduled before use.

```
monitor name {
        condition x;
        condition y;
        /* Shared Variable Declarations */
        function P1 (...) {
                ...
        }

        function P2 (...) {
                ...
        }

        function Pn (...) {
                ...
        }

        initialization_code (...) {
                ...
        }
}
```

Listing 1: Syntax of a Monitor Type

6.2.1 CPU and I/O Bursts

To properly schedule a Process, its CPU Bursts and I/O Bursts need to observed.

Defn 76 (CPU Burst)**.** A *CPU burst* is one of the states of execution for a Process. This is the state when the process is actively using the CPU to perform computations. In this state, the CPU is performing activity for **this** Process, and **IS NOT** waiting for an I/O device to perform some action or return information.

Defn 77 (I/O Burst)**.** An *I/O burst* is one of the states of execution for a Process. This is the state when the process is waiting on the I/O device to return the requested information or perform the desired action. In this state, the CPU is doing no activity for **this** Process.

A Process alternates between these two bursts, with the final CPU Burst terminating this Process's execution. The distribution of length of CPU bursts is an exponential or hyperexponential graph. This means:

- There is a large number of short duration CPU bursts.
- There is a small number of long duration CPU bursts.

We can categorize these into either CPU-Bound programs or I/O Bound programs.

- I/O-bound programs have a small number of CPU bursts which have a relatively short duration relative to the I/O operations. The I/O operations take up a majority of the time the Process executes.
- CPU-bound programs have a large number of CPU bursts, which have a relatively long duration relative to the I/O operations. The CPU operatiosn take up a majority of the time the Process executes.

6.2.2 CPU Scheduler

Whenever the CPU becomes idle, i.e. it has finished the current CPU burst early, or there is an I/O operation, the Operating System must select the next Process and/or Thread to schedule. This is handled by the Short-Term Scheduler.

Defn 78 (Short-Term Scheduler)**.** The *short-term scheduler* is responsible for scheduling either the next Process or Thread for execution on the **CPU** from all the possible ones in memory. This is run quite frequently, every couple hundred milliseconds, usually.

Remark 78.1 (CPU Scheduler)*.* Because the Short-Term Scheduler only schedules tasks for the CPU, it is also called the *CPU Scheduler*.

6.2.2.1 Preemption and Scheduling

There are 4 times when CPU scheduling occurs:

1. When a process switches from the `RUNNING` state to the `WAITING` state.
2. When a process switches from the `RUNNING` state to the `READY` state (for example, when an interrupt occurs).
3. When a process switches from the `WAITING` state to the `READY` state (for example, at completion of I/O).
4. When a process terminates.

In the case of Times 1 and 4, there are no options in terms of scheduling. In the first situation, a Process is being made unschedule-able by the Operating System. So, another process must be switched in for the one that was made to wait. Similarly, when a Process terminates, there is no option for how to schedule it, because it's done executing.

A Nonpreemptive Kernel only allows scheduling during Times 1 and 4. In this system, once a Process gets allocated to the CPU, it keeps the CPU until it terminates, it switches to the `WAITING` state, or it voluntarily yields control of the CPU.

A Preemptive Kernel allows scheduling during all Times (1–4). This can only be done on certain hardware platforms (all major ones today), because a timer is needed, among other special hardware. In this system, Race Conditions appear. We also need to design the Kernel to allow for Preemption, such as when the kernel is busy performing a System Call for a Process. If we don't have to worry about real-time computing, then we can wait for the System Call to finish before moving onto another task.

6.2.2.2 Interrupt Handling

Interrupts can happen **AT ANY TIME**, which must be accepted at almost all times. On multiprocessor systems, it is costly to turn off interrupt handling on all cores, but sometimes it is necessary. If we don't, input might be lost or output overwritten. To ensure that these code sections are not accessed concurrently by several processes, they disable interrupts at entry and reenable interrupts at exit. The sections of code that disable interrupts do not occur often and typically contain few instructions.

6.2.2.3 Dispatcher

The Dispatcher **MUST** be as fast as possible to minimize the amount of time spent working on switching betweeen Processes/Threads. This is measured as the Dipatch Latency.

Defn 79 (Dispatcher)**.** The *dispatcher* is a Short-Term Scheduler function. It is the code responsible for giving control of the CPU to the Process that the scheduler selected. This involves:

1. Performing a Context Switch.
2. Switching to the appropriate mode, User-mode or Kernel-mode.
3. Jumping to the proper location in the Process to continue its execution.

Defn 80 (Dipatch Latency)**.** The *dispatch latency* is the amount of time required by the Dispatcher to stop one Process and switch to another.

6.2.3 Scheduling Criteria

The choice of how to schedule tasks for the CPU is completely dependent on the desired outcome of the scheduling algorithm and the desired performance of the system. The criteria for most algorithms are:

- **CPU utilization**. We want to keep the CPU as busy as possible. In a real system, it utilization should range from 40 percent (for a lightly loaded system) to 90 percent (for a heavily loaded system).
- **Throughput**. If the CPU is busy executing processes, then work is being done. The number of processes that are completed per time unit is called throughput.
- **Turnaround time**. From the point of view of a process, the important criterion is how long it takes to execute that process. The interval from the time of submission of a process to the time of completion is the turnaround time. This includes time spent waiting to get into memory, waiting in the ready queue, executing on the CPU, and doing I/O.
- **Waiting time**. The CPU-scheduling algorithm does not affect the amount of time during which a process executes or does I/O, only the amount of time that a process spends in the ready queue. Waiting time is the sum of the periods spent waiting in the ready queue.
- **Response time**. In an interactive system, turnaround time may not be the best criterion. A process can produce some output early and then continue computing new results while previous results are being output to the user. Thus, another measure is the time from the submission of a request until its response is produced. This measure, called response time, is the time it takes to start responding, not the time it takes to output the response. The turnaround time is generally limited by the speed of the output device.

It is desirable to maximize CPU utilization and throughput and to minimize turnaround time, waiting time, and response time. Usually the average measure is optimized. However, sometimes it is better to optimize the minimum or maximum values rather than the average.

6.2.4 Scheduling Algorithms

Here, we will discuss the different kinds of Scheduling Algorithms used by the Short-Term Scheduler.

Defn 81 (Scheduling Algorithm)**.** The *scheduling algorithm* is responsible for choosing the next Process/Thread to run from the set of all `READY` processes.

6.2.4.1 First-Come First-Served Scheduling In this algorithm, the first task that becomes `READY` is the first to execute. This is easily handled with a FIFO queue. The most recent task to appear in the task queue is appended as the tail of the FIFO queue's list, and moves forward until it gets to execute. Once it has its chance to execute, this Process will execute for its entire period, making this a nonpreemptive scheduling method.

The problem with FCFS scheduling is the average waiting time for Processes, especially if there is a large difference in the amount of CPU time required by some of the processes. This is illustrated visually in Figure 6.1.

Example 6.1: FCFS Calculations.

Suppose 3 processes arrive at the same time and have these CPU bursts required.

Process	Time Required
P_1	24
P_2	3
P_3	3

In a FCFS system, the average waiting time is

$$\frac{0+24+27}{3} = 17\,\text{ms}$$

However, if we were to schedule the short processes first, then the average waiting time would be

$$\frac{0+3+6}{3} = 3\,\text{ms}$$

Defn 82 (Gantt Chart)**.** A *Gantt chart* is a way to visualize the order and amount of time a processor spends executing a task. An example of one is shown in Figure 6.1. The start and end times of a particular task are also shown on the chart.

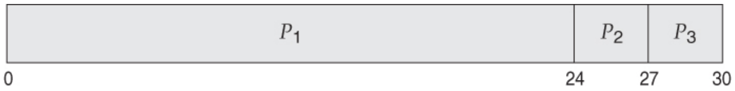


Figure 6.1: Gantt Chart

Additionally, if there are a lot of small I/O tasks and just a few large CPU ones, then the Convoy Effect starts.

Defn 83 (Convoy Effect)**.** The *convoy effect* is a result of having few very CPU-intensive tasks that use the CPU fro their entire duration and a lot of small I/O-intensive tasks. There, the CPU-Bound task will block the I/O Bound tasks. This lowers overall throughput and device utilization.

6.2.4.2 Shortest-Job-First Scheduling Here, the job with the shortest amount of time required for the next CPU burst is scheduled first. If 2 Processes have the same amount of time required, then the tie is broken with FCFS among those tasks. This can be either preemptive or nonpreemptive. The question comes up when a newly arrived Process has a shorter CPU burst than the one currently running. If this new process preempts the currently running one, then it is a preemptive SJF scheduler, and is sometimes called *Shortest-Remaining-Time-First scheduling.*

Note that this is the length of the **next CPU burst**, not the overall length of CPU execution.

Example 6.2: SJF Calculations.

Suppose 4 processes arrive at the same time with their CPU bursts as shown.

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

In this case, these processes would be scheduled in this order.

1. P_4
2. P_1
3. P_3
4. P_2

With an average delay of

$$\frac{0+3+9+16}{4} = 7\,\text{ms}$$

In a FCFS system, the average delay would be 10.25 ms.

This is provably optimal, theoretically making it the best algorithm. However, it is hard for a Process to know the length of its next CPU request. There is also no way to know the length of the next CPU burst.

However, SJF scheduling is used in the long-term scheduler, because time limits can be set on the execution of various tasks, essentially forcibly giving a value to the next CPU burst.

To calculate the length of the next CPU burst, we tend to approximate it as an exponential average of the previous CPU bursts. This is shown in Equation (6.1).

$$\tau_{n+1} = \alpha t_n + (1-\alpha)\tau_n \tag{6.1}$$

τ_{n+1}: The predicted value of the next CPU burst.
t_n: The length of the nth CPU burst.
α: A value to determine how much we take the past into account. $0 \leq \alpha \leq 1$.

- If $\alpha = 0$, then the most recent CPU burst has no effect, and only the longer past is considered.
- If $\alpha = 1$, then **ONLY** the most recent CPU has any effect, and the older past is ignored.

6.2.4.3 Priority Scheduling Priority scheduling is the idea that each Process has a priority associated with it that determines which process should be scheduled next. The process with the highest priority is scheduled next. In fact, the Shortest-Job-First Scheduling is one case of the priority scheduling system.

We discuss scheduling in terms of **high priority** and **low priority**, which is represented by a fixed range of integers. The definition of high and low vary from system to system with 0 being the lowest on some and highest on another.

In this document, we assume the lower the priority number, the higher the priority. This makes a Process or Thread with a priority of 0 have the highest priority.

What makes a Process have a certain priority depends on if the priority is set internally or externally.

- Internally-Defined Priorities use a measurable quantity or quantities to compute the priority of a process.
- Externally-Defined Priorities are set based on criteria outside the Operating System.

Priority scheduling can be nonpreemptive or preemptive. Like in SJF, if a process arrives with a higher priority than the one currently running, the scheduler is preemptive if the higher priority process is allows to Context Switch in. A nonpreemptive scheduler will allow the current Process to finish execution, while the new, higher priority process is put at the front of the job queue.

Example 6.3: Priority Scheduling Calculations.

Suppose 5 processes arrive at the same time with their CPU bursts and priority levels as shown.

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	4
P_4	1	5
P_5	5	2

In this case, these processes would be scheduled in this order.

1. P_2
2. P_5
3. P_1
4. P_3
5. P_4

With an average delay of

$$\frac{0+1+6+16+18}{5} = 13.4\,\text{ms}$$

In a FCFS system, the average delay would be 13.4 ms.

A major problem with priority scheduling is the concept of Starvation. A process that is ready to run, but waiting for the CPU is considered blocked. If there is a system where enough high priority Processes are created to the point where a lower priority process never gets a chance to execute, the low priority process is said to be starved.

To solve this problem, Process Aging is used.

Defn 84 (Aging)**.** *Aging* is a process in a priority-based system that forces a CPU to eventually execute the lowest priority Processes by gradually increasing the priority of the Process. Eventually, the process would reach a high enough priority to be executed.

6.2.4.4 Round-Robin Scheduling

This algorithm is designed for time-sharing systems. It is similar to First-Come First-Served Scheduling, but preemption is allowed and the process list is circular. New tasks are added to the tail of the circular list. A small amount of time, called a Time Slice is used, and each Process in this circular list is allowed to execute for one of these slices.

Defn 85 (Time Slice)**.** A *time slice* is a small, indivisible amount of processor time, typically in the range of 10 ms to 100 ms. Inside this time slice, a single Process/Thread is run. When this time slice ends, a new task is executed.

Remark 85.1 (Time Quantum). A Time Slice is also called a *Time Quantum*.

In this scheduling algorithm, no process is allocated the CPU for more than 1 Time Slice in a row (unless it is the only runnable process). If a task requires more CPU time than a single Time Slice can provide, then that task is interrupted and is allowed to execute again the next time it is given a Time Slice. If a task requires less CPU time than a single Time Slice, then the next time slice begins when the process terminates. This makes the round-robin algorithm preemptive by definition.

To find the amount of time a Process will have the CPU, use Equation (6.2). To find how long the Process will have to wait to get the CPU again, use Equation (6.3).

$$PT = \frac{1}{n} \tag{6.2}$$

$$W = (n-1)q \tag{6.3}$$

PT: The amount of processor time a task will get.
n: The number of Processes in the `RUNNING` queue.
W: The amount of time a Process will have to wait to get the CPU allocated to it again.
q: The duration of a Time Slice.

The duration of a Time Slice is a major factor in the relative efficiency of a round-robin algorithm. If the Time Slice is:

- too large, then this becomes a FCFS algorithm.
- too small, then there will be a large number of Context Switches.

The duration of a Time Slice should also take the time required for a Context Switch into account. A time slice should be large relative to the time required for a context switch.

6.2.4.5 Multilevel Queue Scheduling

Depending on the situation, there are times when Processes/Threads are easily grouped. For example, foreground and background processes (interactive and batch). These groups have different requirements on them, thus having different scheduling needs. Additionally, since foreground processes are in direct interaction with the user, they have a ghigher priority than background ones. This forms the basis for a Multilevel Queue scheduling algorithm.

Defn 86 (Multilevel Queue)**.** A *multilevel queue* is a system that uses multiple queues for different groups of tasks that have different parameters they must adhere to. Processes/Threads assigned to one queue are assigned there permanently, based on some property about the process.

Each queue can have its own scheduling algorithm, ensuring the different demands from the queues are met. Additionally, there is scheduling for which queue will be chosen next.

An example Multilevel Queue is shown below. In order from the highest priority to lowest, are 5 queues, each containing different processes.

1. System Processes
2. Interactive Processes
3. Interactive Editing Processes
4. Batch Processes
5. Student Processes

In this system, each queue has absolute priority over another, meaning Interactive Processes can execute **ONLY IF** there are no System Processes left to handle. If an Interactive Process is currently executing, and a System Process comes into its queue, the Interactive Process is switched out as soon as possible, and the System Process is switched in.

Another possibility is to give a certain amount of processor time to each queue and allow the queue to fill up that time as it sees fit.

6.2.4.6 Multilevel Feedback Queue Scheduling

A Multilevel Queue does not allow a Process/Thread to move between one of the queue groups. However, in a *Multilevel Feedback Queue Scheduling* (*MLFQS*) system, they can. The separate queues still maintain their different scheduling algorithms, and each queue must be scheduled according to some master controller. However, there is also an algorithm to move tasks between the different queues.

In this system, a Process is moved between queues based on characteristics of their CPU Bursts. If a process uses too much CPU time, it is moved down in priority. This allows I/O Bound processes get quick access to the CPU and execute quickly. Then, when these higher priority queues are empty, a low priority task can execute longer.

Since this is effectively a Priority Scheduling system, Aging must be used to ensure a Process does not sit in a lower-level queue for too long.

In general, this scheduling algorithm is defined by the following parameters:

- The number of queues.
- The scheduling algorithm for each queue.
- The method used to determine when to upgrade a process to a higher-priority queue.
- The method used to determine when to demote a process to a lower-priority queue.
- The method used to determine which queue a process will enter when that process needs service.

6.3 Thread Scheduling

> **On operating systems that support them, Kernel Threads, not Processes are scheduled by the operating system.** However, the terms “process scheduling” and “thread scheduling” are often used interchangeably. Process scheduling is used when discussing general scheduling concepts and thread scheduling to refer to thread-specific ideas.

6.3.1 User- vs. Kernel-Level Thread Scheduling

On systems implementing the Many-To-One Model (Section 5.1.1) and Many-To-Many Model (Section 5.1.3), the thread library schedules user-level threads to run on an available LWP.

Defn 87 (Process-Contention Scope)**.** *Process-Contention Scope* is where each of the Threads **WITHIN A SINGLE Process** compete with each other for execution.

In Process-Contention Scope, the Thread Library schedules the User Threads onto available Lightweight Processes, or directly onto Kernel Threads. However, this does not mean that the User Thread are being scheduled for execution. For that to happen, the Kernel must be involved.

To decide what Threads can execute on the CPU, we broaden our view of contention to System-Contention Scope.

Defn 88 (System-Contention Scope)**.** *System-Contention Scope* is where **ALL** of the Threads on the system, from all Processes compete with each other for execution.

If a Kernel uses the One-To-One Model, then **ALL** threads are scheduled using System-Contention Scope.

6.3.2 Multiprocessor Scheduling

If multiple processors are available for use in a system, then Load Sharing is possible.

Defn 89 (Load Sharing)**.** *Load sharing* involves splitting the load of running Processes and their Threads between multiple processors. This does not limit the possibility of multithreading, rather it complements it.

In this course, we consider each processor to be equivalent, or homogenous. This means that each one will have the same basic set of functionality and can reach all resources present in the system. This does not mean that all processors can reach all the resources with the same cost/delay. There may be an I/O device attached to the private bus of a core, or there may be Non-Uniform Memory Access.

6.3.2.1 Approaches to Multiprocessor Scheduling There are 2 main approaches to multiprocessor scheduling, without taking the idea of non-uniform resource availability.

1. Asymmetric Multiprocessor System
2. Symmetric Multiprocessor System

In an Asymmetric Multiprocessor System, one of the processors acts as the master server. It runs the scheduler, allocating jobs to each of the slave worker processors. This reduces the need for data sharing, making coding and debugging such a thing much easier.

The other approach, Symmetric Multiprocessor System, allows each processor to schedule itself. Tasks to execute may be in 2 types of queues:

1. A common queue for all processors.
2. A private queue, one for each processor.

Each processor must select a job from the ready queue and execute it. We must ensure that no two processors schedule and execute the same task at the same time, and that processes are not lost from the queue.

> Throughout this section, and most of this document, we discuss Symmetric Multiprocessor System (SMP) systems. These are more commonly in use in the desktop space and are more interesting to discuss.

6.3.3 Processor Affinity

Processes/Threads can migrate between processors, no matter the type of multiprocessor system used. However, if such a migration happens, the processor's cache must be invalidated from the origin and the destination cache must be populated. This is a very high cost to system productivity, so we attempt to keep a Process/Thread running on the same processor for as long as possible, this is known as Processor Affinity.

Defn 90 (Processor Affinity)**.** *Processor affinity* is the idea of keeping one Process/Thread running on the **same** processor for as long as possible. This prevents relatively costly process migrations from becoming common.

There are 2 kinds of processor affinity:

1. Soft Affinity
2. Hard Affinity

Defn 91 (Soft Affinity)**.** *Soft affinity* is where Processor Affinity is used, but no guarantees about the migration of a Process can be made. The Operating System will attempt to keep a process running on the same processor for as long as possible, but the process can still migrate between processors.

Defn 92 (Hard Affinity)**.** *Hard affinity* is where once a Process/Thread is assigned to a set of processors, it will **ONLY EXECUTE ON THOSE**.

The organization of Memory in a system will affect the performance of the Processor Affinity choices made. In a Non-Uniform Memory Access system, not all memory is **DIRECTLY** available to every processor. In this type of system, a Process's affinity should be set according to the memory location it inhabits. Otherwise, there will be long delays during memory acccesses. This is illustrated in Figure 6.2.

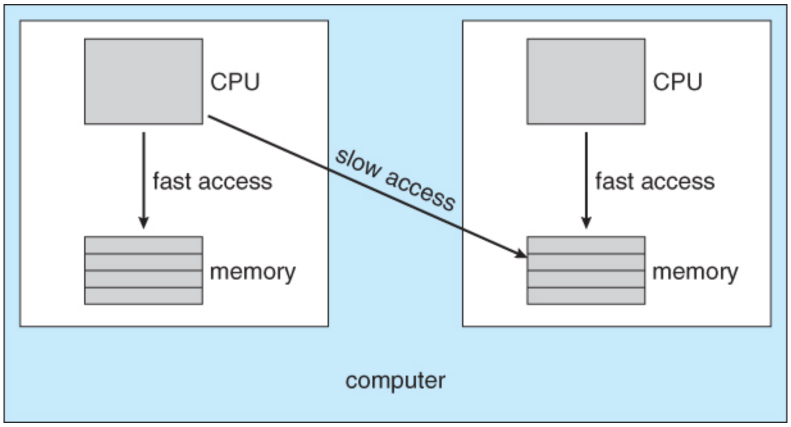


Figure 6.2: Non-Uniform Memory Access, Processor Affinity, and CPU Scheduler Choices

6.3.4 Load Balancing

Because we have multiple processors available to us, we need to make sure they are all doing a fair amount of work. We do not want to have one processor sitting idle while others have very high loads with long queues. This forms the basis of Load Balancing.

Defn 93 (Load Balancing)**.** *Load balancing* is the process of making sure that every processor in a system is assigned an even amount of work. This ensures that **ALL** processors are active at one time, preventing the issue of some processors sitting idle while others have very high loads and long queues.

There are 2 main ways to provide load balancing:

1. Push Migration
2. Pull Migration

Remark 93.1 (Common vs. Private Queues). Like stated earlier in this section, some multiprocessor designs use a common task queue for all processors, and others use private queues for each individual processor. In the case of a common queue, then Load Balancing is unnecessary, because each processor will extract a job from the common queue. Load Balancing is only necessary on systems that use private queues, which most multiprocessors today use to some extent.

Push Migration and Pull Migration **ARE NOT** mutually exclusive. In fact, most systems support both.

Defn 94 (Push Migration)**.** In *push migration*, there is a task inserted into the queue that checks the load on each processor. If it finds a large imabalance, then that processor's tasks are evenly redistributed among all other processors.

Defn 95 (Pull Migration)**.** *Pull migration* is where each processor, once it becomes idle, goes to other processors and attempts to pull a waiting task from the other processor's queue.

Load Balancing counteracts the benefits of Processor Affinity. The benefit of keeping a process running on the same processor is that the process can take advantage of its data being in that processor's cache memory. Either pulling or pushing a process from one processor to another removes this benefit.

6.3.5 Multicore Processors

In more recent times, multiple processors are being built onto the same physical chip, making a *multicore processor*. To the Operating System, they appear as separate CPUs, because each core maintains its own architectural state. This allows for multicore processor systems that are faster and consume less power than traditional multiprocessor systems.

The rise of multicore processors has also lead to the rise of hardware threads. This is because a Central Processing Unit spends much of its execution time waiting for Memory and its contents to become available. When a CPU waits for memory to returns its contents, it is called a Memory Stall.

Defn 96 (Memory Stall)**.** A *memory stall* is when a CPU must go to memory to retrieve a value. This could happen because of a cache miss, for instance.

By having multiple hardware threads, when one of the threads has a Memory Stall, the other thread can take over execute while the first waits for the memory to be returned. These are called *logical processors*.

Each of these logical processors appears to the Operating System as a separate physical CPU.

The number of processors that the Operating System "sees" can be calculated by Equation (6.4).

$$C = Pt \tag{6.4}$$

C: The number of cores the Operating System sees.
P: The number of processors present in the system.
t: The number of hardware threads present in each processor.

There are 2 ways to multithread a processor core:

1. Coarse-Grained Multithreading
2. Fine-Grained Multithreading

Defn 97 (Coarse-Grained Multithreading)**.** In *coarse-grained multithreading*, a hardware thread will execute until it reaches a long-latency event, such as a Memory Stall. The processor then switches to the other thread and continues execution while waiting for the long-latency event to return.

This has a high cost, because the entire instruction pipeline must have the first thread's instructions emptied and the new thread's instructions fill the pipeline. This is quite costly.

Defn 98 (Fine-Grained Multithreading)**.** *Fine-grained multithreading* switches between the hardware threads much more frequently and quickly, typically between every other instruction. To ensure this does not take too much time, hardware logic is built-in for thread switching.

The use of hardware threads means there is another layer of scheduling required.

1. The highest layer is scheduling User Threads onto Kernel Threads by the Thread Library.
2. The next layer is the Operating System scheduling Kernel Threads for execution.
3. Next is the hardware scheduler for which **hardware thread** to execute next.

Each one of these layers can use different scheduling algorithms, to meet performance criteria in each section.

6.4 Real-Time Scheduling

Real-time operating systems have their own class of scheduling issues. This depends on whether the Operating System is a Soft Real-Time System or a Hard Real-Time System.

Defn 99 (Soft Real-Time System)**.** *Soft real-time systems* do not provide a guarantee about the scheduling of a critical real-time process.

Defn 100 (Hard Real-Time System)**.** *Hard real-time systems* guarantee the execution time of a real-time process. These tasks will be serviced by its deadline, otherwise the process will not be executed at all.

POSIX also provides support for real-time scheduling through 2 functions with 2 scheduling types.

1. `pthread_attr_getsched_policy(pthread_attr_t *attr, int *policy)`
2. `pthread_attr_setsched_policy(pthread_attr_t *attr, int policy)`

1. `SCHED_FIFO`
2. `SCHED_RR`

6.4.1 Minimizing Latency

The key aspect here is the amount of time it takes for a system to respond to an event. This is called Event Latency.

Defn 101 (Event Latency)**.** *Event latency* is the amount of time that elapses from when an event occurs to when it is serviced. Different events can have different event latency requirements.

There are 2 factors that affect Event Latency.

1. Interrupt Latency. The amount of time from the arrival of an Interrupt to the start of the Interrupt Service Routine (ISR). This includes the amount of time needed to get the currently running instruction to a point where it can be switched. Also included is the amount of time needed to perform the switch.
2. Dispatch Latency the amount of time the scheduler needs to stop one process and start another. There are 2 parts that affect the value of the dispatch latency:
   (a) Preemption of **ANY** process running tin the kernel.
   (b) Release of resources used by low-priority process for higher-priority processes.

6.4.2 Scheduling

In this case, there are not as many choices of Scheduling Algorithm for real-time systems as other systems. All algorithms must be roughly based on a priority-based system all of which must support Preemption.

Most modern Operating Systems offer support for Soft Real-Time Systems with their scheduling priorities. Note however, that pure priority-based algorithms only guarantee soft real-time functionality, not hard.

Processes are considered periodic; they require the CPU at constant intervals. Once a periodic process has acquired the CPU, it has a fixed processing time t, a deadline d by which it must be serviced by the CPU, and a period p. The relationship of the processing time, the deadline, and the period can be expressed as $0 \leq t \leq d \leq p$. The rate of a periodic task is $\frac{1}{p}$. Schedulers can take advantage of these characteristics and assign priorities according to a process's deadline or rate requirements. What is different about this algorithm is a process may have to announce its deadline to the scheduler. Using an admission-control algorithm, the scheduler either admits the process, guaranteeing that the process will complete on time, or rejects the request if it cannot guarantee that the task will be serviced by its deadline.

6.4.2.1 Rate-Monotonic Scheduling

Defn 102 (Rate-Monotonic Scheduling)**.** *Rate-monotonic scheduling* is a Scheduling Algorithm for periodic tasks that uses a static priority policy with preemption. If a higher-priority process arrives, and a lower priority one is running, it is immediately preempted. The priority is statically calculated based on the inverse of the period of the task. Less frequent (longer period) tasks have a lower priority, and more frequent ones have higher priority. Additionally, the size of the CPU burst is assumed to be constant during every period.

Rate-Monotonic Scheduling is considered optimal because given a set of processes that cannot be scheduled by this algorithm, no other static-priority algorithm can schedule them either.

The worst-case CPU utilization for scheduling N processes is shown in Equation (6.5)

$$N\left(2^{\frac{1}{N}} - 1\right) \tag{6.5}$$

6.4.2.2 Earliest-Deadline-First Scheduling

Defn 103 (Earliest-Deadline-First Scheduling)**.** *Earliest-Deadline-First scheduling* dynamically assigns priorities based on the deadlines of tasks. The earlier/sooner the deadline, the higher the priority. To ensure this works, when a process becomes runnable, it must announce its deadline requirement.

Unlike Rate-Monotonic Scheduling, Earliest-Deadline-First Scheduling does not require that processes be periodic, nor must a process require a constant amount of CPU time per burst. EDF is theoretically optimal; it can schedule processes so that each process can meet its deadline requirements and CPU utilization will be 100 percent. However, it is impossible to achieve this due to the cost of Context Switching between Processes and Interrupt handling.

6.4.2.3 Proportional Share Scheduling

Defn 104 (Proportional Share Scheduling)**.** In *proportional share scheduling*, the CPU execution time is split into T shares of time. Each application receives N shares of that T, $\frac{N}{T}$ shares of total processing time. In addition to this, there needs to be an admission-control policy to guarantee that an application is run only if there are enough time slots for the process to execute.

6.5 Algorithm Evaluation

Now that we have selected a Scheduling Algorithm to use, how do we know that it was the right choice? First, we need to know what our criteria were. Some systems might have multiple criteria at a time, such as:

- Maximum CPU response time is 1 second.
- Turnaround time is (on average) linearly proportional to total execution time.

To do this, there are 4 main ways to do this:

1. Deterministic Modeling
2. Queuing Models
3. Simulations
4. Implementation

6.5.1 Deterministic Modeling

Deterministic modeling is simple and fast. It gives us exact numbers, allowing us to compare the algorithms. However, it requires **exact numbers for input**, and its answers apply *only* to those cases.

This method takes a particular predetermined workload and defines the performance of each algorithm for that workload.

The main uses of deterministic modeling are in describing Scheduling Algorithms and providing examples. In cases where we are running the same program repeatedly, we can measure the program's processing requirements exactly, allowing us to select a Scheduling Algorithm. Furthermore, over a set of examples, deterministic modeling may indicate trends that can then be analyzed and proved separately.

6.5.2 Queuing Models

On many systems, the processes that are run vary from day to day, so deterministic modeling is impossible. Instead, we can find the the distribution of CPU Bursts and I/O Bursts.

Commonly, this distribution is exponential and is described by its mean. Similarly, we can describe the distribution of times when processes arrive in the system (the arrival-time distribution). From these two distributions, it is possible to compute the average throughput, utilization, waiting time, and so on for most algorithms.

The CPU is described as a server with a queue of `READY` processes. The I/O system with its device queues is another instance of these servers. Knowing arrival rates and service rates, we can compute utilization, average queue length, average wait time, among other parameters. For a more detailed discussion of these topics, refer to ETSN10: Network Architecture and Performance.

Little's Formula, Equation (6.6), shown below, is useful because we can calculate a large variety of information from just a few parameters.

$$n = \lambda \times W \tag{6.6}$$

n: The average queue length, excluding the process currently executing on the CPU.
λ: The average arrival rate of new processes.
W: The average amount of time a process waits in the queue.

Queueing analysis can be useful in comparing scheduling algorithms, but the classes of algorithms and distributions that can be handled is limited. The mathematics of complicated algorithms and distributions are difficult to work with, and arrival and service distributions are often defined in mathematically tractable (but unrealistic) ways. Generally, it is necessary to make a number of independent assumptions, which may not be accurate. This means queuing models are only approximations of real systems, and the accuracy of the computed results are questionable.

6.5.3 Simulations

To get a more accurate evaluation of scheduling algorithms, simulations can be used. Running simulations involves programming a model of the computer system. Software is used to represent major components of the system. As "time" progresses, the simulator modifies the system state to reflect the activities of the devices, the processes, and the scheduler. As the simulation executes, statistics that indicate algorithm performance are gathered. Typically, input is generated from a random-number generated that is programmed according to probability distributions.

However, simulations can be expensive, often requiring hours of processor time. A more detailed simulation provides more accurate results, but takes more computer time.

6.5.4 Implementation

Even a simulation is of limited accuracy. The only completely accurate way to evaluate a Scheduling Algorithm is to code it, put it in the Operating System, and see how it works. This approach puts the actual algorithm in the real system for evaluation under real operating conditions. The major difficulty with this approach is the high cost.

One of the biggest difficulties is the expense incurred in coding the algorithm and modifying the operating system to support it (along with its required data structures). The environment around the algorithm used will change not only in the usual way (New programs written and the types of problems change) but also as a result of the performance of the scheduler. If short processes are given priority, then users may break larger processes into sets of smaller processes. If interactive processes are given priority over noninteractive processes, then users may switch to interactive use.

6.6 Deadlocks

Deadlock is a serious issue in CPU Schedulers because Processes lock resources for themselves. A good example of a deadlock is "When two trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone."

Defn 105 (Deadlock)**.** *Deadlock* is when 2 processes require information or resources from each other to continue running. If this happens, neither process will provide the other with its required information, so they will both wait for each other, forever.

There are only 2 options for handling Deadlocks:

1. Prevent them from happening in the first place.
2. Identify them and fix the problem that is causing them.
3. Hope they don't happen and consider them as unlikely events to occur.
   - This is what most desktop Operating Systems do.

Most Operating Systems do **NOT** provide functionality to identify Deadlocks and correct them.

A system consists of a finite number of resources to be distributed among a number of competing processes. The resources may be partitioned into several types (or classes), each consisting of some number of identical instances. CPU cycles, files, and I/O devices (such as printers and DVD drives) are examples of resource types. If a system has two CPUs, then the resource type CPU has two instances. Similarly, the resource type printer may have five instances. If a process requests an instance of a resource type, the allocation of **any** instance of the type should satisfy the request. If it does not, then the instances are not identical, and the resource type classes have not been defined properly. Under the normal mode of operation, a process may utilize a resource in only the following sequence:

1. Request. The process requests the resource. If the request cannot be granted immediately (for example, if the resource is being used by another process), then the requesting process must wait until it can acquire the resource.
2. Use. The process can operate on the resource (for example, if the resource is a printer, the process can print on that printer).
3. Release. The process releases the resource.

For each use of a Kernel-managed resource by a Process or Thread, the Operating System checks to make sure that the process has requested and has been allocated the resource. A system table records whether each resource is free or allocated. For each resource that is allocated, the table also records the process to which it is allocated. If a process requests a resource that is currently allocated to another process, it can be added to a queue of processes waiting for this resource.

> A set of Processes is in a Deadlocked state when every process in the set is waiting for an event that can be caused only by another process in the set.

6.6.1 Conditions for Deadlocks

A deadlock situation can arise if the following **four conditions hold simultaneously** in a system:

1. Mutual exclusion. At least one resource must be held in a nonsharable mode; that is, only one process at a time can use the resource. If another process requests that resource, the requesting process must be delayed until the resource has been released.
2. Hold and wait. A process must be holding at least one resource and waiting to acquire additional resources that are currently being held by other processes.
3. No preemption. Resources cannot be preempted, so, a resource can be released voluntarily only by the process holding it, after that process has completed its task.
4. Circular wait. A set $\{P_0, P_1, \dots, P_n\}$ of waiting processes must exist such that P_0 is waiting for a resource held by P_1, P_1 is waiting for a resource held by P_2, …, P_{n-1} is waiting for a resource held by P_n, and P_n is waiting for a resource held by P_0.

All four conditions must hold for a deadlock to occur. The circular-wait condition implies the hold-and-wait condition, so the four conditions are not completely independent.

6.6.2 Resource-Allocation Graph

Deadlocks can be described by a directed graph, called a *system resource allocation graph.* In Figure 6.3, there is a representation of the set of processes P_i and resources R_i. If there is an arrow pointing $P_i \rightarrow R_j$ then Process i is requesting Resource j, forming a *Request Edge.* If there is an arrow pointing $R_i \rightarrow P_j$ then Resource j is allocated to Process j, forming a *Assignment Edge.*

In Figure 6.3, there are:

- The sets P, R, and E:
  - $P = \{P_1, P_2, P_3\}$

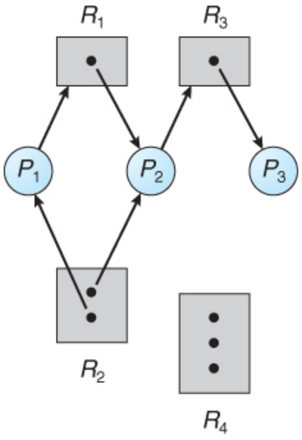
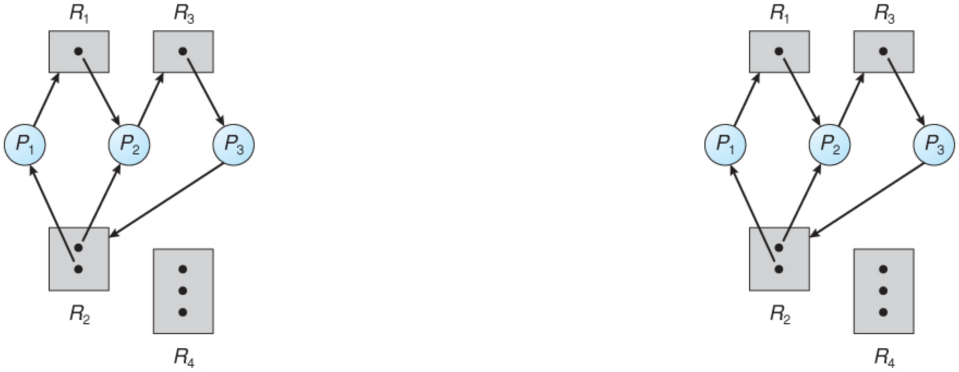


Figure 6.3: Resource Allocation Graph

- Resource instances:
  - One instance of resource type R_1
  - Two instances of resource type R_2
  - One instance of resource type R_3
  - Three instances of resource type R_4
- Process states:
  - Process P_1 is holding an instance of resource type R_2 and is waiting for an instance of resource type R_1.
  - Process P_2 is holding an instance of R_1 and an instance of R_2 and is waiting for an instance of R_3.
  - Process P_3 is holding an instance of R_3.

Given the definition of a resource-allocation graph, if the graph contains no cycles, then no process in the system is Deadlocked. If the graph does contain a cycle, then a Deadlock may exist.

- If each resource type has exactly one instance, then a cycle implies that a Deadlock has occurred.
  - In this case, a cycle in the graph is both a necessary and a sufficient condition for the existence of Deadlock.
- If each resource type has several instances, then a cycle does not necessarily imply that a Deadlock has occurred.
  - In this case, a cycle in the graph is a necessary but not a sufficient condition for the existence of Deadlock.
  - This is illustrated by Figures 6.4a to 6.4b.



(a) RAG with Cycle and Deadlock

(b) RAG with Cycle but no Deadlock

Figure 6.4: Resource Allocation Graph with Cycle

6.7 Handling Deadlocks

There are 3 main ways to handle a deadlock:

1. We can use a protocol to prevent (Section 6.7.1) or avoid (Section 6.7.2) deadlocks, ensuring that the system will never enter a deadlocked state.
2. We can allow the system to enter a deadlocked state, detect it, and recover (Section 6.7.3).
3. We can ignore the problem altogether and pretend that deadlocks never occur in the system.

The third method of handling a Deadlock may not make sense, but from a cost perspective, it does. Ignoring the possibility of deadlocks is cheaper. In many systems, deadlocks occur infrequently (once per year), the extra expense of the methods may not seem worthwhile. In addition, methods used to recover from other conditions may be put to use to recover from deadlock. In some circumstances, a system is in a frozen state but not in a deadlocked state.

6.7.1 Deadlock Prevention

Defn 106 (Deadlock Prevention)**.** *Deadlock prevention* is done by providing a set of methods that ensure any one of the Conditions for Deadlocks cannot occur.

6.7.1.1 Mutual Exclusion That is, at least one resource must be nonsharable. Sharable resources, in contrast, do not require mutually exclusive access and thus cannot be involved in a deadlock. A process never needs to wait for a sharable resource.

Read-only files are a good example of a sharable resource. If several processes attempt to open a read-only file at the same time, they can be granted simultaneous access to the file.

6.7.1.2 Hold and Wait To ensure that the hold-and-wait condition never occurs in the system, we must guarantee that, whenever a process requests a resource, it does not hold any other resources.

We can implement this provision by requiring that system calls requesting resources for a process precede all other system calls. An alternative protocol allows a process to request resources only when it has none.

Both these protocols have two main disadvantages. First, resource utilization may be low, since resources may be allocated but unused for a long period. Second, Starvation is possible. A process that needs several popular resources may have to wait indefinitely, because at least one of the resources that it needs is always allocated to some other process.

6.7.1.3 No Preemption To ensure that no Preemption of resources that have already been allocated occurs, we can use the following protocol. If a process is holding some resources and requests another resource that cannot be immediately allocated to it (that is, the process must wait), then all resources the process is currently holding are preempted, implicitly releasing them. The preempted resources are added to the list of resources for which the process is waiting. The process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting.

This protocol is often applied to resources whose state can be easily saved and restored later, such as CPU registers and memory space. It cannot generally be applied to such resources as mutex locks and semaphores.

6.7.1.4 Circular Wait One way to ensure that this condition never holds is to impose a total ordering of all resource types and to require that each process requests resources in an increasing order of enumeration. Possible side effects of preventing deadlocks are low device utilization and reduced system throughput.

Formally, we define a one-to-one function

$$F : R \to \mathbb{N}$$

where R is the set of resources and $\mathbb{N}$ is the set of natural numbers.

Each process can request resources only in an increasing order of enumeration. Meaning, a process can initially request any number of instances of a resource type, R_i. After that, the process can request instances of resource type R_j if and only if $F(R_j) > F(R_i)$. This could be similarly defined using a more generous comparison; a process can request instances of resource type R_j if and only if $F(R_j) \geq F(R_i)$.

This property can be proven, Paragraph 6.7.1.4.

Proof by Contradiction of Circular Waiting. Let the set of processes involved in the circular wait be $\{P_0, P_1, \ldots, P_n\}$, where P_i is waiting for a resource R_i, which is held by process[3] P_{i+1}.

Then, since process P_{i+1} is holding resource R_i while requesting resource R_{i+1}, we must have

$$\forall i . F(R_i) < F(R_{i+1})$$

But this condition means

$$F(R_0) < F(R_1) < \cdots < F(R_n) < F(R_0)$$

By transitivity, $F(R_0) < F(R_0)$, which is impossible.
$\therefore$ there can be no circular wait. ■

[3] Modulo arithmetic is used on the indexes.

Keep in mind that developing an ordering, or hierarchy, does not in itself prevent deadlock. It is up to application developers to write programs that follow the ordering.

6.7.2 Deadlock Avoidance

Defn 107 (Deadlock Avoidance)**.** *Deadlock avoidance* requires the Operating System be gined additional information in advnace about what resources a process will request and possible use within its lifetime.

To avoid Deadlocks, the Operating System can require additional information about how resources are to be requested. With knowledge of the complete sequence of requests and releases for each process, the system can decide for each request whether or not the process should wait in order to avoid a possible future deadlock. Each request requires that in making this decision the system consider the resources currently available, the resources currently allocated to each process, and the future requests and releases of each process.

There are 2 major ways to achieve this:

1. Safe State
2. Resource Allocation Graph Algorithm

6.7.2.1 Safe State A system is in a safe state only if there exists a safe sequence. A sequence of processes $\langle P1, P2, \ldots, Pn\rangle$ is a safe sequence for the current allocation state if, for all resource requests that P_i makes, they can be satisfied by the currently available resources plus the resources held by all P_j, where $j < i$. If the resources that P_i needs are not immediately available, then P_i can wait until all P_j have finished. When P_j has finished, P_i can obtain all of its needed resources, complete its designated task, return its allocated resources, and terminate. When P_i terminates, P_{i+1} can obtain its needed resources, and so on. If no such sequence exists, then the system state is said to be *unsafe*.

A safe state is not a deadlocked state. Conversely, a deadlocked state is an unsafe state. Not all unsafe states are deadlocks, however.

6.7.2.2 Resource Allocation Graph Algorithm If we have a resource-allocation system **with only one** instance of each resource type, we can use a variant of the resource-allocation graph. The resources must be claimed a priori in the system.

We introduce a new type of edge, called a claim edge. A claim edge $P_i \to R_j$ indicates that process P_i may request resource R_j at some time in the future. Before process P_i starts executing, all its claim edges must already appear in the resource-allocation graph.

6.7.3 Deadlock Detection

Defn 108 (Deadlock Detection)**.** *Deadlock detection* is an algorithm that determines if the current state of a system indicates a Deadlock has occurred.

In this system, either of these options may be provided.

- An algorithm that examines the state of the system to determine whether a deadlock has occurred.
- An algorithm to recover from the deadlock.

6.7.3.1 Single Instance of a Resource Type If all resources have only a single instance, then we can define a deadlock-detection algorithm that uses a variant of the resource-allocation graph, called a wait-for graph. We obtain this graph from the resource-allocation graph by removing the resource nodes.

An edge from P_i to P_j in a wait-for graph implies that process P_i is waiting for process P_j to release a resource that P_i needs. More formally,

$$P_i \to P_j = P_i \to R_q, R_q \to P_j$$

6.7.3.2 Multiple Instances of a Resource Type The algorithm employs several time-varying data structures that are similar to those used in the banker's algorithm. I do not heavily invest in working with this variant of this problem.

6.7.3.3 Usage of Detection Algorithms There are 2 main questions about when we should invoke these detection algorithms.

1. How **often** is a deadlock likely to occur?
2. How **many** processes will be affected by deadlock when it happens?

Resources allocated to deadlocked processes will be idle until the deadlock can be broken. If deadlocks occur frequently, then the detection algorithm should be invoked frequently. In addition, the number of processes involved in the deadlock cycle may grow.

6.7.4 Deadlock Recovery

When a detection algorithm determines that a deadlock exists, several alternatives are available.

1. One possibility is to inform the operator that a Deadlock has occurred and to let the operator deal with the Deadlock manually.
2. Another possibility is to let the system recover from the Deadlock automatically. There are two options for breaking a Deadlock.
   (a) Simply abort one or more processes to break the circular wait.
   (b) Preempt some resources from one or more of the Deadlocked processes.

6.7.4.1 Process Termination To eliminate deadlocks by aborting a process, there are two methods. In both, the system reclaims all resources previously allocated.

1. Abort all deadlocked processes. This method clearly will break the deadlock cycle, but at the cost of lost work among all terminated processes.
2. Abort one process at a time until the deadlock cycle is eliminated. This method incurs considerable overhead, since after each process is aborted, a deadlock-detection algorithm must be invoked to determine whether any processes are still deadlocked.

Which one to choose depends on a variety of factors.

- What the priority of the process is.
- How long the process has computed.
- How much longer the process will compute before completing its designated task.
- How many and what types of resources the process has used.
- How many more resources the process needs in order to complete.
- How many processes will need to be terminated.
- Whether the process is interactive or batch.

6.7.4.2 Resource Preemption In this system, we successively preempt some resources from processes and give these resources to other processes until the deadlock cycle is broken. If preemption is required to deal with deadlocks, then three issues need to be addressed:

1. **Selecting a victim**. Which resources and which processes are to be preempted? As in process termination, we must determine the order of preemption to minimize cost. Cost factors may include parameters such as:
   - Number of resources a deadlocked process is holding
   - Amount of time the process has thus far consumed
2. **Rollback**. If we preempt a resource from a process, what should be done with that process? It cannot continue with its normal execution; it is missing some needed resource. We must roll back the process to some safe state and restart it from that state. It is more effective to roll back the process only as far as necessary to break the deadlock, however, this method requires the system to keep more information about the state of all running processes. So the process is rolled back to the beginning usually.
3. **Starvation**. How do we ensure that starvation will not occur?

7 Main Memory

To truly benefit from CPU Scheduling and Synchronization, discussed in Section 6, we must be able to keep multiple Processes in memory at the same time.

In a Central Processing Unit, the only things that can be accessed directly are Registers and main memory. The CPU can reach the registers within one clock cycle, but accessing main memory takes several clock cycles, because access is done through the memory bus. To prevent Memory Stalls, we can use multiple Threads, and we can add additional Caches to the CPU itself. This Hardware automatically speeds up memory access, without Operating System intervention.

Defn 109 (Cache)**.** A *cache* is a very small amount of memory, built onto the Central Processing Unit itself, and acts as a buffer between the CPU and main memory. A cache will have a copy of a small portion of what is in main memory, and the CPU goes to find the next thing, whatever it may be, from the cache first. Because the cache sits on the CPU itself, and does not have to interact with the memory bus, it is significantly faster than accessing main memory, but still slightly slower than accessing a register.

Not only do we want our memory and its access to be fast, we also want to make sure that the memory and its contents are used correctly. For proper system operation we must protect the operating system from access by user processes. On multiuser systems, we must additionally protect user processes from one another. This protection must be provided by the hardware because the operating system doesn't usually intervene between the CPU and its memory accesses (because of the resulting performance penalty). A Memory Management Unit implements this production, in hardware, in several different possible ways.

Defn 110 (Memory Management Unit)**.** The *Memory Management Unit* (*MMU*) is a piece of hardware built onto a Central Processing Unit (See Remark 110.1). It is the main controller for all main memory accesses made by a CPU.

It handles the run-time mapping from Virtual Addresses to Physical Addresses.

Remark 110.1 (MMU Location)*.* The location of the Memory Management Unit is **typically** on the CPU. This holds true for modern CPUs, however, older CPUs like the Motorola 68000 series have physically separate MMUs, which can be attached to the motherboard that the CPU sits on.

To ensure that everything works, the first thing that needs to be done is to separate each Process into its own memory space. This protects the processes from each other and is fundamental to having multiple processes loaded in memory for concurrent execution. To separate memory spaces, we need the ability to determine the range of legal addresses that the process may access and to ensure that the process can access only these legal addresses.

The simplest version of this protection can be realized by using two registers, usually a `base` and a `limit`. The base register holds the smallest legal physical memory address; the limit register specifies the size of the range. Thus, to find the largest legal physical memory address, we must add the limit register's value to the base register's. The only way these registers can be loaded is by using a special, privileged, instruction. Since privileged instructions can only be executed in Kernel-mode, only the Operating System can load the base and limit registers. This allows only the OS to change the value of these registers, and not any User-Processes.

7.1 Address Binding

Just as in programming languages, there are different possible times when a Program stored on a disk can have Memory addresses bound to it, this is called Address Binding.

Defn 111 (Address Binding)**.** *Address binding* is the act of putting "something" (a variable, a function, a value, anything) at a location in Memory. Because these memory locations have unique addresses assigned to them, the "something" that was put there is bound to that memory address.

For a Program to be executed, it must be brought into memory and placed within a Process. The processes that are waiting for their binary images to be brought to memory from the disk before beginning execution form the Input Queue.

Defn 112 (Input Queue)**.** The *input queue* is the queue in which Processes are placed while they wait for their Program binary image to arrive from the disk.

There are 3 major times when Address Binding can occur:

1. Compile-Time Address Binding
2. Load-Time Address Binding
3. Execution-Time Address Binding

7.1.1 Compile-Time Address Binding

If the addresses that the Process will use are known at compile-time, then Absolute Code can be generated.

Defn 113 (Absolute Code)**.** In *absolute code*, the memory location of the Process is fixed during every execution, and because the Program is always the same size, anything that requires a memory can be referenced by this unchanging value.

If, at some later time, the starting location changes, then the whole program must be recompiled. In the case of assembly languages, this might mean recalculating the absolute memory locations of everything in the program.

These reasons led to the developement of relative addressing in assembly languages and the use of Load-Time Address Binding.

7.1.2 Load-Time Address Binding

If it is not known at compile time where the process will reside in memory, then the compiler must generate Relocatable Code.

Defn 114 (Relocatable Code)**.** *Relocatable code* uses relative addressing from certain known points. For example, a compiler will know that to access some variable `x`, the location where `x` is stored in memory is 14 bytes past the beginning of the function's start of the frame. Thus, if the starting address of the function changes, the code only needs to be reloaded to find a newly changed value.

In this case, the final binding of "stuff" to memory addresses is delayed until load time. If the starting address changes, the user code only needs to be reloaded to incorporate this changed value. This is how most programs are written and executed. If you change something in a C program, you must recompile and reload the program to have the changes take effect.

7.1.3 Execution-Time Address Binding

If the process can be moved during its execution from one memory segment to another, then binding must be delayed until run time. Special hardware must be available for this scheme to work. Most general-purpose operating systems use this method.

There are 4 major items that affect how this works:

1. Dynamic Loading
2. Dynamic Linking
3. Swapping
4. Paging

7.2 Logical, Physical, Virtual Address Spaces

The compile-time and load-time address-binding methods generate identical logical and physical addresses.

Defn 115 (Logical Address)**.** The CPU generates virtual/*logical address*es. How these logical addresses look, behave, and correspond to Physical Addresses depend on the memory management technique used by the Memory Management Unit.

The user program deals with logical addresses. The memory-mapping hardware converts logical addresses into Physical Addresses.

Defn 116 (Physical Address)**.** The *physical address* is the actual value of a particular byte of memory's address. How the physical address is calculated from the Logical Address is handled by the Memory Management Unit.

The user program deals with Logical Addresses. The memory-mapping hardware converts logical addresses into physical addresses.

However, the execution-time address-binding scheme results in differing logical and physical addresses, so we call the Logical Address a Virtual Address instead.

Defn 117 (Virtual Address)**.** The CPU generates logical/*virtual address*es. How these virtual addresses look, behave, and correspond to Physical Addresses depend on the memory management technique used by the Memory Management Unit.

The user program deals with logical/virtual addresses. The memory-mapping hardware converts logical/virtual addresses into Physical Addresses.

Remark 117.1 (Use of Logical and Virtual Address). In this document, I use Logical Address and Virtual Address interchangeably.

The set of all logical addresses/Virtual Addresses generated by a program is a Logical Address Space/Virtual Address Space.

Defn 118 (Logical Address Space)**.** The *logical address space* consists of all the Logical Addresses generated by a Program.

Remark 118.1. The Logical Address Space is only calculated by one Program/Process at a time. To find the total logical address space used, all Processes must have their logical address spaces aggregated.

The set of all Physical Addresses corresponding to these logical addresses is the Physical Address Space.

Defn 119 (Physical Address Space)**.** The *physical address space* consists of all the Physical Addresses that the Logical Addresses/Virtual Addresses map to.

Remark 119.1. The Physical Address Space is only calculated by one Program/Process at a time. To find the total physical address space used, all Processes must have their physical address spaces aggregated.

Thus, in the execution-time address-binding scheme, the logical and physical address spaces differ. The Memory Management Unit handles the mapping of the Virtual Address Space/Logical Address Space to the Physical Address Space. The Program generates only Logical Addresses and thinks that the Process runs in memory locations from 0 to max.

For example, assume a Process's base register, for the lowest valid memory address is R. If we wanted to access the 14th byte from the beginning of the Process, the CPU would attempt to retrieve 14, the Logical Address. However, on the way to memory, the Memory Management Unit would intercept this and redirect the access to $R + 14$, the Physical Address.

7.3 Dynamic Loading

Because of the way we have set up our memory and Processes before, a Process could only be as big as our physical memory. However, we can skirt these issues by using Dynamic Loading.

Defn 120 (Dynamic Loading)**.** *Dynamic Loading* is used to load routines into memory only when needed. The routines that can by dynamically loaded must be stored on disk in a Relocatable Code format. If the main program that was loaded in and began execution needs a routine, it checks to see if the routine has been loaded. If it has not, the loader loads the desired routine into memory, then updates the Process's address tables to point to the newly retrieved routine.

The advantage of Dynamic Loading is that a routine is loaded only when it is needed. This is particularly useful when large amounts of code are needed to handle infrequently occurring cases, such as error routines. This allows the total program size to be large, but the portion used (and hence loaded) be much smaller.

Dynamic Loading does not require special support from the operating system. It is the responsibility of the users to design their programs to take advantage of such a method. Operating Systems may help the programmer, however, by providing library routines to implement Dynamic Loading.

7.4 Dynamic Linking

Operating Systems provide many useful libraries to allow programmers and their work to use higher-level abstractions to make their programming life easier. An example of this is a language library for localization, allowing a programmer to write their input and output statements in one language and it be translated to another automatically.

To achieve this, Dynamic Linking is used, and Stubs are generated during the compilation process to inform the running Process where to find the necessary information.

Defn 121 (Dynamic Linking)**.** A Program that makes use of *dynamic linking* is compiled like normal. However, the library routines that would be provided by a *dynamically linked library* (*Shared Library*) are left as Stubs. When the program begins execution, the Process executes like normal, potentially using Dynamic Loading in the meantime. However, once the Process reaches a Stub, it will: proceed like normal (if the stub is replaced by the actual code), or will fetch and load the routine, replace the stub, and then execute the routine.

Remark 121.1 (Dynamic Linking vs. Dynamic Loading). In Dynamic Linking, a Program is compiled down to the machine code, with the Stubs in place, which are replaced **DURING** program execution. This allows us to share a binary library file **BETWEEN DIFFERENT** Programs. Whereas, in Dynamic Loading, the code is brought in from memory from the **same** Program binary image.

This means that if an Operating System did not support Dynamic Linking, each Program that required a certain library must include it. This leads to space inefficiencies on both the disk and in main memory.

Defn 122 (Stub)**.** A *stub* is a small piece of code that indicates how to locate the appropriate memory-resident library routine or how to load the library if the routine is not already present. A stub is included in the Program's binary image **FOR EACH** library-routine reference.

When the stub is executed, it checks to see whether the needed routine is already in memory. If it is not, the program loads the routine into memory and replaces the stub with the address of the routine and executes the routine. Then, the next time that routine is reached, the routine is executed directly, incurring no cost for Dynamic Linking.

This feature can be extended to handle library updates (such as bug fixes). If a library is replaced by a new version, all programs that use that library will automatically use the new version. Without Dynamic Linking, all such programs would need to be relinked to gain access to the new library. Version information is included in the Program and the library so that programs will not accidentally execute new, incompatible versions of libraries. Multiple versions of the same library may be loaded into memory, and each program uses its version information to decide which library to use.

Unlike Dynamic Loading, Dynamic Linking and dynamically linked libraries require help from the Operating System. If the Processes in memory are protected from one another, then the operating system is the only entity that can check all the Processes. Only the OS can:

- See if the needed routine is in another process's memory space.
- Allow multiple processes to access the same memory addresses.

7.4.1 Static vs. Dynamic Linking

As programmers, we are more familiar with Static Linking; where a library is compiled **INTO** and assembled **WITH** our code **INTO** our executable binary image.

Defn 123 (Static Linking)**.** *Static linking* is the act of running a linker after the compiler has generated Stubs for library routines. By running the linker, the library's code is brought into our program before it is assembled. This means that the library (and all the code supporting the library) is compiled **INTO** our binary image as well.

7.5 Swapping

A Process can only be executed if it is in memory. However, while it is **NOT** being executed, it is not required for it to be in memory. This idea forms the basis of Swapping.

Defn 124 (Swapping)**.** *Swapping* is the action of moving a Process out of memory to a Backing Store, or vice versa.

Defn 125 (Backing Store)**.** A *backing store* is another form of storage media. There are typically very few requirements on the type of storage media used in a backing store, but it **MUST** be readily assessible, and be quick (not as fast as RAM, but faster than traditional file system storage). Typically, a fast disk is used as the backing store.

Remark 125.1 (Swap). Sometimes the Backing Store is called *the swap*, *swap-area*, *swap partition*, *swapfile*, etc. They all mean the same thing[4].

Swapping allows for the total Physical Address Space of **ALL** Processes to exceed the real physical memory of the system. However, the Context Switch time in a swapping system is fairly high.

The system maintains the ready queue consisting of all processes whose memory images are on the backing store or in memory and are ready to run. Whenever the CPU scheduler decides to execute a process, it calls the Dispatcher. The dispatcher checks to see where the next Process is.

- If the process is in memory, the dispatcher will reload registers and transfer control, like normal.
- If the process is in the swap, the dispatcher will swap the selected process into memory, reload registers, and transfer control.
- If the process is in the swap, **and** if there is no free memory region, the dispatcher swaps out a process currently in memory and swaps in the desired process, reloads registers, and transfers control.

Clearly, it would be useful to know exactly how much memory a User Process **is** using, not simply how much it **might** be using. This way, we only need to swap what is actually used, thereby reducing swap time. For this method to be effective, the user **must** keep the system informed of any changes in memory requirements. Thus, a process with dynamic memory requirements will need to issue system calls (`request_memory()` and `release_memory()`) informing the Operating System of its changing memory needs.

Swapping is constrained by other factors as well. **If we want to swap a process, we must be sure that it is COMPLETELY idle.** Of particular concern is any pending I/O. A process may be waiting for an I/O operation when we want to swap that process to the Backing Store. However, if the I/O is asynchronously accessing user memory for I/O buffers, then the process cannot be swapped.

There are two main solutions to this problem:

1. Never swap a process with pending I/O.
2. Execute I/O operations only into Operating System buffers.
    - Transfers between operating-system buffers and process memory only occur when the process is **swapped in**.
    - Double buffering adds overhead.
    - Now need to copy the data twice, once into kernel memory, then from kernel memory to user memory, before the user process can access it.

Standard Swapping as described above is not used in modern operating systems. However, modified versions of swapping, are used on many systems. One common variation, is to disable swapping until the amount of free memory (unused memory available for the operating system or processes to use) falls below a threshold amount. Swapping is then halted when the amount of free memory increases again. Another variation involves swapping portions of processes, rather than the entire process, to decrease swap time. Typically, these modified forms of swapping work in conjunction with Virtual Memory.

[4] Swap Partition and Swapfile have specify the type of the Backing Store

7.6 Contiguous Memory Allocation

Main memory must contain everything for the system to run, including both the Operating System and User Processes. It is our jobs, as operating system engineers to make the allocation of memory for the Operating System as efficient as possible. The earliest and simplest method is that of Contiguous Memory Allocation.

Memory is usually divided into two partitions: one for the Operating System and one for the user processes. We can place the operating system in either low memory or high memory, depending on the location of the Interrupt Vector. Typically, the interrupt vector is in low addresses, so the OS is usually put there too. Throughout this document, we assume that the OS inhabits the lowest addresses.

Defn 126 (Contiguous Memory Allocation)**.** In *contiguous memory allocation*, each Process is contained in a single contiguous section of memory that is also contiguous with the next process.

In short, this means that each Process sits in its own contiguous block and is right next to the next process.

7.6.1 Memory Protection

In Contiguous Memory Allocation, we can provide memory protection by using concepts from earlier. If the `base` register is considered as the `relocation` register (because of Logical Address conversion to Physical Address), and use the `limit` register as before, then we can protect this Process. Since the Operating System is the only entity that can change the values of the `relocation` and `limit` registers, this (currently executing) process and others cannot interfere with each other.

When the CPU Scheduler selects a Process for execution, the Dispatcher loads the `relocation` and `limit` registers with the correct values as part of the Context Switch. Because every address generated by a CPU is checked against these registers, we can protect the operating system and other users' programs and data from being modified by this running process. This scheme is an effective way to allow the Operating System to change size dynamically, which is highly desireable.

7.6.2 Memory Allocation

Within the User memory, there are 2 main methods of Process-memory allocation:

1. Multiple-Partition Scheme
2. Variable-Partition Scheme

Both methods use the same idea of dividing all free memory into separate partitions, however the size of these partitions and how they are divided is the differentiating factor.

7.6.2.1 Multiple-Partition Scheme In the *multiple-partition scheme*, all free memory is statically divided into equal sized partitions. Thus, the size of a partition is fixed throughout the execution of the Operating System. When a partition is free, a Process is selected from the input queue and placed into the free partition. When the process terminates, the partition is returned to the pool of available partitions.

7.6.2.2 Variable-Partition Scheme In the *variable-partition scheme*, all free memory is pooled together. The free memory is called a *hole*.

> In many ways, this mirrors the use of the heap in programs. Many of the principles from heap and the allocation of stuff to the heap also apply in this case as well.

As Processes are selected from the input queue to run, their memory requirements are considered. The system searches the set for a hole that is large enough for this process. If the hole is too large, it is split into two parts. The process is then given an appropriate amount of space from memory, taken from the pool of free memory; the other is returned to the set of holes. When a process terminates, it releases its block of memory, which is then placed back in the set of holes. If the new hole is adjacent to other holes, these adjacent holes are merged to form one larger hole.

At this point, the system may need to check whether there are processes waiting for memory and whether this newly freed and recombined memory could satisfy the demands of any of these waiting processes. The next process to run has its memory requirements considered, **AND** the free memory available. What happens next depending on the Operating System:

- Wait until a large enough block of memory is available for this process.
- Skip through the input queue to find a process that can use the memory (because of smaller requirements).

Just like in heap allocation and garbage collection, this is a particular instance of the general dynamic storage-allocation problem. In Operating Systems, there are 3 common strategies used to allocate this memory to Processes:

1. First-Fit
2. Best-Fit
3. Worst-Fit

First-Fit Allocate the first hole that is big enough. Searching can start either at the beginning of the set of holes or at the location where the previous first-fit search ended. Stop searching as soon as we find a free hole that is large enough.

Best-Fit Allocate the smallest hole that is big enough, the best fitting hole. We must search the entire list, unless the list is ordered by size. This strategy produces the smallest leftover hole.

Worst-Fit Allocate the largest hole, the worst fitting hole. Again, we must search the entire list, unless it is sorted by size. This strategy produces the largest leftover hole, which may be more useful than the smaller leftover hole from a best-fit approach.

7.6.3 Fragmentation

When allocating space to Processes, we may run into the issue of Fragmentation.

Defn 127 (Fragmentation)**.** *Fragmentation* is when memory that was allocated to a Process is **not** used. Technically, this is an inefficiency, not a problem.

There are 2 kinds of fragmentation possible:

1. External Fragmentation
2. Internal Fragmentation

7.6.3.1 External Fragmentation Statistical analysis of First-Fit reveals that, given N allocated blocks, another $0.5N$ blocks will be lost to External Fragmentation. Meaning, one-third of memory may be unusable. This property is known as the *50-percent rule.*

Defn 128 (External Fragmentation)**.** *External fragmentation* is when there is enough total unused memory to satisfy a request, but the unused memory is **not** contiguous. If the memory is fragmented into a large number of small holes, then contiguous memory requests cannot be satisfied. As processes are loaded and removed from memory, the free memory space is broken into little pieces.

This is not necessarily a problem by itself, as much as it is an inefficiency. However, this inefficiency will lead to problems if it is not handled.

One solution to the problem of External Fragmentation is *compaction* (like garbage collection for the heap). The goal is to shuffle the memory contents so as to place all free memory together in one large block, however it cannot always be used. When compaction is possible, we must determine its cost, because it can be quite expensive.

- If memory locations are static and done at assembly or load time, compaction cannot be done.
- If memory locations are dynamic and done at execution time, compaction can be done by relocation.
  - Relocation moves the program and data, then changes the `base/relocation` register to reflect the new base address.

The simplest compaction algorithm is to move all processes toward one end of memory; all holes move in the other direction, producing one large hole of available memory.

Another solution to the External Fragmentation problem is to permit the logical address space of the processes to be noncontiguous. This allows a process to be allocated physical memory **wherever** memory is available. Two complementary techniques (which can also be combined) can solve this problem:

1. Segmentation (Section 7.7)
2. Paging (Section 7.8)

7.6.3.2 Internal Fragmentation Memory fragmentation can be internal as well as external. Consider a multiple-partition allocation scheme with a hole of 18464 bytes. Suppose that the next process requests 18462 bytes. If we allocate exactly the requested block, we are left with a hole of $18464 - 18462 = 2$ bytes. The difference between these two numbers is Internal Fragmentation.

Defn 129 (Internal Fragmentation)**.** *Internal Fragmentation* is the issue of unused memory that is internal to a partition. This means that a Process is given more memory than it actually needs, and will not be using all of it.

Like External Fragmentation, this is not necessarily a problem as much as it is an inefficiency that can lead to problems.

7.7 Segmentation

Dealing with memory in terms of its physical properties is inconvenient to both the Operating System and the programmer. If the hardware could provide a memory mechanism that mapped the programmer's view to the actual physical memory, the system would have more freedom to manage memory, while the programmer would have a more natural programming environment. Segmentation provides such a mechanism.

Defn 130 (Segmentation)**.** *Segmentation* is a memory-management scheme that supports a programmer's view of memory of segments of a program. Each segment has a name and a length. Segments vary in length, and the length of each is intrinsically defined by its purpose in the program. Elements within a segment are identified by their offset from the beginning of the segment Therefore, when a programmer specifies something in the program, it is reached by an address by two quantities: a segment name and an offset.

This makes a Logical Address Space is a collection of segments. These addresses specify both the segment name and the offset within the segment.

Remark 130.1 (Memory Locations when using Segmentation). Segmentation is a method of breaking up a program into segments that behave as logical units in a program and are each referenced, and thus located, separately. This allows the Physical Address Space of a process to be noncontiguous.

However, it makes no attempt to avoid External Fragmentation.

For example, a C compiler might create separate segments for:

1. Code
2. Global variables
3. The heap, from which memory is allocated
4. The stacks used by each thread
5. The standard C library

7.7.1 Hardware Support for Segmentation

The values that the programmer specifies are now 2-dimensional objects, and a memory address is one-dimensional, so the Memory Management Unit must handle the mapping of these 2D Logical Addresses to the 1D Physical Addresses.

A logical address consists of two parts: a segment number, s, and an offset (displacement) into that segment, d. To map the logical address pair to the physical address, the *segment table* is used. The segment table is essentially an array of `base`–`limit` register pairs. Each entry in the segment table has a `segment base` and a `segment limit`. The segment `base` contains the starting physical address where the segment resides in memory, and the segment `limit` specifies the length of the segment.

The segment number is used as an **INDEX** to the segment table. The offset d of the logical address must be between 0 and the `segment limit`. If it is not, we trap to the operating system (logical addressing attempt beyond end of segment). When an offset is legal, it is added to the `segment base` to produce the address in Physical Memory of the desired byte.

7.8 Paging

Most memory-management schemes used before the introduction of Paging suffered from the problem of fitting memory chunks of varying sizes on the Backing Store This arises because space must be found on the backing store, when main memory needs to be swapped out. The backing store has the same Fragmentation problems discussed in connection with main memory, but access is much slower, so compaction is impossible.

Defn 131 (Paging)**.** *Paging* allows the Physical Address Space of a Process to be noncontiguous. This is achieved breaking up Physical Memory and Logical Address Space into equally, fixed-size blocks.

- Physical Memory is broken up into *frames*.
- Logical Address Space is broken up into *pages*.
- The Backing Store is also broken up, as a multiple (1 through n) of the frame size.

The list of pages and their mapping to frames for this Process is stored in the Page Table. There is a page table in each process, which is used when this process Context Switches into the CPU. Therefore, paging also increases context switch time.

Paging avoids the issue of External Fragmentation and solves the problem of fitting memory chunks of varying sizes on the Backing Store. However, Internal Fragmentation is still an issue.

Paging is implemented through cooperation between the operating system and the computer hardware. Similar to how Segmentation has a segment table, **EACH Process** in a Paging system has a Page Table.

Defn 132 (Page Table)**.** A *page table* is a table that maintains the mapping of logical pages to physical frames in memory. The page table is a simple lookup table, where the current Process's current page number is also the value of the index. The value contained at that element is the location of the frame in memory. This is combined with the use of Logical Addresses that are generated by the CPU.

To reach an address, the CPU generates a Logical Address that has 2 parts, a page number p and a page offset d. Like before, the page number is used as an **INDEX** in the Page Table. The page table contains the base address of each page in physical memory. This base address is combined with the page offset to define the physical memory address that is sent to the memory unit.

The frame size, and thus the page size, are defined by the hardware. The size of a page is a power of 2, varying between 512 bytes and 1 GiB[5] per page, depending on the computer architecture. A power of 2 as a page size makes the translation of a Logical Address into a page number and page offset particularly easy.

If the size of the logical address space is 2^m, and a page size is 2^n bytes, then the high-order $m - n$ **bits** of a Logical Address designate the page number, and the n low-order **bits** designate the page offset.

$$\begin{aligned} p &= m - n \\ d &= n \end{aligned} \tag{7.1}$$

Thus, to translate the Logical Address to a Physical Address, Equation (7.2) is used.

$$f = \big(i(p) \times s\big) + d \tag{7.2}$$

f: Resulting Physical Address.
$i(p)$: Mapped frame number of the given page number p from the Page Table.
s: Size of the page/frame.

If Process size is independent of page size, we expect Internal Fragmentation to average one-half page per process. This consideration suggests that small page sizes are desirable. However, overhead is involved in maintaining the Page Table itself, with each page-table entry increasing the overhead. Also, disk I/O is more efficient when the amount data being transferred is larger.

Generally, page sizes have grown over time as processes, data sets, and main memory have become larger. Today, pages typically are between 4 KiB and 8 KiB in size, and some systems support even larger page sizes. Some CPUs and kernels now support multiple page sizes. Variable on-the-fly page size is still being developed.

A 32-bit CPU uses 32-bit addresses, meaning that a given Process's memory space can only be 2^{32} bytes (4 GiB). However, a single 32-bit entry can point to one of 2^{32} different physical frames. If frame size is 4 KB (2^{12}), then a system with 4-byte (32-bit) entries can address 2^{44} bytes (or 16 TiB) of physical memory. Therefore, paging lets us use physical memory that is larger than what can be addressed by the CPU's address pointer length. This means that the size of physical memory in a paged memory system is different from the maximum logical size of a process.

When a Process arrives in the system to be executed, its size, in pages, is examined. Because pages and frames are the same size, if the process requires n pages, at least n frames must be available in memory. If the required n frames are available, they are allocated to this arriving process. The first page of the process is loaded into one of the allocated frames, and the that frame's number is put in the Page Table for this process for this page. The next page is loaded into another frame, its frame number is put into the page table, and so on.

Paging offers a clear separation between the programmer's view of memory and the actual hardware. The logical addresses that the programmer uses are translated into physical addresses that the hardware uses. This mapping is hidden from the programmer and is controlled by the operating system. This allows the programmer to view memory as one contiguous space, containing only this one program (which helps create our definition of Virtual Memory). However, the user program may be scattered throughout Physical Memory, which also holds other programs. The difference between the programmer's view of memory and the actual physical memory is reconciled by the address-translation hardware in the Memory Management Unit.

Because the Operating System is managing Physical Memory, it must be aware of the allocation details of physical memory, including:

- Which frames are allocated.
- Which frames are available.
- The total number of frames.
- etc.

This information is generally kept in a data structure called a Frame Table.

[5] GiB is a gibibyte, or 2^{30} bytes

Defn 133 (Frame Table)**.** The *frame table* has one entry for each physical frame, indicating whether it is free or allocated and, if it is allocated, to which page of which process or processes.

This behaves like an ownership or state table, rather than a lookup table. It says whether this frame is in use, and if it is, who is using it.

7.8.1 Hardware Support for Paging

Every access to memory must go through the paging map, so efficiency is a major consideration. Each Operating System has its own methods for storing Page Tables. Some allocate a page table for each Process, then a pointer to the page table is stored with the other register values in the Process Control Block. Other operating systems provide only a few page tables, which decreases the overhead involved when processes are Context Switched.

The hardware implementation of the Page Table can be done in several ways. In the simplest case, the page table is implemented as a set of high-speed, dedicated registers, making paging-address translation efficient. The CPU Dispatcher reloads these registers, along with all the other registers. Instructions to load or modify the page-table registers are privileged so that only the Operating System can change the memory map.

Registers can be used for the Page Table only if the page table is reasonably small. However, modern computers, allow the page table to be quite large, making the use of registers to implement the page table not feasible. Instead, the page table is kept in main memory, and a `page-table base register` (`PTBR`) points to the page table. Thus, changing the currently active page table requires changing only this one register, substantially reducing Context Switch time. However, now this requires 2 memory access:

1. Memory Access 1 is needed to enter the Page Table and find the frame entry.
2. Memory Access 2 is needed to travel to Physical Memory and retrieve the value.

7.8.1.1 Translation Look-Aside Buffers To accomodate the Page Table existing in memory, a hardware cache is usually provided on the CPU, called a *translation look-aside buffer* (*TLB*). The TLB is associative, high-speed memory that contains two part entries: a key and a value. When the associative memory is presented an item, the item is compared with all keys **simultaneously**. If the item is found, the corresponding value is returned. This search is very fast. In modern hardware, a TLB lookup is part of the instruction pipeline, essentially adding no performance penalty. To be able to execute the search within a pipeline step, the TLB is small, typically between 32 and 1,024 Page Table entries in size.

1. When a Logical Address is generated by the CPU, its page number is presented to the TLB.
2. These steps are executed as part of the instruction pipeline within the CPU, adding no performance penalty compared with a system that does not implement paging.
3. If the page number is found, its frame number is immediately available and is used to access memory.
4. If the page number is not in the TLB (a *TLB miss*), a memory reference to the Page Table must be made.
    - Depending on the CPU, this may be done automatically in hardware or via an Interrupt to the Operating System.
    - When the frame number is obtained, we can use it to access memory.
    - In addition, the page number and frame number are added to the TLB, so that they will be found quickly on the next reference.
    - If the TLB is already full of entries, an existing entry must be selected for replacement. Replacement policies vary.
        - Least Recently Used (LRU)
        - Round-robin
        - Random
    - Some CPUs allow the operating system to participate in LRU entry replacement, while others handle the matter themselves.

Some TLBs allow certain entries to be wired down, meaning that they cannot be removed from the TLB. Typically, TLB entries for key kernel code are wired down.

TLBs are a hardware feature and the Operating System designer needs to understand the function and features of **that** hardware platform's TLBs. For optimal operation, Paging must be implemented according to the platform's TLB design. Likewise, a change in the TLB design may necessitate a change in the paging implementation of the operating systems that use it.

7.8.1.2 Address-Space Identifiers Some TLBs store *address-space identifier*s (*ASID*s) in **each** TLB entry. An ASID uniquely identifies each process and provides address-space protection for that process. When the TLB attempts to resolve virtual page numbers, it ensures that the ASID for the currently running Process matches the ASID associated with the virtual page. **If the ASIDs do not match**, the attempt is treated as a **TLB miss**. ASIDs also allow the TLB to contain entries for several **different** processes simultaneously. If the TLB does not support separate ASIDs, every time a new page table is selected (context switch), the TLB must be flushed (erased) to ensure that the next executing process does not use the wrong translation information. Otherwise, the TLB could include old entries that contain valid virtual addresses but have incorrect or invalid physical addresses left over from the previous process.

7.8.2 Memory Protection

The User Process, by definition, is unable to access memory it does not own. The user process has no way of addressing memory outside of its Page Table, since the page table includes **only** those pages that this process owns. In addition, the operating system must be aware that user processes operate in **user space**, and all Logical Addresses must be mapped to the proper user memory to produce Physical Addresses. If a user makes a system call and provides an address as a parameter (a buffer, for instance), that address must be mapped to produce the correct physical address.

On top of the ability for **only** the Operating System to manipulate the currently active memory map, there are explicit bits that are used to protect the current memory map and its pages. Normally, these bits are kept in the page table and are associated with each page.

7.8.2.1 Page Permission Bits Some bits, the *permission bits*, can define a page's permissions (read–write, read-only, execute-only, etc.) or any combination of these. Every memory reference goes through the page table to find the frame number. At the same time the physical address is being computed, the permission bits can be checked. A violation of the given permissions will cause a hardware Trap to the operating system (for memory-protection violation).

7.8.2.2 Page Valid-Invalid Bit One additional bit is generally attached to each entry in the page table: a *valid–invalid bit.*

- When this bit is set to valid, the associated page is in the Process's Logical Address Space and is a legal (or valid) page.
- When the bit is set to invalid, the page is not in the process's logical address space.

Illegal addresses are trapped by use of the valid–invalid bit. The operating system sets this bit for each page to allow or disallow access to the page.

This runs into issues when Internal Fragmentation occurs. A Process can request a page, but not need all of it, and the permission bit applies to the whole page, it is possible to access a memory address in the page, but is not used by the Process.

7.8.2.3 Page-Table Length Register Because a Process may be given a much larger Logical Address Space than it will use, it would be wasteful to create a Page Table with entries for every possible page. Some systems provide hardware, in the form of a *page-table length register* (*PTLR*), to indicate the size of the page table. This value is checked against every Logical Address to verify that the address is in the valid range for the process. Failure of this test causes an error Trap to the Operating System.

7.8.3 Shared Pages

An advantage of paging is the possibility of sharing common code. This consideration is particularly important in a time-sharing environment. If the code is Reentrant code (or pure code), the code pages can be shared. Each Process will then get its own data page. Thus, two or more processes can execute the same code at the same time, while maintaining its own data.

Defn 134 (Reentrant)**.** *Reentrant* means that something can be reentered at any time, and it will behave the same as if it were entered as soon as it were reached. Reentrant code then, is non-self-modifying code: it never changes during execution.

Heavily used programs can be shared, such as:

- Compilers
- Window systems
- Run-time libraries (And through Dynamic Linking)
- Database systems
- etc.

To be sharable, the code must be Reentrant. The read-only nature of shared code **should not** be left to the correctness of the code; the **Operating System should enforce this property**.

The sharing of memory among Processes on a system is similar to the sharing of the address space of a process by multiple Threads. Furthermore, Shared-Memory can be used as a method of interprocess communication (Paragraph 3.4.5.2). Some Operating Systems implement shared memory using shared pages. Organizing memory according to pages provides numerous benefits in addition to allowing several processes to share the same physical pages.

7.9 Page Table Structure

Because of the ever-increasing size of Page Tables, we need to start organizing them more efficiently. For example, consider a system with a 32-bit logical address space. If the page size in such a system is 4 KiB[6] (2^{12}), then a page table may consist of up to 1 million entries ($\frac{2^{32}}{2^{12}}$). Assuming that each entry consists of 4 bytes, each process may need up to 4 MiB of physical address space for the page table alone. Allocating this page table contiguously is not what we want to do, because if not all the pages are in-use, then we want to be able to use the space that would otherwise be taken up by the page table.

There are 3 techniques for handling this discussed in the textbook:

1. Hierarchical Paging
2. Hashed Page Tables
3. Inverted Page Tables

7.9.1 Hierarchical Paging

One simple solution to this problem is to divide the page table into smaller pieces. We can accomplish this division in several ways. One way is to use a **two-level page table**, in which the page table itself is also paged.

For example, consider the system with a 32-bit Logical Address Space and 4 KiB again. Fromt he perspective of the CPU, theLogical Address is divided into a page number consisting of 20 bits and a page offset consisting of 12 bits. However, because we page the page table, the page number is further divided into a 10-bit outer page number and a 10-bit page offset.

If the memory capacity of the computer increased, and therefore the page count did as well, then this would start becoming problematic again. We could divide the outer page table and page it again, giving us a three-level Paging scheme. If we continued to do this, a machine with a 64-bit Logical Address Space would require 7 level of paging. Remember that each time a Page Table is used, we need another memory lookup and access. This makes multiple levels of paging prohibitively slow.

7.9.2 Hashed Page Tables

A hashed page table, is a Page Table where the page number is the hash value. Each entry in the hash table contains a linked list of elements that hash to the same location (to handle collisions). Each element consists of three fields:

1. Hashed page number.
2. Frame number the requested page is mapped to.
3. Pointer to the next element in the linked list (or `NULL`).

The algorithm works as follows:

Algorithm 7.1: Hashed Page Table Usage

```
The page number in the Logical Address is hashed into the hash table.
The virtual page number is compared with Field 1() in the first element in the linked list.
if Field 1() == Field 2() then There is a matching page
    Corresponding frame (Field 2()) is used to form the desired physical address.
else There is no match
    Subsequent entries in the linked list are searched for a matching virtual page number.
```

7.9.2.1 Clustered Page Tables A variation of Hashed Page Tables that is useful for 64-bit address spaces, called *clustered page tables*, has been proposed. They are similar to their origin, except that each entry in the hash table refers to several pages (such as 16) rather than a single page. Therefore, a single clustered Page Table entry can store the mappings for multiple frames. Clustered page tables are particularly useful for sparse address spaces, where memory references are noncontiguous **AND** scattered throughout the address space.

7.9.3 Inverted Page Tables

Usually, each Process has an associated page table with one entry for each page that is in use. However, each Page Table may consist of millions of entries, and there may be many page tables. These tables may consume large amounts of physical memory just to keep track of how memory is being used.

To solve this problem, we can use an inverted page table. An inverted page table has **one entry for each frame** of memory. Each entry consists of

- The Logical Address of the page stored in that physical frame

[6] KiB is a kibibyte, or 2^{10} bytes

- Address-Space Identifiers, information about the Process that owns the page.
  - The table usually contains several different process address spaces that are mapped to physical memory.
  - Ths way the logical page for a particular process is mapped to the correct corresponding physical frame.

Thus, only one page table is in the system, and it has only one entry for each page of physical memory.

To use the table, a tuple (Equation (7.3)) is created by the CPU as the Logical Address.

$$\langle \texttt{PID}, p, d \rangle \tag{7.3}$$

PID: The Process ID.
p: The page number.
d: The offset of the desired location within the frame, i.e. in physical memory.

Although this scheme decreases the amount of memory needed to store each page table, it increases the amount of time needed to search the table because it is sorted by physical address, and lookups occur on virtual addresses, meaning the whole table might need to be searched before a match is found. To skirt this issue, a hash table is used, just like in Hashed Page Tables to limit the search. However, each access to the hashed inverted page table adds another memory reference. So one virtual memory reference requires at least two real memory reads:

1. One for the hashed inverted page table entry.
2. One for the resulting page table.

One downside of inverted page tables is that Shared-Memory is difficult to implement. Shared memory is usually implemented as multiple Logical Addresses (one for each Process sharing the memory) that are mapped to the same Physical Address. However, the usual method does not work here, because there is only one entry for every frame, one frame cannot have multiple shared Logical Addresses mapped to it.

8 Virtual Memory

As our natural definition of Von Neumann computers, the instructions being executed must be in Physical Memory. Thus, the first approach to meeting this requirement is to place the entire Logical Address Space in physical memory. This is unfortunate, since it limits the size of a program to the size of physical memory. Dynamic Loading can help ease this restriction, but it generally requires special precautions and extra work by the programmer.

However, an examination of real Programs shows us that, in many cases, the entire program is not needed. Even in those cases where the entire program is needed, it may not all be needed at the same time. The ability to execute a program that is only partially in memory has many benefits:

- Programs are no longer constrained by amount of Physical Memory available. Users able to write programs for an extremely large Virtual Address Space, simplifying the programming task.
- Each user program takes less physical memory, more programs could be run at the same time. This yields a corresponding increase in CPU utilization and throughput but with no increase in response time or turnaround time.
- Less I/O needed to load or swap user programs into memory, so each user program would run faster.

Defn 135 (Virtual Memory)**.** Virtual memory involves the separation of logical memory as perceived by users from Physical Memory. This separation allows:

- Extremely large virtual memory to be provided for programmers when less physical memory is available.
- Processes can share files easily.
- Shared-Memory can be implemented.
  - For example, sharing a library between different processes can be handled just by mapping the virtual memory location into the process's Virtual Address Space.
  - Although each process considers the library to be part of **its** virtual address space, the frames where the libraries reside in physical memory are shared by all the processes.
  - Typically, a library is mapped read-only into the space of each process that is linked with it.
  - This is typically implemented with Shared Pages.
- An efficient method for Process creation.

Virtual memory makes the task of programming much easier, because the programmer no longer needs to worry about the amount of physical memory available; they can concentrate instead on the problem to be programmed.

Defn 136 (Physical Memory)**.** *Physical memory* is the memory that is physically installed in the computer. There is a finite amount of this, determined by how much is installed by the system designer.

Defn 137 (Virtual Address Space)**.** The *virtual address space* of a Process consists of all the Virtual Addresses generated by a Program. It refers to the logical (virtual) view of **how a Process is stored in memory**. Typically, this view is one of perfectly contingous memory locations, when in fact, the process could be in many different, noncontiguous locations and the Memory Management Unit handles the Paging.

Remark 137.1. The Virtual Address Space is only calculated by one Program/Process at a time. To find the total virtual address space used, all Processes must have their virtual address spaces aggregated.

The large blank space between the heap and the stack is part of the virtual address space but will require actual physical pages only if the heap or stack grows. Virtual address spaces that include these holes are known as Sparse Address Spaces.

Defn 138 (Sparse Address Space)**.** A *sparse address space* is a Virtual Address Space that is not completely mapped to Physical Memory. Typically, this is done in the case of programs for the memory space between the stack and heap, which is overwhelmingly empty.

Sparse address spaces are beneficial because these holes can be filled on demand, when the Process needs more Physical Memory, or to dynamically link shared objects during program execution.

8.1 Demand Paging

Because we can support the ability to Dynamic Loading Programs, we don't need to load the **entire** program into memory initially. For example, suppose a program starts with a list of available options from which the user is to select. Loading the entire program into memory means loading the executable code for **ALL** options, no matter what option is chosen.

If we chose to load in parts of a Program only when they are needed, this is Demand Paging.

Defn 139 (Demand Paging)**.** *Demand paging* is when individual portions of a Program are loaded into memory using Dynamic Loading **only when they are needed**.

With demand-paged Virtual Memory, pages are loaded only when they are demanded during program execution. Thus, pages that are never accessed are never loaded into physical memory.

When Demand Paging is combined with Swapping, we do not want to swap the whole Process into memory if we don't need it. Thus, we use a Lazy Swapper.

Defn 140 (Lazy Swapper)**.** A *lazy swapper*, like a regular swapper, swaps Processes into memory from the Backing Store. However, **it only swaps in pages of the process that will be needed**, and never swaps a page in that will not be used.

A lazy swapper can be implemented as a Pager.

When a Process is to be swapped in, the Pager guesses which pages will be used before the process is swapped out again. Instead of swapping in a whole process, the pager brings only those pages into memory, avoiding reading pages into memory that will not be used anyway, decreasing the swap time and the amount of physical memory needed.

Defn 141 (Pager)**.** In a Demand Paging and Swapping system, we are not swapping whole Processes into and out of the Backing Store; we are swapping individual pages of the process. Thus, the task of moving a process's pages into and out of the backing store is handled by the *pager*, rather than the swapper.

In addition, the Pager will only page logical pages that contain Anonymous Memory.

Defn 142 (Anonymous Memory)**.** *Anonymous Memory* is memory that does not have a File backing it. Typically, these include function-local variables, heap-allocated objects, etc. However, the executable code for a Program is **NOT** anonymous, because there is an exact copy on disk.

With a Pager, we need some form of hardware support to distinguish between the pages that are in memory and the pages that are on the disk. The Page Valid-Invalid Bit scheme can be used for this purpose.

- If this bit is set to "valid" the associated page is **both** legal and in memory.
- If the bit is set to "invalid" the page either:
  - Is not valid, i.e. not in the Logical Address Space of the Process.
  - Is valid but is currently on the disk.

The page-table entry for a page that is brought into memory is set as usual, but the page-table entry for a page that is not currently in memory is either simply marked invalid or contains the address of the page on disk. Marking a page invalid will have no effect if the process never attempts to access that page. If we guess right and page in all pages that are actually needed and only those pages, the Process will run exactly as though we had brought in all pages.

While the Process executes and accesses pages that are *memory resident*, execution proceeds normally. Attempting to access a page marked invalid causes a Page Fault. The Paging hardware (Memory Management Unit), in translating the address through the page table, will notice the invalid bit is set, causing a Trap to the Operating System.

Defn 143 (Page Fault)**.** A *page fault* is a hardware Trap raised by the Memory Management Unit. It is caused by a Process attempting to access a page that has not been brought into memory by the Pager.

The following sequence executes when a page fault occurs:

1. Trap to the operating system.
2. Save the user registers and process state.
3. Determine that the interrupt was a page fault.
4. Check that the page reference was legal and determine the location of the page on the disk.
5. Issue a read from the disk to a free physical frame:
   (a) Wait in a queue for this device until the read request is serviced.
   (b) Wait for the device seek and/or latency time.
   (c) Begin the transfer of the page to a free frame.
6. While waiting, the CPU can be allocated to some other user (CPU scheduling, optional).
7. Receive an interrupt from the disk I/O subsystem (I/O completed).
8. Save the registers and process state for the other user (if step 6 is used).
9. Determine that the interrupt was from the disk.
10. Correct the Page Table and other tables to show that the desired page is now in memory.
11. Wait for the CPU to be allocated to this process again.
12. Restore the user registers, process state, and new page table. Then resume the interrupted instruction.

Handling a Page Fault in straightforward.

1. We check an internal table (usually kept with the Process Control Block) for this Process to determine whether the reference was a valid or an invalid memory access.
2. If the reference was invalid, we terminate the process (attempt to access memory that is not owned by this Process). If it was valid and legal, but we have not yet brought in that page, we now page it in.
3. We find a free physical frame (by taking one from the free-frame list, for example).
4. We schedule a disk operation to read the desired page into the newly allocated frame.
5. When the disk read is complete, we modify the page-frame internal table of the Process to indicate that the page is now in memory.
6. **We restart the instruction that was interrupted by the trap.** The process can now access the page as though it had always been in memory.

A Page Fault may occur at any memory reference. A crucial requirement for Demand Paging is the ability to restart any instruction after a page fault. We save the state (registers, condition code, instruction counter) of the interrupted Process when the page fault occurs. This lets us restart the process in exactly the same place and state, except that the desired page is now in memory and is accessible.

8.1.1 Problems with Demand Paging

8.1.1.1 Multiple Page Faults Theoretically, some programs could access several new pages of memory with each instruction execution (one page for the instruction and many for data), possibly causing multiple page faults per instruction. This situation would result in unacceptable system performance. Fortunately, analysis of running processes shows that this behavior is exceedingly unlikely. Programs tend to have locality of reference giving reasonable performance from demand paging.

The major difficulty arises when one instruction may modify several different locations. If a block (source or destination) straddles a page boundary, a page fault might occur after the move is partially done. In addition, if the source and destination blocks overlap, the source block may have been modified, in which case we cannot simply restart the instruction. This particular problem can be solved in two different ways.

1. The microcode computes and attempts to access **both ends** of **both blocks**. If a Page Fault is going to occur, it will happen at this step, before anything is modified. The instruction can then execute, knowing that no page fault can occur, since all relevant pages are in memory.
2. Use temporary registers to hold the values of overwritten locations. If there is a Page Fault, all the old values are written back into memory before the Trap occurs. This restores memory to its state before the instruction was started, so that the instruction can be repeated.

8.1.1.2 Implementation Problems There are 2 major implementation problems with Demand Paging. The development of:

1. *Frame Allocation Algorithm*
   - How do we decide the number of frames to allocate to each Process?

2. *Page Replacement Algorithm*
   - When do we perform Page Replacement?
   - What pages are replaced?
   - Further discussed in Section 8.3.2.

Designing appropriate algorithms to solve these problems is an important task, because disk I/O is so expensive (time-wise). Even slight improvements in demand-paging methods yield large gains in system performance.

8.1.2 Hardware Required

The hardware to support demand paging is the same as the hardware for Paging and Swapping:

1. Page table. This table has the ability to mark an entry invalid through a valid–invalid bit or a special value of protection bits.
2. Secondary memory. This memory holds those pages that are not present in main memory. The secondary memory is usually a high-speed disk. It is known as the *swap device*, and the section of disk used for this purpose is known as swap space.

8.1.3 Performance

Demand paging can significantly affect the performance of a computer system. To illustrate, the Effective Access Time for demand-paged memory can be computed.

Defn 144 (Effective Access Time)**.** *Effective access time* is the average amount of time required to access a page in a Demand Paging system. It accounts for the possibility of a page **NOT** being in memory and needing to be paged in from the swap and a page being in memory and having a quick, direct access.

$$\text{EAT} = \big((1-p) \times \text{MAT}\big) + (p \times \text{PFT}) \tag{8.1}$$

EAT: Effective Access Time.
p: Probability of a Page Fault ($0 \leq p \leq 1$).

- We expect p to be close to zero (we expect to have few page faults).

MAT: Memory Access Time (Typically 10 ns to 200 ns).
PFT: Page Fault Time.

The Page Fault Time has 3 major components. The typical times for these steps, with no waiting in queues, is shown in parentheses:

1. Service the page-fault interrupt (1 µs to 100 µs).
2. Read in the page (8 ms).
3. Restart the process (1 µs to 100 µs).

These only consider the device-service time. If a queue of processes is waiting for the device, the device-queueing time must be added further increasing the swap time.

> It is important to keep the page-fault rate low in a demand-paging system. Otherwise, the effective access time increases, slowing process execution dramatically.

8.1.4 Swap Usage

An additional aspect of demand paging is the handling and overall use of swap space. Disk I/O to the swap space is generally faster than that to the standard filesystem. It is faster because swap space is allocated in much larger blocks, and file lookups and indirect allocation methods are not used.

8.2 Copy-on-Write

Recall that the `fork()` System Call creates a child Process that is a nearly perfect duplicate of its parent. Traditionally, this was done by creating a copy of the parent's address space for the child, thereby **duplicating** the pages belonging to the parent. However, considering that many child processes invoke the `exec()` system call immediately after creation, the copying of the parent's address space may be unnecessary. Copy-on-Write works by allowing the parent and child processes initially to share the same pages allowing the `fork()` system call to bypass the need for Demand Paging by using a technique similar to page sharing (Section 7.8).

Defn 145 (Copy-on-Write)**.** *Copy-on-Write* allows the `fork()` ing parent Process to share its pages with its newly spawned child process. This bypasses the need for Demand Paging, by essentially allowing pages to be shared (like in Shared-Memory schemes). These shared pages are marked as Copy-on-Write pages; only pages that **can be** modified need be marked as copy-on-write. Pages that cannot be modified (pages containing executable code) can always be shared by the parent and child.

This allows for rapid process creation and minimizes the number of new pages that must be allocated to the newly created process. The pages marked as copy-on-write pages, mean if **EITHER** process writes to any of the shared pages, a copy of the shared page is created. The writer has its Page Table changed to point to this one, which is a complete copy (except for the newly written changes). The process that did nothing to the page continues to point to the original page.

To handle the allocation of pages for a Copy-on-Write page, the location that it is allocated from is important. Many Operating Systems provide a pool of free pages for such requests. These free pages are typically allocated when the stack or heap for a Process must expand or when there are copy-on-write pages to be managed. Operating systems typically allocate these pages using a technique known as Zero-Fill-on-Demand.

Defn 146 (Zero-Fill-on-Demand)**.** *Zero-fill-on-demand* pages have been zeroed-out before being allocated, thus erasing the previous contents.

8.2.1 `vfork()`

Several versions of UNIX have a variation of the `fork()` System Call, `vfork()` (virtual memory fork), that operates differently from `fork()` with regards to Copy-on-Write. With `vfork()` , the parent Process is suspended, and the child process uses the address space of the parent. Because `vfork()` does not use copy-on-write, if the child process changes any pages of the parent's address space, the altered pages will be visible to the parent once it resumes. Therefore, `vfork()` must be used with caution to ensure that the child process does not modify the address space of the parent. `vfork()` is intended to be used when the child process calls `exec()` immediately after creation. Because no copying of pages takes place, `vfork()` is an extremely efficient method of process creation.

8.3 Page Replacement

If a Process of ten pages actually uses only half of them, then Demand Paging saves the I/O necessary to load the five pages that are never used. This also increases the degree of multiprogramming by running more processes, Over-Allocating memory.

Defn 147 (Over-Allocating)**.** *Over-allocating* is the process of putting more load on a component in the system than would normally be possible.

In the context of Paging and Demand Paging, this means that main memory has more Processes in it than would be normal in normal Paging schemes. This is because **ONLY** the pages that are needed to run these processes are loaded, and nothing more.

If we run multiple Processes, each of which is multiple pages in size but actually only uses some of them, we can achieve higher CPU utilization and throughput, with physical frames to spare. It is possible that each of these processes, for some reason, may suddenly try to use **all** of their pages **simulataneously**, resulting in a need for more physical frames than the system has. The operating system has several options at this point:

1. Terminate a user process.
    - Demand Paging is the operating system's attempt to improve the system's utilization and throughput.
    - Users should not be aware that their processes are running on a paged system—
    - Paging should be logically transparent to the user.
    - Not the best choice.
2. Replace one page in memory with the requested one in swap (Page Replacement).
    - Operating System swaps out a process, freeing **all** its frames.
    - Reduce the level of multiprogramming.
    - Good option in certain circumstances (Thrashing).

Defn 148 (Page Replacement)**.** *Page replacement* is the process of replacing a page in memory with one that is Swapping in from the swap.

Page replacement is basic to Demand Paging. It completes the separation between logical memory and Physical Memory. With this mechanism, an enormous Virtual Memory can be provided for programmers on a smaller physical memory. Without demand paging, user addresses are still mapped into physical addresses, and the two sets of addresses can be different, however, all the pages of a process still must be in physical memory. With demand paging, the size of the Logical Address Space is no longer constrained by physical memory.

The procedure for performing this replacement is listed in Section 8.3.1.

Buffers for I/O also consume a considerable amount of memory. Deciding how much memory to allocate to I/O and how much to program pages is a significant challenge. Some systems allocate a fixed percentage of memory for I/O buffers, others allow user processes and the I/O subsystem to compete for all system memory.

8.3.1 Replacement Procedure

The basic steps to perform a Page Replacement are shown below:

1. Find the location of the desired page on the disk.
2. Find a free frame:
   (a) If there is a free frame, use it.
   (b) If there is no free frame, use a page-replacement algorithm to select a victim frame.
   (c) Write the victim frame to the disk; change the page and frame tables accordingly.
3. Read the desired page into the newly freed frame; change the page and frame tables.
4. Continue the user process from where the page fault occurred.

If no frames in memory are free, two page transfers (move one page out and one in) are required, effectively doubling the Page Fault service time and increases the Effective Access Time accordingly. Reducing this overhead can be done by using a Modify Bit (Dirty Bit).

Defn 149 (Modify Bit)**.** The *modify bit* is a signalling bit associated with each page or frame has a modify bit associated with it in the hardware. The modify bit for a page is set by the hardware whenever any byte in the page is written, indicating that the page has been modified.

Remark 149.1 (Dirty Bit). The Modify Bit is sometimes called the *dirty bit*, because if it is set, then the memory can be considered "dirty" and must be written before any further changes are made.

When we select a page for replacement, we examine its Modify Bit.

- Modify Bit set, we know the page has been modified since the **last** read-in from the disk.
  - Must write the page to the disk.
- Modify Bit not set, the page **has not been modified** since it was read into memory.
  - No need to write the memory page to the disk; an exact replica is already there.

Remark. This also applies to read-only pages (for example, pages of binary code). Since such pages cannot be modified, they may be discarded when desired. This can significantly reduce the time required to service a page fault, since it reduces **I/O time** by one-half if the page has not been modified.

8.3.2 Algorithms

In general, we select a particular replacement algorithm with the lowest Page Fault rate. We evaluate an algorithm by running it on a particular string of memory references, called a reference string, and computing the number of page faults.

To determine the number of Page Faults for a particular reference string and Page Replacement algorithm, we also need to know the number of frames available. Obviously, as the number of frames available increases, the number of page faults decreases. Adding physical memory increases the number of frames. Between the number of frames and the number of page faults, we generally expect a negative-exponential curve.

8.3.2.1 FIFO Page Replacement The simplest page-replacement algorithm is a first-in, first-out algorithm. A FIFO replacement algorithm associates with each page the time when that page was brought into memory. When a page must be replaced, the oldest page is chosen.

It is not really necessary to record the time when a page is brought in. Instead, we can use a FIFO queue to hold all pages in memory. When a page is brought into memory, we insert it at the tail of the queue. When a page is replaced, we replace the page at the head of the queue.

Notice that, even if we select a page that is being actively used for replacement, everything still works correctly. After we replace the active page with a new one, a Page Fault will occur almost immediately to retrieve the active page from the swap. Then, some other page must be replaced to bring the active page back into memory. Thus, a bad replacement choice increases the page-fault rate and slows process execution, but does not cause incorrect execution.

The FIFO Page Replacement algorithm is easy to understand and program. However, its performance is not always good. Sometimes, the number of faults for more frames is greater than the number of faults for fewer frames. This unexpected result is known as Belady's Anomaly.

Defn 150 (Belady's Anomaly)**.** *Belady's Anomaly* states that if the number of available frames to hold pages increases, the number of Page Faults will increase.

8.3.2.2 Optimal Page Replacement A result of the discovery of Belady's Anomaly was the search for an optimal Page Replacement algorithm. This is the algorithm with the lowest Page Fault rate of all algorithms and will never suffer from Belady's Anomaly. It was found and is called OPT Algorithm.

Defn 151 (OPT Algorithm)**.** The *OPT* or *MIN* Page Replacement *Algorithm* is that has the lowest Page Fault rate of any and all algorithm, and never suffers fro Belady's Anomaly. It is:

Replace the page that will not be used for the longest period of time.

Use of this Page Replacement algorithm guarantees the lowest possible Page Fault rate for a fixed number of frames.

Unfortunately, the optimal page-replacement algorithm is difficult, if not impossible, to implement, because it requires **future** knowledge of the reference string. This is a similar situation as with the Shortest-Job-First Scheduling algorithm in Paragraph 6.2.4.2. As a result, the optimal algorithm is used mainly for comparison studies. For instance, a new algorithm may not be optimal, but it is within 12.3 % of optimal at worst and within 4.7 % on average.

8.3.2.3 Least-Recently-Used (LRU) Page Replacement If the OPT Algorithm is not feasible, perhaps an approximation of it is possible. If we assume the recent past as an approximation of the near future, then we can replace the page that has not been used for the longest period of time. This approach is the Least Recently Used Algorithm.

Defn 152 (Least Recently Used Algorithm)**.** The *Least Recently Used* (*LRU*) *Algorithm* assumes that the past is a good approximation of the near future. This allows it to replace the page that has not been used for the longest time first, because it is unlikely that the page will be used.

Like the OPT Algorithm, LRU replacement does not suffer from Belady's Anomaly. Both belong to a class of Page Replacement algorithms, called Stack Algorithms, that can never exhibit Belady's anomaly.

Remark 152.1 (OPT and LRU Algorithm Performance). Let S_R be the reverse of a reference string S. The Page Fault rate for the OPT Algorithm on S is the same as the page-fault rate for the OPT algorithm on S_R. Likewise, the page-fault rate for the LRU algorithm on S is the same as the page-fault rate for the LRU algorithm on S_R.

The Least Recently Used Algorithm is often used as a Page Replacement algorithm and is considered to be good. The major problem is how to implement it. The LRU page-replacement algorithm may require substantial hardware assistance to determine an order for the frames defined by the time of last use. There are two reasonably feasible implementations:

1. **Counters**. In this case, we associate with each Page Table entry a Time-of-Use field and add to the CPU a logical clock or counter which is incremented for **every** memory reference. Whenever a reference to a page is made, the contents of the clock register are copied to the Time-of-Use field in the page-table entry for that page. This way, we always have the "time" of the last reference to each page. We replace the page with the smallest time value.
   - This scheme requires a search of the page table to find the LRU page and a write to memory (to the time-of-use field in the page table) for each memory access.
   - The times must also be maintained when page tables are changed (due to CPU scheduling).
   - Overflow of the clock must be considered.
2. **Stack**. Another approach to implementing LRU replacement is to keep a stack of page numbers. Whenever a page is referenced, it is put on the top. In this way, the most recently used page is always at the top of the stack and the least recently used page is always at the bottom. Because entries must be removed from the middle of the stack, it is best to implement this approach by using a doubly linked list with a head pointer and a tail pointer.
   - Removing a page and putting it on the top of the stack then requires changing six pointers at worst.
   - Each update is a little more expensive, but there is no search for a replacement. The tail pointer points to the bottom of the stack, the LRU page.
   - This approach is particularly appropriate for software or microcode implementations of LRU replacement.

Both implementations of the Least Recently Used Algorithm need additional hardware assistance beyond the standard TLB registers. For example, updating the clock fields or stack must be done for every memory reference. If we were to use an interrupt allowing software to update these data structures, it would signficantly slow every memory reference.

Defn 153 (Stack Algorithm)**.** A *stack algorithm* is an algorithm for which it can be shown that the set of pages in memory for n frames is always a **subset** of the set of pages that would be in memory with $n + 1$ frames.

For the Least Recently Used Algorithm, the set of pages in memory would be the n most recently referenced pages. If the number of frames is increased, the same n pages will still be the most recently referenced and will still be in memory.

8.3.2.4 LRU-Approximation Page Replacement Few computer systems provide sufficient hardware support for true LRU page replacement. Many provide some support, in the form of a Reference Bit.

Defn 154 (Reference Bit)**.** A *Reference bit* is another bit that is associated with each entry in the Page Table. The reference bit for a page is set by the hardware whenever that page is referenced (either a read or a write to any byte in the page).

Initially, all bits are cleared by the Operating System. As a user Process executes, the Reference Bit associated with each page is set by the hardware. After some time, we can determine **which** pages have been used by examining the reference bits, although **we do not know the order of use**. This information is the basis for many Page Replacement algorithms that approximate Least-Recently-Used (LRU) Page Replacement.

There are 3 major implementation methods for this algorithm.

1. Additional-Reference-Bits Algorithm
2. Second-Chance Algorithm
3. Enhanced Second-Chance Algorithm

Additional-Reference-Bits Algorithm We can gain additional ordering information by recording the reference bits at regular intervals using a n-bit number for each page in a table in memory. The number of bits (of history) included in the shift register is not fixed, and is based on the hardware available to make updating as fast as possible.

At regular intervals, a timer interrupt transfers control to the Operating System. The operating system shifts the Reference Bit for each page into the high-order bit, shifting the other bits right by 1 bit and discarding the low-order bit. These shift registers contain the history of page use for the last n time periods.

For example, in an 8 bit shift register, if it contains `00000000`, then the page has not been used for eight time periods. A page that is used at least once in each period has a shift register value of `11111111`.

If we interpret these bit strings as unsigned integers, the page with the lowest number is the LRU page, and it can be replaced. Note that the numbers are not guaranteed to be unique. We can either replace (swap out) all pages with the smallest value or use the FIFO method to choose among them.

Second-Chance Algorithm The basic algorithm of second-chance replacement is a FIFO Page Replacement algorithm. When a page has been selected, however, we inspect its Reference Bit.

- If the Reference Bit is 0, we proceed to replace this page.
- If the Reference Bit is set to 1, we give the page a second chance and move on to select the **next** FIFO page.
  - When a page gets a second chance, its Reference Bit is cleared, and its arrival time is reset to the current time.
  - Thus, a page that is given a second chance will not be replaced until all other pages have been replaced (or given second chances).
  - If a page is used often enough to keep its Reference Bit set, it will never be replaced.

When all bits are set, the worst case, the pointer cycles through the whole queue, giving each page a second chance, clearing all the Reference Bits before selecting the next page for replacement. Second-chance replacement degenerates to FIFO Page Replacement if all the pages' bits are set.

Enhanced Second-Chance Algorithm We can enhance the Second-Chance Algorithm by considering the Reference Bit and the Modify Bit as an ordered pair. With these two bits, there are four possible classes:

1. $(0, 0)$ Neither recently used nor modified. **Best page to replace**.
2. $(0, 1)$ Not recently used but modified. **Not as good**. Page will need to be written before replacement
3. $(1, 0)$ Recently used but clean. **Probably will be used again soon**.
4. $(1, 1)$ Recently used and modified. **Probably will be used again soon and page will be need to be written before it can be replaced**.

When page replacement is called for, we use the same scheme as in the Second-Chance Algorithm. Instead of examining whether the page to which we are pointing has the reference bit set to 1, we examine the class to which that page belongs replacing the first page in the lowest nonempty class. We may have to scan the circular queue several times before we find a page to be replaced. In this algorithm, we give preference to those pages that have been modified in order to reduce the amount of I/Os required.

8.3.2.5 Counting-Based Page Replacement Keep a counter of the number of references that have been made to each page, leading to the following schemes.

1. The Least Frequently Used (LFU) Page Replacement algorithm. This requires that the page with the **smallest count** be replaced because it is the least frequently used page. This means that an actively used page should have a large reference count. A problem arises when a page is used heavily once but then is never used again; thus, it has a large count but remains in memory even though it is no longer needed.

- A solution is to shift the counts right by 1 bit at regular intervals, forming an exponentially decaying average usage count.

2. The Most Frequently Used (MFU) Page Replacement algorithm is based on the argument that the page with the smallest count was probably just brought in and has yet to be used.

Neither algorithm, MFU or LFU, is common; their implementation is expensive.

8.3.2.6 Page-Buffering Algorithms Other procedures are often used in conjunction with another Page Replacement algorithm. One of these is that systems will commonly keep a pool of free frames. When a Page Fault occurs, the victim frame is chosen according to the page replacement algorithm. However, the desired page is read into a free frame **from the pool** before the victim is written out. This allows the Process that caused the page fault to restart as soon as possible, without waiting for the victim page to be written out. The victim is later written out, adding its newly freed frame to the free-frame pool.

Another version of this idea is to maintain a list of modified pages. Whenever the paging device is idle, a modified page is selected and is written to the disk. That page's Modify Bit is then reset. This increases the probability that a page will be clean when it is selected for replacement and will not need to be written out.

Another verion is to keep a history of which page was in each frame inside of a frame-pool. This way, if the page is needed after being written to disk, we just need to go to that frame and use the data from there. This works because when a frame is written to the disk, the contents are not changed. This means we may not need I/O in this case. When a Page Fault occurs, we first check whether the desired page is in the free-frame pool. If it is not, we must select a free frame and read into it.

8.3.3 Applications and Page Replacement

In certain cases, applications accessing data through the Operating System's Virtual Memory perform worse than if the OS provided no buffering at all. A typical example is a database, which has its own memory management and I/O buffering. Applications like this understand their memory use and disk use better than an operating system that is implementing algorithms for general-purpose use. If the operating system and the application are buffering I/O, then twice the memory is being used for I/O.

Because of such problems, some Operating Systems give certain programs the ability to use a disk partition as a large sequential array of logical blocks, **without** any file-system data structures. This is sometimes called the raw disk, and I/O to this array is termed raw I/O. Raw I/O bypasses **all** file-system services, such as file I/O demand paging, file locking, prefetching, space allocation, file names, and directories. Although certain applications are more efficient when implementing their own special-purpose storage services on a raw partition, most applications perform better when they use the regular file-system services.

8.4 Thrashing

If a Process does not have the number of frames (Physical Memory) it needs to support pages in active use, it will quickly page-fault. At this point, it must replace some pages. However, since all the pages are in active use, the OS will replace a page that will be needed again right away. Consequently, the process faults repeatedly, replacing pages that it must bring back in immediately.

Defn 155 (Thrashing)**.** *Thrashing* is when a Process is spending more time Paging than executing. This happens when there are not enough frames in the system to support the number of pages the process needs. The Page Replacement algorithm will replace some pages that the process needs right now, so it must page the first one back in, overwritting another page that is needed. Thus, the cycle continues.

8.4.1 Cause of Thrashing

Thrashing results in severe performance problems. The CPU Scheduler sees the decreasing CPU utilization and increases the degree of multiprogramming as a result. The new Process tries to get started by taking frames from running processes, causing more Page Faults and a longer queue for the paging device (Backing Store). As a result, CPU utilization drops even further, and the CPU scheduler tries to increase the degree of multiprogramming even more.

This leads to system throughput plunging. The Page Fault rate increases tremendously, increasing the Effective Access Time. No work is getting done, because the processes are spending all their time Paging.

8.4.2 Limiting Thrashing

We can limit the effects of Thrashing by using a local replacement algorithm. With local replacement, if a Process starts thrashing, it cannot steal frames from another, causing the second one to thrash as well. However, this does not entirely the problem.

Remark. The current best practice in implementing a computer system is to include enough Physical Memory to avoid Thrashing and Swapping. Providing enough memory to keep all working sets in memory concurrently, except under extreme conditions, gives the best user experience.

If Processes are Thrashing, they will be in the queue for the paging device most of the time. The average service time for a Page Fault will still increase because of the longer average queue for the paging device. Thus, the Effective Access Time will increase even for a process that is not thrashing. To prevent thrashing, we must provide a process with as many frames as it **NEEDS**.

8.4.3 Working-Set Model

The *Working-Set Model* uses the Locality Model of Process execution.

Defn 156 (Locality Model)**.** The *locality model* states, as a Process executes, it moves from locality to locality. A locality is a set of pages that are actively used together. A Program is generally composed of several different localities, which may overlap.

For example, when a function is called, it defines a new locality. In this locality, memory references are made to the instructions of the function call, its local variables, and a subset of the global variables. When we exit the function, the process leaves this locality, since the local variables and instructions of the function are no longer in active use. We may return to this locality later.

Localities are defined by the program structure and its data structures. The Locality Model states that all programs will exhibit this basic memory reference structure.

> *Remark.* Note that the Locality Model is the unstated principle behind our mentions of caching so far. If accesses to any types of data were random rather than patterned, caching would be useless.

This model uses a parameter, Δ, to define the **working-set window**. The idea is to examine the most recent Δ page references. The set of pages in the most recent Δ page references is the **working set**. If a page is in active use, it will be in the working set. If it is no longer being used, it will drop from the working set Δ time units after its last reference. Thus, the working set is an approximation of the program's locality.

The accuracy of the working set depends on the selection of Δ.

- Δ is too small, it will not encompass the entire locality.
- Δ is too large, it may overlap several localities.
- Δ is ∞, working set is the set of **ALL** pages touched during the Process's execution.

Using this set, if we can find its size for all the Processes in the system, we can calculate the entire system's demand. If the demand is greater than the total number of frames, then Thrashing will happen.

Once Δ is selected, use of the working-set model is simple. The Operating System monitors the working set of each Process and allocates to it enough frames to provide it with its working-set size. If there are enough frames left over, another process can be initiated. If the sum of the working-set sizes increases, making the demand of the system exceed the total number of available frames, the OS selects a process to suspend. The process's pages are swapped out, and its frames are reallocated to other processes. The suspended process can be restarted later.

8.4.4 Page-Fault Frequency

A strategy using the Page Fault Frequency (PFF) can take a more direct approach. Thrashing has a high page-fault rate. Thus, we want to control the page-fault rate.

- High, the process needs more frames.
- Low, the process may have too many frames.

We can establish upper and lower bounds on the desired Page Fault rate.

- Page Fault rate exceeds the upper limit, allocate the process another frame.
- Page Fault rate falls below the lower limit, remove a frame from the process.

Thus, we can directly measure and control the Page Fault rate to prevent Thrashing. As with the working-set strategy, we may have to swap out a process. If the page-fault rate increases and no free frames are available, we must select some process and swap it out to Backing Store. The freed frames are then distributed to processes with the highest page-fault rates.

8.5 Memory-Mapped Files

The sequential read of a File on disk using the standard System Calls `open()` , `read()` , and `write()` . Each file access requires a system call and disk access. To alleviate the pain of this, we could use Memory Mapping.

Defn 157 (Memory Mapping)**.** *Memory mapping* is the process of taking something and mapping it to a page in memory. This allows a page (possibly multiple) in the Virtual Address Space to be logically associated with a page-sized amount of something.

8.5.1 Basic Mechanism

Memory mapping a file is accomplished by mapping a disk block to a page (or pages) in memory. The steps involved are:

1. Initial access to the File proceeds through ordinary Demand Paging, resulting in a Page Fault.
2. A page-sized portion of the file is read from the file system into a physical frame.
   - Some systems may read in more than a page-sized chunk of memory at a time
3. Subsequent reads and writes to the file (within the loaded paged-size amount of the file) are handled as routine memory accesses.

8.5.2 Benefits of Memory Mapping

Manipulating Files through memory rather than incurring the overhead of using the `read()` and `write()` system calls simplifies and speeds up file access and usage.

Multiple Processes may be allowed to map the same File concurrently, to allow sharing of data. Writes by any of the processes modify the file's data in Virtual Memory which can be seen by all others that map the same section of the file. The Memory Mapping System Calls can also support Copy-on-Write functionality. This allows processeses to share a file in read-only mode but to have their own copies of any data they modify. to coordinate access to the shared data, the processes involved will use one of the mechanisms for achieving Mutex-like behavior.

8.5.3 Caveats of Memory Mapping

Writes to the File mapped in memory are not necessarily immediate (synchronous) writes to the file on disk. Some systems may choose to update the physical file when the operating system periodically checks whether the page in memory has been modified. When the file is closed, all the data is written back to disk and removed from the Virtual Memory of the Process.

8.5.4 Memory Mapped I/O

Each I/O controller includes registers to hold commands and the data being transferred. Usually, special I/O instructions allow data transfers between these registers and system memory. For more convenient access to I/O devices, many computer architectures provide memory-mapped I/O.

Defn 158 (Memory-Mapped I/O)**.** *Memory-Mapped I/O* assigns ranges of memory addresses that map to the I/O device's registers. Reads and writes to these memory addresses cause the data to be transferred to and from the device registers automatically. This is appropriate for devices that have fast response times, such as video controllers.

Memory-mapped I/O is also convenient for other devices, such as the serial and parallel ports. The CPU transfers data through these kinds of devices by reading and writing a few device registers, called an I/O port.

To send out a long string of bytes through a memory-mapped **serial** port, the CPU writes one data byte to the data register and sets a bit in the control register to signal that the byte is available. The device takes the data byte and then clears the bit in the control register to signal that it is ready for the next byte. Then the CPU can transfer the next byte. There are 2 ways for the CPU to interact with these devices:

1. Programmed I/O
2. Interrupt-Driven

Defn 159 (Programmed I/O)**.** *Programmed I/O* (*PIO*) is when the CPU transfers one byte, word, chunk, etc. one at a time, in a looping fashion. Typically, this is done with Polling to watch the `control` bit, constantly looping to see whether the device is ready.

Defn 160 (Interrupt-Driven)**.** An *interrupt-driven* system is one where the CPU does not poll the control bit, but instead receives an Interrupt when the device is ready for the next byte.

8.6 Allocating Kernel Memory

When a Process running in User mode requests additional memory, pages are allocated from the list of free page frames maintained by the Kernel. This list is typically populated using a Page Replacement algorithm and most likely contains free pages scattered throughout physical memory. Additionally, Internal Fragmentation may result, as the process will be granted an entire page frame, even if it doesn't need all of it..

Kernel memory is often allocated from a free-memory pool **different** from the list used to satisfy ordinary user-mode processes. There are two primary reasons for this:

1. The Kernel requests memory for data structures of varying sizes, some of which are less than a page in size. As a result, the kernel must use memory conservatively and attempt to minimize waste due to Fragmentation. Many Operating Systems do not subject kernel code or data to the paging system.
2. Pages allocated to User-mode processes do not necessarily have to be in contiguous physical memory. However, certain hardware devices interact directly with physical memory, not the Virtual Memory interface. Consequently, the devices may require memory residing in **physically** contiguous pages.

We discuss 2 systems for allocating memory to Kernel Processes.

1. Buddy System
2. Slab Allocation

8.6.1 Buddy System

The buddy system allocates memory from a fixed-size segment consisting of **physically contiguous pages**. Memory is allocated from this segment using a *power-of-2 allocator*, which satisfies requests in units sized as a power of 2 (4 KiB, 8 KiB and 16 KiB, and so forth). All requests are rounded up to the next appropriate highest power of 2. For example, a request for 11 KiB is satisfied with a 16 KiB segment.

8.6.1.1 Benefits of the Buddy System An advantage of the buddy system is how quickly adjacent buddies can be combined to form larger segments using a technique known as *coalescing*.

8.6.1.2 Drawbacks of the Buddy System The drawback to the buddy system is that rounding up to the next highest power of 2 will likely cause Fragmentation within allocated segments.

8.6.2 Slab Allocation

There are several components that make up the slab allocation scheme:

- Slab
- Cache
- Object

Defn 161 (Slab)**.** A *slab* is made up of one or more physically contiguous pages.

Defn 162 (Cache)**.** A *cache* consists of one or more Slabs. There is a single cache for each unique kernel data structure.

The caches do not necessarily keep the Objects in order. They only guarantee that the objects will be in contiguous memory because the Slabs they map to are contiguous.

For example, a separate cache for the data structure representing Process Descriptors, a separate cache for file objects, a separate cache for Semaphores, and so forth.

Defn 163 (Object)**.** *Objects* that are instantiations of the kernel data structure the Cache represents.

For example, the cache representing Semaphores stores instances of semaphore objects, the cache representing Process Descriptors stores instances of process descriptor objects, and so forth.

The slab-allocation algorithm uses Caches to store Kernel objects. When a Cache is created, a number of Objects are allocated to the Cache,which are initially marked as `free`. The number of Objects in the Cache depends on the size of the associated Slab.

For example, a 12 KiB slab (made up of three continguous 4 KiB pages) could store six 2 KiB objects. When a new object for a kernel data structure is needed, the allocator can assign any free object from the cache to satisfy the request. The object assigned from the cache is marked as `used`.

8.6.2.1 Benefits of Slab Allocation

There are 2 main benefits of the slab allocation algorithm:

1. No memory is wasted due to Fragmentation. Fragmentation is not an issue because each unique Kernel data structure has an associated Cache, and each cache is made up of one or more Slabs that are divided into chunks the size of the Objects being represented. Thus, when the kernel requests memory for an object, the slab allocator returns the exact amount of memory required to represent the object.
2. Memory requests can be satisfied quickly. The slab allocation scheme is thus particularly effective for managing memory when Objects are frequently allocated and deallocated, as is often the case with requests from the Kernel. The act of allocating and releasing memory can be a time-consuming process, however, objects are created in advance allowing for quick allocation from the Cache. Furthermore, when the kernel has finished with an object and releases it, it is marked as `free` and returned to its cache, thus making it immediately available for subsequent requests from the kernel.

8.7 Other Topics to Consider

Here, we mention considerations, other than a Page Replacement algorithm and frame allocation policy to choosing how to create our Paging system.

8.7.1 Prepaging

An obvious property of pure Demand Paging is the large number of Page Faults that occur when a Process is started or when a swapped out process is restarted. This situation results from trying to get the initially executing locality into memory. Prepaging helps ease this situation.

Defn 164 (Prepaging)**.** *Prepaging* is an attempt to prevent this high level of initial paging. The strategy is to bring into all the pages that will be needed into memory at one time.

In a system using the Working-Set Model, for example, we could keep with each Process a list of the pages in its working set. If we must suspend a process, we remember the working set for that process. When the process is to be resumed, we automatically bring back into memory its **entire working set** before restarting the process.

Prepaging may offer an advantage in some cases. The question is whether the cost of using prepaging is less than the cost of servicing the corresponding page faults. Prepaging becomes less effective if many of the pages brought back into memory by prepaging will not be used.

8.7.2 Page Size

The designers of an Operating System for an existing machine rarely have a choice concerning the page size. However, a new machine can have different page sizes than its predecessors. There is no single best page size. Page sizes are almost always powers of 2, generally ranging from 4096 B to 4 194 304 B (2^{12} to 2^{22} byte, 4 KiB to 4 MiB).

How do we select a page size?

- One concern is the size of the page table.
  - For a given virtual memory space, decreasing the page size increases the number of pages and hence the size of the page table.
- Because each active process must have its own copy of the Page Table, a large page size is desirable.
- Memory is better utilized with smaller pages.
  - To minimize Internal Fragmentation, we need a small page size.
- Time required to read or write a page. Minimization of I/O time argues for a larger page size.
  - I/O time is composed of seek, latency, and transfer times. Transfer time is proportional to the amount transferred, meaning a small page size.
  - Latency and seek time normally dwarf transfer time.
- With a smaller page size, total I/O should be reduced, since locality will be improved.
  - A smaller page size allows each page to match program locality more accurately.
- With a smaller page size, then, we have better resolution, allowing us to isolate only the memory that is actually needed.
  - With a larger page size, we must allocate and transfer not only what is needed but also anything else that happens to be in the page, whether it is needed or not.
  - Thus, a smaller page size should result in less I/O and less total allocated memory.
- To minimize the number of page faults, we need to have a large page size.
- What is the relationship between page size and sector size on the paging device?

This problem has no best answer. As we have seen, some factors (Internal Fragmentation, locality) argue for a small page size, whereas others (table size, I/O time) argue for a large page size. The historical trend is toward larger page sizes.

8.7.3 TLB Reach

Recall that the hit ratio for the Translation Lookaside Buffer (TLB) refers to the percentage of virtual address translations that are resolved in the TLB rather than the page table. Clearly, the hit ratio is related to the number of entries in the TLB, and the way to increase the hit ratio is by increasing the number of entries in the TLB. However, the associative memory used to construct the TLB is both expensive and power hungry. Related to the hit ratio is another metric: the TLB Reach.

Defn 165 (TLB Reach)**.** *TLB reach* refers to the amount of memory accessible from the Translation Lookaside Buffer (TLB). It is the number of entries multiplied by the page size.

Ideally, the working set for a Process is stored in the TLB. If it is not, the process will spend a considerable amount of time resolving memory references in the Page Table rather than the TLB.

There are 3 methods to increase the TLB Reach:

1. Increase the number of entries in the TLB.
2. Increase the size of a page.
   - For example, increase the page size from 8 KiB to 32 KiB, quadruple the TLB Reach.
   - However, may to an increase in Fragmentation.
3. Provide multiple page sizes.
   - Providing support for multiple page sizes requires the operating system —not hardware —to manage the TLB.
   - One of the fields in a TLB entry must indicate the size of the page frame corresponding to the TLB entry.
   - Managing the TLB in software and not hardware comes at a cost in performance.
   - The increased hit ratio and TLB reach offset the performance costs.
   - Recent trends indicate a move toward software-managed TLBs and operating-system support for multiple page sizes.

8.7.4 Inverted Page Tables

The purpose of this form of page management is to reduce the amount of Physical Memory needed to track virtual-to-physical address translations, by keeping information about which Virtual Memory page is stored in each physical frame. We accomplish this savings by creating a table that has one entry per page of physical memory, indexed by the pair $\langle \texttt{PID}, page - number\rangle$. However, the inverted page table no longer contains complete information about the Logical Address Space of a Process, and that information is required if a referenced page is not currently in memory.

Demand Paging requires this information to process Page Faults. For the information to be available, an external page table (one per Process) must be kept. This table looks like the traditional per-process page table and contains information on where each virtual page is located.

Since these tables are referenced only when a Page Fault occurs, they do not need to be available quickly. Instead, they are themselves paged in and out of memory as necessary. But now a page fault may cause the virtual memory manager to generate another page fault as it pages in the external page table it needs to locate the virtual page on the Backing Store. This special case requires careful handling in the Kernel and a delay in the page-lookup processing.

8.7.5 Program Structure

Demand Paging is designed to be transparent to the User Program. In many cases, the user is completely unaware of the paged nature of memory. However, system performance can be improved if the user (or compiler) has an awareness of the underlying demand paging.

Good selection of data structures and programming structures can increase locality and hence lower the Page Fault rate and the number of pages in the working set.

- A stack has good locality, since access is always made to the top.
- A hash table is designed to scatter references, producing bad locality.

Of course, locality of reference is just one measure of the efficiency of the use of a data structure. Other heavily weighted factors include search speed, total number of memory references, and total number of pages touched.

At a later stage, the compiler and loader can have a significant effect on Paging. Separating code and data and generating Reentrant code means that code pages can be read-only and hence will never be modified meaning they never have to be paged out to be replaced. The loader can avoid placing routines across page boundaries, keeping each routine completely in one page. Routines that call each other many times can be packed into the same page. This packaging is a variant of the bin-packing problem: try to pack the variable-sized load segments into the fixed-sized pages so that interpage references are minimized. This is particularly useful for large page sizes.

8.7.6 I/O Interlock and Page Locking

When using I/O devices with Demand Paging, we sometimes need to allow some of the pages to be locked in memory.

One solution is never to execute I/O to User memory. Instead, data is copied between Kernel memory and user memory, then the I/O takes place only between kernel memory and the I/O device. To write a block on tape, we first copy the block to system memory and then write it to tape. This extra copying may result in unacceptably high overhead.

Another solution is to allow pages to be locked into memory. Here, a *lock bit* is associated with every physical frame. If the frame is locked, it and its contents cannot be selected for replacement. Locked pages cannot be replaced. When the I/O is complete, the pages are unlocked. Under this approach, to write a block on tape, we lock into memory the pages containing the block. The system can then continue as usual.

Lock bits are used in various situations. Frequently, some or all of the Operating System Kernel is locked into memory. Many operating systems cannot tolerate a Page Fault caused by the kernel or by a specific Kernel Module, including the one performing memory management.

User processes may also need to lock pages into memory. Such pinning of pages in memory is fairly common, and most operating systems have a system call allowing an application to request that a region of its Logical Address Space be pinned. This feature could be abused and could cause stress on the memory-management algorithms. Therefore, an application usually requires special privileges to make such a request.

Using a lock bit can be dangerous: the lock bit may get turned on but never turned off. Should this situation occur, the locked frame becomes unusable.

9 Mass-Storage Structure

9.1 Structure of Storage Media

In this section, the structure of secondary storage is discussed. Starting with the physical structure of magnetic disks, magnetic tapes, and solid-state storage.

9.1.1 Magnetic Disks

Magnetic disks (typically called hard drives) provide the bulk of storage. Inside each unit, there are disk platters that have a flat circular shape. The two surfaces of a platter are covered with a magnetic material. Information is stored by recording it magnetically on the platters. Typical disks can transfer several megabytes of data per second, and they have seek times and rotational latencies of several milliseconds.

- A read–write head “flies” just above each surface of every platter.
- The heads are attached to a disk arm that moves all the heads as a unit.
- The surface of a platter is logically divided into circular tracks, which are subdivided into sectors.
- The set of tracks that are at one arm position makes up a cylinder.

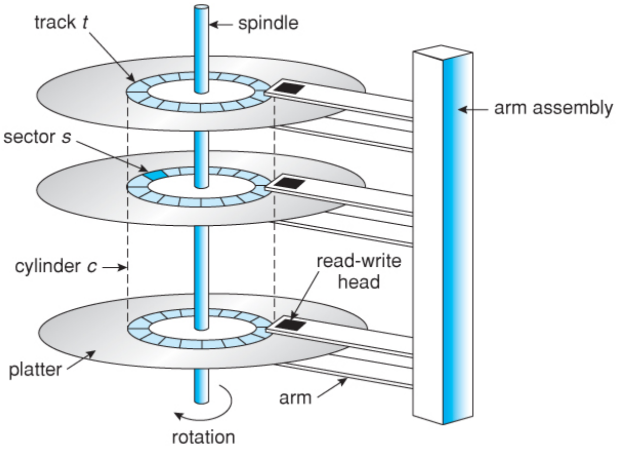


Figure 9.1: Magnetic Disk Moving head Mechanism

When the disk is in use, a drive motor spins it at high speed. Common drives spin at 5400 RPM, 7200 RPM, 10 000 RPM and 15 000 RPM. Disk speed has two parts.

1. The transfer rate is the rate at which data flow between the drive and the computer.

2. The positioning time, or random-access time. Itself consisting of 2 parts:
   (a) Time necessary to move the disk arm to the desired cylinder, called the seek time,
   (b) Time necessary for the desired sector to rotate to the disk head, called the rotational latency.

There is a danger that the head will make contact with the disk surface. This accident is called a head crash, and cannot be repaired; the entire disk must be replaced.

A disk drive is attached to a computer by an I/O bus. Several kinds of buses are available, including:

- Advanced Technology Attachment (ATA)
- Serial ATA (SATA)
- eSATA
- Universal Serial Bus (USB)
- Fiber Channel (FC)

The data transfers on a bus are carried out by special electronic processors called controllers.

Host Controller: The controller at the computer end of the bus.
Disk Controller: Built into each disk drive.

To perform a disk I/O operation, the computer places a command into the host controller, typically using memory-mapped I/O ports. The host controller then sends the command via messages to the disk controller, and the disk controller operates the disk-drive hardware to carry out the command.

9.1.2 Magnetic Tapes

Magnetic tapes are relatively permanent and can hold large quantities of data, its access time is slow compared with that of main memory and magnetic disk. In addition, random access to magnetic tape is about a thousand times slower than random access to magnetic disk, so tapes are not very useful for active secondary storage.

A tape is kept in a spool and is wound or rewound past a read–write head. Moving to the correct spot on a tape can take minutes, but once positioned, tape drives can write data at speeds comparable to disk drives. Tape capacities vary greatly, depending on the particular kind of tape drive

Tapes are used mainly for backup, for storage of infrequently used information, and as a medium for transferring information from one system to another.

9.1.3 Solid-State Storage

A Solid-State Disk (SSD) is nonvolatile storage that can be used like a traditional magnetic disk hard drive. There are many variations of this technology, from DRAM with a battery to flash-memory technologies like single-level cell (SLC) and multilevel cell (MLC) chips. SSDs have the same characteristics as traditional hard disks but:

- Are more reliable because they have no moving parts.
- Aare faster because they have no seek time or latency.
- They consume less power.

However their uses are somewhat limited because,

- They are more expensive per megabyte than traditional hard disks.
- They have less capacity than the larger hard disks.
- May have shorter life spans than hard disks.

Because SSDs can be much faster than magnetic disk drives, standard I/O Bus interfaces can bottleneck a system. Some SSDs are designed to connect directly to the system bus (PCI).

Some of the topics discussed here for magnetic disks also pertain to SSDs, some don't. For example, because SSDs have no disk head, disk-scheduling algorithms largely do not apply. However, throughput and formatting do.

9.2 Disk Structure

Here, we view all potential storage media (Section 9.1) as being the same.

Drives are addressed as large one-dimensional arrays of Logical Blocks.

Defn 166 (Logical Block)**.** The *logical block* is the smallest unit of transfer. The size of a logical block is usually 512 bytes, although some disks can use a different Low-Level Formatting to have a different logical block size, such as 1,024 bytes.

This one-dimensional array of logical blocks is mapped onto the sectors of the disk sequentially. Sector 0 is the *first sector* of the *first track* on the *outermost cylinder*. The mapping proceeds in order through that track, then through the rest of the tracks in that cylinder, and then through the rest of the cylinders from outermost to innermost.

In theory, we can convert a Logical Block number into a disk address that consists of a cylinder number, a track number within that cylinder, and a sector number within that track. However, in practice, it is difficult to perform this translation.

1. Most disks have some defective sectors after manufacturing.
   - The mapping hides this by substituting spare sectors from elsewhere on the disk.
2. The number of sectors per track is not a constant on some drives, because of the distance from the center.

Handling the issue of the number of sectors is done through one of 2 methods.

1. **Constant Linear Velocity** (CLV). The density of bits per track is uniform. The farther a track is from the center of the disk, the greater its length, so the more sectors it can hold. The number of sectors per track decreases from outer tracks to inner ones. The drive increases its rotation speed as the head moves from the outer to the inner tracks to keep the same rate of data moving under the head. This method is used in CD and DVD drives.
2. **Constant Angular Velocity** (CAV). The disk rotation speed can stays constant The density of bits decreases from inner tracks to outer tracks to keep the data rate constant. This method is used in traditional hard disks.

9.3 Disk Attachment

This section is concerned with how these physical disks or tapes are attached to the computer for use. There are 2 ways to access disk storage:

1. Host-Attached Storage
2. Network-Attached Storage

9.3.1 Host-Attached Storage

In Host-Attached Storage any combination of I/O bus architectures and protocols can be used. The I/O commands that initiate data transfers to a host-attached storage device are reads and writes of logical data blocks directed to specifically identified storage units (such as bus ID or target logical unit).

Defn 167 (Host-Attached Storage)**.** *Host-Attached Storage* is disk storage that is attached to the computer through the local I/O bus.

9.3.2 Network-Attached Storage

Network-Attached Storage provides a convenient way for all the computers on a LAN to share a pool of storage with the same ease of naming and access enjoyed with local Host-Attached Storage. However, it tends to be less efficient and have lower performance than some direct-attached storage options.

Defn 168 (Network-Attached Storage)**.** *Network-Attached Storage* (*NAS*) is disk storage that is attached to the local computer by making a connection to a remote host that serves a distributed file system to connectees. The remote procedure calls (RPCs) are carried via TCP or UDP over an IP network. Typically, the client and server lie on the same local-area network (LAN) that carries all data traffic to the clients.

9.3.3 Storage-Area Network

Storage-Area Networks require an interconnect between the storage arrays, one that allows for very high-speed communication.

Defn 169 (Storage-Area Network)**.** *Storage-Area Network*s, (*SAN*s) behave somewhat opposite a Network-Attached Storage system. A SAN is a private network (using storage protocols rather than networking protocols) connecting servers and storage units. The power of a SAN lies in its flexibility. Multiple hosts and multiple storage arrays can attach to the same SAN, and storage can be dynamically allocated to hosts. Here, the data is stored in physically separate machines and all brought together with a network backbone.

A SAN switch allows or prohibits access between the hosts and the storage. Instead, any service can connect to the SAN and access the data within.

9.4 Disk Scheduling

Just like with CPU Scheduling and Virtual Memory, the Operating System attempts to maximize the efficient use of hardware resources. For disk drives, this means minimizing access time and maximizing bandwidth.

Defn 170 (Disk Bandwidth)**.** The *disk bandwidth* is the total number of bytes transferred, divided by the total time between the first request for service and the completion of the last transfer.

The service time will include the seek time (time for disk arm to move heads to cylinder) and the rotational latency (time for platter to spin to correct sector).

When performing disk I/O, we need to know a few things:

- Whether this operation is input or output.
- What the disk address for the transfer is.
- What the memory address for the transfer is.
- What the number of sectors to be transferred is.

If the desired disk drive **and** controller are available, the request can be serviced immediately. If the drive or controller is busy, any new requests for service will be placed in the queue of pending requests for that drive.

Like before, the choice of how to handle pending requests in the queue is handled by the choice of disk-scheduling algorithm. Choosing the best one is difficult because performance depends heavily on the number and types of requests. Shortest-Seek-Time-First Scheduling is common and has a natural appeal because it increases performance over First-Come First-Serve Scheduling. SCAN Scheduling and Circular SCAN Scheduling perform better for systems that place a heavy load on the disk, because they are less likely to cause a starvation problem. For any particular list of requests, we **can** define an optimal order of retrieval, but the computation needed to find an optimal schedule may not justify the savings over SSTF or SCAN. Because of the complexity involved with this topic, and the potential cost by choosing the wrong algorithm, the disk-scheduling algorithm should be a separate module of the OS, so it can be replaced if need be.

Requests for disk service can be greatly influenced by the file-allocation method. A program reading a contiguously allocated file will generate several requests that are close together on the disk, resulting in limited head movement. A linked or indexed file, in contrast, may include blocks that are widely scattered on the disk, resulting in greater head movement. The location of directories and index blocks is also important. Since every file must be opened to be used, and opening a file requires searching the directory structure, the directories will be accessed frequently.

9.4.1 First-Come First-Serve Scheduling

This version of *First-Come First-Serve Scheduling* is like all the others discussed earlier. The first disk seek request that comes into the queue is handled first, without regard to the distance the head must travel to find the requested data.

9.4.2 Shortest-Seek-Time-First Scheduling

Shortest-Seek-Time-First Scheduling services all the requests close to the current head position before moving the head far away to service other requests. This method selects the request with the least seek time from the current head position.

This is a variant of Shortest-Job-First Scheduling, and like that algorithm, this one can also experience Starvation.

9.4.3 SCAN Scheduling

SCAN Scheduling starts the disk arm at one end of the disk and moves toward the other end, servicing requests as it reaches each cylinder, until it gets to the other end of the disk. At the other end, the direction of head movement is reversed, and servicing continues on the way back. The head continuously scans back and forth across the disk.

9.4.3.1 Circular SCAN Scheduling *Circular SCAN* (*C-SCAN*) *Scheduling* is a variant of SCAN Scheduling designed to provide a more uniform wait time. Like SCAN, C-SCAN moves the head from one end of the disk to the other, servicing requests along the way. When the head reaches the other end, it immediately returns to the beginning of the disk without servicing any requests on the return trip. Essentially, this treats the cylinders as a circular list that wraps around from the final cylinder to the first.

9.4.4 LOOK Scheduling

LOOK Scheduling is a refinement of SCAN Scheduling and Circular SCAN Scheduling. Instead of going to one end of the disk and then going back, the head will only go as far as the last request before going back.

9.5 Disk Management

The OS handles many other aspects of the disks and their usage as well.

9.5.1 Formatting

There are 2 kinds of formatting:

1. Low-Level Formatting
2. High-Level Formatting

Most hard disks are low-level-formatted at the factory as a part of the manufacturing process. This enables the manufacturer to test the disk and to initialize the mapping from logical block numbers to defect-free sectors on the disk.

Defn 171 (Low-Level Formatting)**.** *Low-Level Formatting* or *Physical Formatting* is the process of dividing the sectors in the tracks on the platters. This fills each sector with a special data structure typically consisting of a header, a data area (usually 512 bytes), and a trailer. The header and trailer contain information used by the disk controller: a sector number and an error-correcting code.

The ECC contains enough information, if only a few bits of data have been corrupted, to enable the controller to identify which bits have changed and calculate what their correct values should be. It then reports a recoverable soft error. The controller automatically does the ECC processing whenever a sector is read or written.

It is usually possible to choose among a few data sizes, such as 256, 512, and 1,024 bytes. Formatting a disk with a larger sector size means that fewer sectors can fit on each track; but it also means that fewer headers and trailers are written on each track and more space is available for user data. Operating Systems may not support sizes other than a sector size of 512 bytes.

Defn 172 (High-Level Formatting)**.** *High-Level Formatting* or *Logical Formatting* is the process an operating system goes through to partition the disk into groups of cylinders and put a file system onto these partitions. Each partition can be logically viewed as a separate disk, which can have its own file system. This stores the initial file system data structures, which can include maps of free and allocated storage and an initial empty directory.

To increase efficiency, most File Systems group blocks together into larger chunks, frequently called clusters. Disk I/O is done via blocks, but file system I/O is done via clusters.

Sometimes we want to use a disk partition just as a large sequential array of logical blocks, without any structure. This array is called a raw disk, and I/O to this array is termed raw I/O. Because there are no structures, and hence no file syste, raw I/O bypasses all file-system services, such as the buffer cache, file locking, prefetching, space allocation, file names, and directories.

9.5.2 Boot Block

A computer requires a bootstrap program that starts the computer when it is given a power-on command. The first part of this involves starting the CPU from a cold, unpowered, state and initializing it and putting the Kernel into memory.

The bootstrap program lives in ROM, on the motherboard itself. Because it is ROM, the CPU always knows where to find it, and the program stored there is protected from infection. This program is just step one of 2 for booting, and is reponsible for finding the code for step 2. It looks for and brings in the Bootloader from disk. At this point, there are no device drivers, because those are provided by the Kernel.

The Bootloader can be changed easily, as it is on read-write storage. It is stored in the boot blocks at a fixed location on the disk. Its responsibility is to load the entire Operating System from a non-fixed location on-disk. A disk containing the boot blocks/boot partition is a boot disk or system disk.

9.5.3 Bad Blocks

Frequently, one or more sectors become defective. Most disks even come from the factory with bad blocks. Depending on the disk and controller in use, these blocks are handled in a variety of ways.

However, there are 2 common ways to handle this problem:

1. Manually handling the blocks when they go bad. Any bad blocks that are discovered are flagged as unusable so that the file system does not allocate them. If blocks go bad during normal operation, a special program must be run manually to search for the bad blocks and to lock them away. Data that resided on the bad blocks usually is lost.
2. **Sector Sparing** or **Forwarding** has the disk manage these blocks itself. The controller maintains a list of bad blocks on the disk. The list is initialized during the low-level formatting at the factory and is updated over the life of the disk. Low-level formatting also sets aside spare sectors not visible to the operating system. The controller can be told to replace each bad sector logically with one of the spare sectors.

Such a redirection by the controller could invalidate any optimization by the operating system's disk-scheduling algorithm! For this reason, most disks are formatted with a few spare sectors in each cylinder and spare cylinders. When a bad block is remapped, the controller uses a spare sector from the same cylinder, if possible.

A special kind of sector sparing is **Sector Slipping**. In this case, if a block goes bad, to move the data off the failing sector, each sector is "slipped". This means that one of last blocks goes onto one of the spares, then each previous block is slipped into the current one. Thus, if block i goes bad, and s is the first spare block, then blocks $i + 1$ through $s - 1$ are slipped one sector towards s. Once all those blocks are slipped down, the data on block i is slipped to $i + 1$ and the known bad block i is marked as unusable.

9.6 Swap-Space Management

Swap-space management is another low-level task of the Operating System. Swapping occurs when the amount of physical memory reaches a critically low point and Processes are moved from memory to swap space to free available Physical Memory. Virtual Memory uses disk space as an extension of main memory.

Most systems combine swapping with virtual memory techniques and swap pages, not necessarily entire processes. In addition, most swapping systems only swap Anonymous Memory. "Swapping" and "Paging" are used interchangeably now.

Since disk access is much slower than memory access, using swap space significantly decreases system performance. The main goal for the design and implementation of swap space is to provide the best throughput for the virtual memory system.

Each swap area consists of a series of page-sized slots, which are used to hold swapped pages. Associated with each swap area is a *swap map*, which is an array of integer counters, each corresponding to a page slot in the swap area.

- If the value of a counter is 0, the corresponding page slot is available.
- Values greater than 0 indicate that the page slot is occupied by a swapped page, where the value of the counter indicates the number of mappings to the swapped page.

9.6.1 Swap-Space Usage

The amount of swap space needed on a system can vary depending on the amount of Physical Memory, the amount of Virtual Memory it is backing, and the way in which the virtual memory is used.

It is safer to overestimate than to underestimate the amount of swap space required, because if a system runs out of swap space it may be forced to abort Processes or may crash entirely. Overestimation wastes disk space that could otherwise be used for Files, but it does no other harm.

Some Operating Systems allow the use of multiple swap spaces, including both swap files and swap partitions. These are usually placed on separate disks so that the load placed on the I/O system by Paging and Swapping can be spread over the system's I/O bandwidth.

9.6.2 Swap-Space Location

A swap space can reside in one of two places:

1. It can be carved out of the normal file system, a Swap File.
2. It can be in a separate disk partition, a Swap Partition.

9.6.2.1 Swap File If the swap space is simply a large file within the file system, normal file-system routines can be used to create it, name it, and allocate its space. This approach is easy to implement, but inefficient. External Fragmentation can greatly increase Swapping times by forcing multiple seeks during reading or writing of memory contents.

9.6.2.2 Swap Partition Swap space can be created in a **separate raw** partition. No file system or directory structure is placed in this space. Instead, a separate swap-space storage manager is used to allocate and deallocate the blocks from the raw partition.

This manager allows the use of algorithms optimized for speed rather than for storage efficiency, because swap space is accessed much more frequently than file systems. Internal Fragmentation may increase, but this trade-off is acceptable because the life of data in the swap space generally is much shorter than that of files in the file system. In addition, swap space is reinitialized at boot time, so any fragmentation is short-lived.

However, adding more swap space requires either repartitioning the disk (which involves moving the other file-system partitions or destroying them and restoring them from backup) or adding another swap space elsewhere.

9.7 RAID Structure

Having a large number of disks in a system presents opportunities for improving the rate at which data can be read or written, if the disks are operated in parallel. It also offers the potential for improving the reliability of data storage, because redundant information can be stored on multiple disks. Allowing the failure of one disk to prevent loss of data.

Defn 173 (RAID)**.** *RAID* (*Redundant Array of Independent Disks*) is a collection of disk-organization techniques. These allow multiple physically separate disks to be viewed by the Operating System as a single, larger, logical disk.

There are 2 main ways to implement support for RAID:

1. **Software RAID**. This relies on the Kernel and Operating System handling the disks for RAID functionality. This means that the RAID-ed disks cannot be used for booting, because the RAID modules are only loaded once the kernel is loaded.
2. **Hardware RAID**. There are 2 alternatives here.
   (a) RAID support is built into the hardware.
   (b) RAID support is not built into the hardware, and a separate RAID card must be used.

There are a variety of levels to RAID, each of which has different properties.

9.7.1 Reliability via Redundancy

If we store extra information that is not normally needed but that can be used in the event of failure of a disk to rebuild the lost information, we can greatly improve reliability. Thus, even if a disk fails, data are not lost.

The simplest and most expensive approach to introducing redundancy is to duplicate the contents of every disk onto another. This technique is called mirroring. With mirroring, a logical volume consists of two physical disks, and every write is carried out on both disks simultaneously. The result is called a mirrored Volume. Data will be lost only if the second disk fails before the first failed disk is replaced.

However, power failures are a particular source of concern, since they occur far more frequently than natural disasters. Even with mirroring of disks, if writes are in progress to the same block in both disks, and power fails before both blocks are fully written, the two blocks can be in an inconsistent state. The usual solution is to add a write-cache, typically called solid-state nonvolatile RAM (NVRAM) to the RAID array. This write-back cache is protected from data loss during power failures, so the write can be considered complete when it is written to the cache, since even if there is a failure, no data is lost.

9.7.2 Performance via Parallelism

With disk mirroring, the rate at which **read** requests can be handled is doubled, since read requests can be sent to either disk (as long as both disks in a pair are functional). The **transfer** and **write** rate of each read is the same as in a single-disk system.

With multiple disks, we can improve the transfer rate by striping data across the disks. Data striping consists of splitting a unit of data across multiple disks. However, this also means that if any single disk were to fail, all data would be unrecoverable.

There are several types of striping that is possible:

- Bit-level Striping, where each bit of every byte is striped across the disks.
- Block-level striping, where blocks of a File are striped across the disks.
- Sector-level striping.
- etc.

The main goals of using striping in the parallel manner are:

1. Increase the throughput of multiple small accesses (page accesses) by load balancing.
2. Reduce the response time of large accesses.

9.7.3 RAID Levels

Numerous schemes to provide redundancy at lower cost by using disk striping combined with "parity" bits have been proposed. These schemes have different cost–performance trade-offs and are classified according to RAID levels.

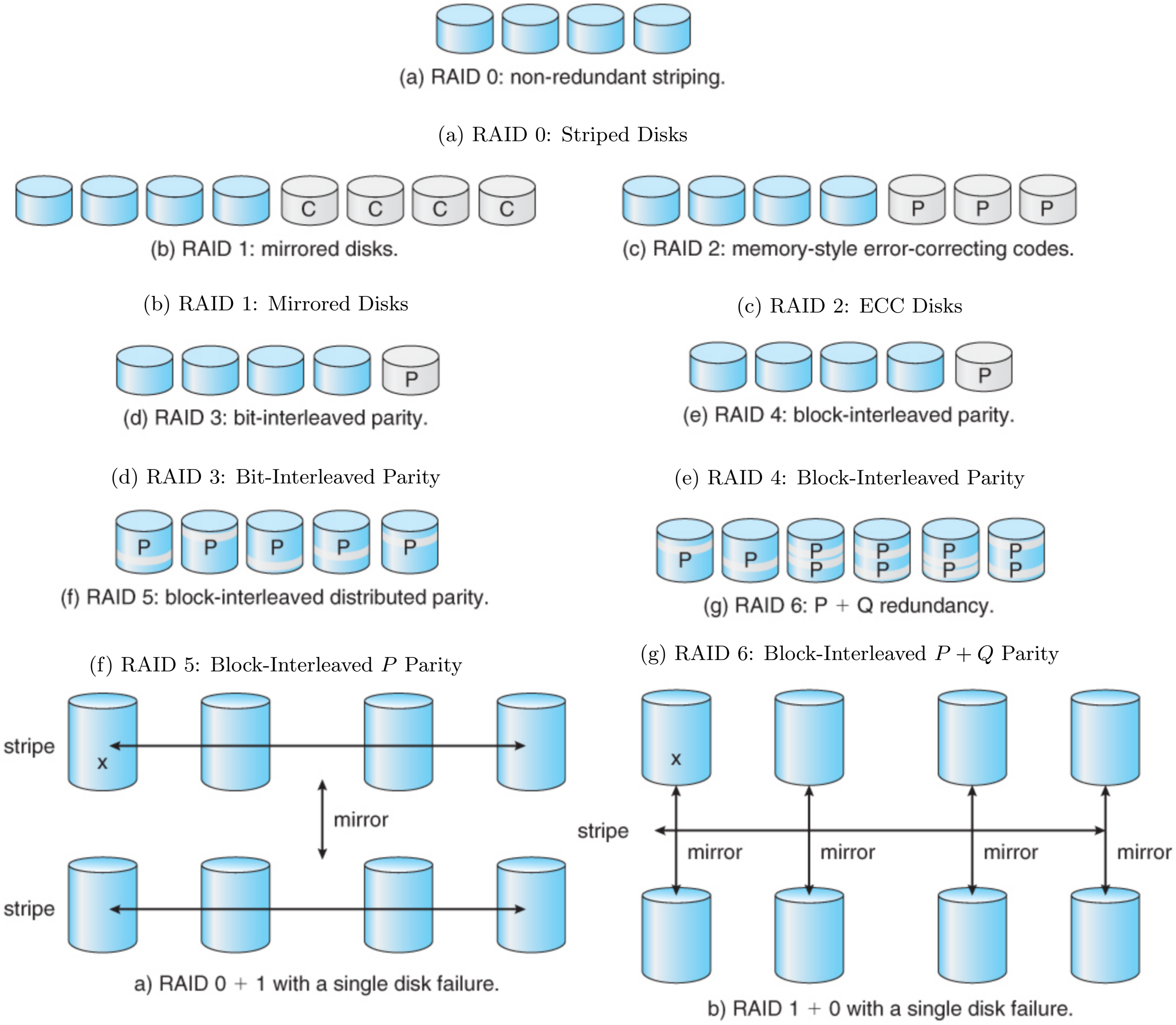
P indicate error-correcting bits and C indicates a copy of the data.

9.7.3.1 RAID 0 RAID level 0 refers to disk arrays with block striping without any redundancy.

Seen in Figure 9.2a.

9.7.3.2 RAID 1 RAID level 1 refers to full-disk mirroring.

Figure 9.2b shows a mirrored organization.


(a) RAID 0: non-redundant striping.
C
C
C
C
(b) RAID 1: mirrored disks.
P
P
P
(c) RAID 2: memory-style error-correcting codes.
P
(d) RAID 3: bit-interleaved parity.
P
(e) RAID 4: block-interleaved parity.
P
P
P
P
P
(f) RAID 5: block-interleaved distributed parity.
P
P
P
P
P
P
P
P
P
P
(g) RAID 6: P + Q redundancy.
stripe
x
mirror
stripe
a) RAID 0 + 1 with a single disk failure.
x
stripe
mirror
mirror
mirror
mirror
b) RAID 1 + 0 with a single disk failure.

(a) RAID 0: Striped Disks

(b) RAID 1: Mirrored Disks

(c) RAID 2: ECC Disks

(d) RAID 3: Bit-Interleaved Parity

(e) RAID 4: Block-Interleaved Parity

(f) RAID 5: Block-Interleaved P Parity

(g) RAID 6: Block-Interleaved $P + Q$ Parity

(h) RAID 01: Mirrored Stripes

(i) RAID 10: Striped Mirrors

Figure 9.2: RAID Levels

9.7.3.3 RAID 2 RAID level 2 is also known as memory-style error-correcting-code (ECC) organization. Each byte in a memory system may have a parity bit associated with it that records whether the number of bits in the byte set to 1 is even (parity = 0) or odd (parity = 1). If one of the bits in the byte is damaged (including the stored parity bit), the parity of the entire byte changes and thus does not match the stored parity. Thus, all single-bit errors are detected by the memory system. Error-correcting schemes store two or more extra bits and can reconstruct the data if any single bit is damaged. If one of the disks fails, the remaining bits of the byte and the associated error-correction bits can be read from other disks and used to reconstruct the damaged data.

Seen in Figure 9.2c.

9.7.3.4 RAID 3 RAID level 3, improves on RAID 2 by taking into account that disk controllers can detect whether a sector has been read correctly, so a single parity bit can be used for error correction as well as for detection. RAID level 3 has two advantages over level 1.

1. The storage overhead is reduced because only one parity disk is needed for several regular disks.
2. Reads/writes of a byte are spread out over multiple disks with N-way striping of data, the transfer rate for reading or writing a single block is N times as fast as with RAID 1.

On the negative side:

1. RAID level 3 supports fewer I/Os per second, since every disk has to participate in every I/O request.
2. The expense of computing and writing the parity is not minor.

Seen in Figure 9.2d.

9.7.3.5 RAID 4 RAID level 4 uses block-level striping, as in RAID 0 and keeps a parity block on a separate dedicated disk for corresponding blocks from N other disks. If one of the disks fails, the parity block can be used with the corresponding blocks from the other disks to restore the blocks of the failed disk.

A block read accesses only one disk, allowing other requests to be processed by the other disks. Thus, the data-transfer rate for each access is slower, but a higher overall I/O rate. The transfer rates for large reads are high, since multiple read accesses can proceed in parallel. Large writes also have high transfer rates, since the data and parity can be written in parallel. Small independent writes cannot be performed in parallel.

Seen in Figure 9.2e.

9.7.3.6 RAID 5 RAID level 5, or block-interleaved distributed parity, differs from RAID 4 in that it spreads data and parity among all $N + 1$ disks. For each block, one of the disks stores the parity and the others store data. A parity block cannot store parity for blocks in the same disk, because a disk failure would result in loss of data as well as of parity, making the loss recoverable. By spreading the parity across all the disks in the set, RAID 5 avoids potential overuse of a single parity disk, which can occur with RAID 4.

The data for the nth block in an array with D disks is stored on disk $(n \bmod D) + 1$.

Seen in Figure 9.2f.

9.7.3.7 RAID 6 RAID level 6 is similar to RAID 5 but stores more redundant information to guard against multiple disk failures. Instead of parity, error-correcting codes are used. 2 bits of redundant data are stored for every 4 bits of data allowing the system to tolerate two disk failures.

Seen in Figure 9.2g.

9.7.3.8 RAID 01 RAID 01 (read RAID zero-one) refers to a combination of RAID 0 and RAID 1. RAID 0 provides the performance, while RAID 1 provides the reliability. Generally, this level provides better performance than RAID 5. Unfortunately, it doubles the number of disks needed for storage, so it is also relatively expensive. A set of disks are striped, and then the stripe is mirrored to another, equivalent stripe.

Seen in Figure 9.2h.

9.7.3.9 RAID 10 RAID 10 (read RAID one-zero), mirrors disks into pairs, then the resulting mirrored pairs are striped.

Seen in Figure 9.2i.

9.7.4 Choosing a RAID Level

Some considerations are:

- Rebuild performance. If a disk fails, the time needed to rebuild its data can be significant. This may be an important factor if a continuous supply of data is required. Furthermore, rebuild performance influences the mean time to failure. RAID system designers and administrators of storage have to make several other decisions as well.

- The number of disks in a given RAID set.
- The number of bits that are protected by each parity bit. If more disks are in an array, data-transfer rates are higher, but the system is more expensive. If more bits are protected by a parity bit, the space overhead due to parity bits is lower, but the chance that a second disk will fail before the first failed disk is repaired is greater, and that will result in data loss.

9.8 Stable-Storage Implementation

Defn 174 (Stable-Storage)**.** *Stable-Storage* is a secondary storage medium where the data it contains is never lost.

To implement such storage, we need:

- To replicate the required information on multiple storage devices with independent failure modes.
- To coordinate the writing of updates in a way that guarantees that a failure during an update will not leave all the copies in a damaged state.
- When we are recovering from a failure, we can force all copies to a consistent and correct value, even if another failure occurs during the recovery.

When writing to disk in these circumstances, there are 3 possible outcomes:

1. **Successful Completion**. The data was written correctly on disk.
2. **Partial Failure**. A failure occurred during transfer, so only some of the sectors were written with the new data. The sector being written during the failure may have been corrupted.
3. **Total Failure**. The failure occurred before the disk write started, so the previous data values on the disk remain intact.

If a failure occurs **during** the writing of a block, the following steps must be followed:

1. Write the information onto the first physical block.
2. When the first write completes successfully, write the same information onto the second physical block.
3. Declare the operation complete only after the second write completes successfully.
4. During recovery from a failure, each pair of physical blocks is examined.
    - If both are the same and no detectable error exists, then no further action is necessary.
    - If one block contains a detectable error then we replace its contents with the value of the other block.
    - If neither block contains a detectable error, but the blocks differ in content, then we replace the content of the first block with that of the second.

Because waiting for disk writes to complete (synchronous I/O) is time consuming, many storage arrays add NVRAM as a cache. Since the storage is nonvolatile, it can be trusted to store the data en route to the disks. It is considered part of the stable storage. Writes to it are much faster than to magnetic disk, so performance is greatly improved.

10 File-System Interface

So that the computer system will be convenient to use, the Operating System provides a uniform logical view of stored information, the File.

Defn 175 (File)**.** The Operating System abstracts from the physical properties of its storage devices to define a logical storage unit, the *file*. A file is a named collection of related information that is recorded on secondary storage. In general, a file is a sequence of bits, bytes, lines, or records, the meaning of which is defined by the file's creator and user. The operating system maps files onto physical media and accesses these files via the storage devices.

From a user's perspective, a file is the smallest allotment of logical secondary storage; meaning, data cannot be written to secondary storage unless it is within a file.

Files in all Operating Systems have attributes that help describe them.

- **Name**. The symbolic file name is the only information kept in human-readable form.
- **Identifier**. This unique tag, usually a number, identifies the file within the file system; it is the non-human-readable name for the file.
- **Type**. This information is needed for systems that support different types of files.
- **Location**. This information is a pointer to a device and to the location of the file on that device.
- **Size**. The current size of the file and possibly the maximum allowed size are included in this attribute.
- **Protection**. Access-control information determines who can do reading, writing, executing, etc.

- **Time, date, and user identification**. This information may be kept for creation, last modification, and last use. This data can be useful for protection, security, and usage monitoring.

The information about all files is kept in the directory structure, which is also on secondary storage. An entry in a directory consists of the file's name and its unique identifier. The file's identifier in turn locates the other file attributes. It may take more than a kilobyte to record this information for each file. Because directories must also be nonvolatile, they must be stored on the device and brought into memory as needed.

10.1 File Operations

A file is an abstract data type, as such, to define a file properly, we need to consider the operations that can be performed on files.

The typically defined ones are:

- **Creating a file**. Two steps are necessary to create a file. First, space in the file system must be found for the file. Second, an entry for the new file must be made in the directory.
- **Writing a file**. To write a file, we make a system call specifying both the name of the file and the information to be written to the file. Given the name of the file, the system searches the directory to find the file's location. The system must keep a write pointer to the location in the file where the next write is to take place. The write pointer must be updated whenever a write occurs.
- **Reading a file**. To read from a file, we use a system call that specifies the name of the file and where (in memory) the next block of the file should be put. Again, the directory is searched for the associated entry, and the system needs to keep a read pointer to the location in the file where the next read is to take place. Once the read has taken place, the read pointer is updated.
  Usually, a shared pointer per-process for reading and writing is used, marking the current operation location. Both the read and write operations use this same pointer, saving space and reducing system complexity.
- **Repositioning within a file**. The directory is searched for the appropriate entry, and the appropriate pointer is repositioned to a given value. Repositioning within a file need not involve any actual I/O, if the area of the file is already in memory. This is also known as a file seek.
- **Deleting a file**. To delete a file, we search the directory for the named file. Having found the associated directory entry, we release all file space, so that it can be reused by other files, and erase the directory entry.
- **Truncating a file**. The user may want to erase the contents of a file but keep its attributes. Rather than forcing the user to delete the file and then recreate it, this function allows all attributes to remain unchanged (except for file length) but lets the file be reset to length zero and its file space released.

These 6 basic operations can be combined for copying a file, renaming a file, appending to a file, etc. `create()` and `delete()` are System Calls that work with closed rather than open files.

Because we would need to search the current directory for the file entry associated with the file, we `open()` files to memory first. The operating system keeps a table, called the open-file table, containing information about all open files. When a file operation is requested, the file is specified via an index into this table, so no searching is required. When the file is no longer being actively used, it is closed by the process, and the operating system removes its entry from the open-file table. The `open()` system call typically returns a pointer to the entry in the open-file table, called a *file descriptor*. This pointer is used in **all** I/O operations, avoiding further searching and simplifying the System Call interface.

Remark. The process of opening a file can be implicit when the first reference is made, but it is usually explicit.

The implementation of the `open()` and `close()` operations is more complicated in an environment where several processes may open the file simultaneously. Typically, the Operating System uses two internal tables:

1. A per-process table.
   - Contains process-dependent information, such as:
     - File pointer. On systems that do not include a file offset as part of the `read()` and `write()` System Calls, the system must track the last read/write location with a current-file-position pointer. This pointer is unique to each process operating on the file.
     - Access rights. Each process opens a file in an access mode. This information is used to allow or deny subsequent I/O requests.
   - This table tracks **all** files that any given Process has open.
   - Stored in this table is information regarding **this** Process's use of the File.
   - Each entry in the per-process table **points** to an entry in the system-wide open-file table.
2. A system-wide table.
   - Contains process-independent information, such as:

    - Location of file on disk. Most file operations require the system to modify data within the file. The information needed to locate the file on disk is kept in memory so that the system does not have to read it from disk for each operation.
    - Access dates.
    - File size.
- Once a file has been opened by one process, the system-wide table includes an entry for the file.
- When another process executes an `open()` call, the process receives a pointer back to the entry in the system-wide table.
- The table also has an open count associated with each file to indicate how many processes have the file open.
- Each `close()` decreases this open count, and when the open count reaches zero, the file is no longer in use, allowing the removal of that file's entry from the open-file table.

Some Operating Systems allows Processes to lock an open file, or sections of it.

Defn 176 (File Lock)**.** A *File lock* allows one Process to lock a File and prevent other processes from gaining access to it making them useful for files that are shared by several processes. File locks provide functionality similar to Read/Write Locks.

There are 2 kinds of file locks:

1. A **Shared Lock** is akin to a reader lock in that several processes can acquire the lock concurrently, but none of the lock holders can modify the file.
2. An **Exclusive Lock** behaves like a writer lock; only one process at a time can acquire such a lock, and it must be released by the owner.

Remark 176.1 (OS Support for File Locks)*.* Not all operating systems provide both types of locks (Shared and Exclusive). Some systems only provide exclusive file locking.

In addition, there are 2 types of file-locking **MECHANISM**s:

1. **Mandatory File-Locking** uses the Operating System to ensure lock integrity. If a lock is mandatory, then once a process acquires an exclusive lock, the operating system will prevent any other process from accessing the locked file.
2. **Advisory File-Locking** requires developers to ensure that locks are appropriately acquired and released. If the lock is advisory, then the operating system will not stop a Process from acquiring access to a file. Instead, the process must be written so that it manually acquires the lock before accessing the file.

Remark 176.2 (Problems with File Locks)*.* The use of File Locks requires the same precautions as Process Process/Thread Synchronization. Mandatory locking means that we must be careful to hold the exclusive file lock only while they are needed. Otherwise, they will prevent other Processes from accessing the file as well. Also, some special measures must be taken to ensure that two or more processes do not become involved in a Deadlock while trying to acquire file locks.

10.2 File Types

We need to decide whether the operating system should recognize and support File types. If an operating system recognizes the type of a file, it can then operate on the file in reasonable ways.

A common technique for implementing File types is to include the type as part of the file name. The name is split into two parts: the name and the extension, which are separated by a period. This way, the user **and** the operating system can tell from the name alone what the type of a file is.

The system uses the extension to indicate the type of the File and the type of operations that can be done on that file. Application programs also use extensions to indicate file types in which they are interested. These extensions are not always required, so a user may specify a file without the extension, and the application will look for a file with the given name perhaps with the extension it expects. Because these extensions are not supported by the operating system, they should be viewed as "hints" to the applications that operate on them. Sometimes, the program that created the file is also stored with the File Attributes or the file's metadata. In that case, the program needed to open the file does not need to be guessed.

The UNIX system uses a crude *magic number* stored at the beginning of some Files to indicate roughly the type of the file. Not all files have magic numbers, so system features cannot be based solely on this information. UNIX also does not record the name of the creating program. UNIX does allow file-name-extension **hints**, but they are not enforced or depended upon by the operating system. They are meant to aid users in determining what type of contents the file contains. Extensions can be used or ignored by a given application, but that is up to the application's programmer.

10.3 File Structure

File types can also indicate the internal structure of the file. This point brings us to one of the disadvantages of having the operating system support multiple file structures: the resulting size of the operating system is cumbersome. If the operating system defines five different file structures, it needs to contain the code to support these file structures.

Some operating systems impose (and support) a minimal number of file structures. UNIX considers each file to be a sequence of bytes; no interpretation of these bits is made by the **Operating System**. Each application program must include its own code to interpret an input file as to the appropriate structure. This scheme provides maximum flexibility but little support. All operating systems must support at least one structure, the executable file, so that the system is able to load and run programs.

10.3.1 Internal File Structure

Locating an offset within a file can be complicated for the operating system. Disk systems typically have a well-defined block size determined by the size of a sector. All disk I/O is performed in units of one block (physical record), and all blocks are the same size. It is unlikely that the physical record size will exactly match the length of the desired logical record. Because UNIX defines all files to be streams of bytes, each byte can be individually addressed by its offset from the beginning (or end) of the file. In this case, the logical record size is 1 byte. Logical records may vary in length. Packing a number of logical records into physical blocks is a common solution to this problem.

The logical record size, physical block size, and packing technique determine how many logical records are in each physical block. The packing can be done either by the user's application program or by the operating system. In either case, the file may be considered a sequence of blocks.

Because disk space is always allocated in blocks, some portion of the last block of each file is generally wasted. The waste incurred to keep everything in units of blocks (instead of bytes) is Internal Fragmentation. All File Systems suffer from internal fragmentation; the larger the block size, the greater the internal fragmentation.

10.4 Access Methods

Files store information. When they are used, this information must be accessed and read into computer memory. The 2 main ways to access the content of a file are:

1. Sequential Access
2. Direct Access

Not all operating systems support both Sequential Access and Direct Access for files. Some systems allow only sequential file access; others allow only direct access. Some systems require that a file be defined as sequential or direct when it is created. Such a file can be accessed only in a manner consistent with its declaration.

10.4.1 Sequential Access

Information in the file is processed in order, one logical record after the other. This mode of access is by far the most common.

Reads and writes make up the bulk of the operations on a file. A read operation reads the next portion of the file and automatically advances a file pointer, tracking the I/O location. Similarly, the write operation, appends to the end of the file and advances to the end of the newly written material (the new end of file).

The pointers in this file can be reset to the beginning, and on some systems, a program may be able to skip forward or backward n records for some integer n—perhaps only for $n = 1$. Sequential access is based on a tape model of a file and works as well on sequential-access devices as it does on random-access ones.

10.4.2 Direct Access

Another method is direct access (or relative access). In this method, a file is made up of fixed-length logical records that allow programs to read and write records rapidly in no particular order. The direct-access method is based on a disk model of a file.

For direct access, the file is viewed as a numbered sequence of blocks or records. There are no restrictions on the order of reading or writing for a direct-access file. Direct-access files are of great use for immediate access to large amounts of information.

The block number provided by the user to the operating system is normally a relative block number. A relative block number is an index relative to the beginning of the file, starting at 0 for the first block. The first relative block of the file is 0, even though the absolute disk address may be 14703 for the first block. The use of relative block numbers allows the operating system to decide where the file should be placed (called the Allocation Problem).

10.5 Directory and Disk Structure

Each Volume that contains a File System must also contain information about the Files in the system. This information is kept in entries in a device directory (A volume's Table of Contents). The device directory (commonly, the Directory) records information—such as name, location, size, and type—for all files on that volume.

Defn 177 (Volume)**.** A *Volume* is a logical view of the installed disks. Any entity that contains a File System is considered a volume. In the case of a RAID setup, when members are pooled together, they are collectively addressed as a single volume.

10.5.1 Storage Structure

A general-purpose computer system has multiple storage devices, and those devices can be sliced up into Volumes that hold File Systems. Computer systems may have zero or more file systems, and the file systems may be of varying types.

The file systems of computers can be extensive. Even within a file system, it is useful to segregate files into groups and manage and act on those groups. This organization involves the use of directories.

10.5.2 Directory Overview

Defn 178 (Directory)**.** The directory can be viewed as a symbol table that translates file names into their directory entries. Directories are files that are responsible for tracking and holding other files, which themselves may be directories.

The directory itself can be organized in many ways. The organization must allow us to insert entries, to delete entries, to search for a named entry, and to list all the entries in the directory.

Like a File, a Directory can be seen as an abstract data type that needs its computations defined before being concrete.

- **Search for a file**. We need to be able to search a directory structure to find the entry for a particular file. Since files have symbolic names, and similar names may indicate a relationship among files, we may want to be able to find all files whose names match a particular pattern.
- **Create a file**. New files need to be created and added to the directory.
- **Delete a file**. When a file is no longer needed, we want to be able to remove it from the directory.
- **List a directory**. We need to be able to list the files in a directory and the contents of the directory entry for each file in the list.
- **Rename a file**. Because the name of a file represents its contents to its users, we must be able to change the name when the contents or use of the file changes. Renaming a file may also allow its position within the directory structure to be changed.
- **Traverse the file system**. We may wish to access every directory and every file within a directory structure. For reliability, it is a good idea to backup the contents and structure of the entire file system at regular intervals.

10.5.3 Single-Level Directory

All files are contained in the same directory, which is easy to support and understand.

However, there are significant limitations.

- When the number of files increases or when the system has more than one user.
- Since all files are in the same directory, they must have unique names.
- If two users call their data file the same thing, then the unique-name rule is violated.

10.5.4 Two-Level Directory

The standard solution is to create a separate directory for each user. In the two-level directory structure, each user has their own User File Directory (UFD). The UFDs have similar structures, but each lists only the files of a **single** user. When a user job starts or a user logs in, the system's Master File Directory (MFD) is searched for that user's UFD. The MFD is indexed by user name or account number, and each entry points to the UFD for that user.

- When a user refers to a particular file, only their own UFD is searched. Allowing different users to have files with the same name, as long as all the file names within each UFD are unique.
- To create a file for a user, the operating system searches only that user's UFD to ascertain whether another file of that name exists.
- To delete a file, the operating system confines its search to the local UFD. Preventing the accidental deletion of another user's file that has the same name.

The user directories themselves must be created and deleted as necessary. A special system program can be run with the appropriate user name and account information. The program creates a new UFD and adds an entry for it to the MFD.

However, this structure effectively isolates one user from another. Isolation is a disadvantage when the users want to cooperate on some task and to access one another's files. Some systems simply do not allow local user files to be accessed by other users, requiring a dedicated shared space. If access is to be permitted, one user must have the ability to name a file in another user's directory. To name a particular file uniquely in a two-level directory, we must give both the user name and the file name.

Defn 179 (Path Name)**.** A *path name* is the list of directories and their names that must traversed before finally arriving at a file. Every file **MUST** have a path name to be identified. Note that there is no requirement for every file to have a **UNIQUE** path name.

For example, `/etc/fstab` on UNIX-based machines.

There are Absolute Path Names and Relative Path Names. An absolute path name begins at the root and follows a path down to the specified file, giving the directory names on the path. A relative path name defines a path from the current directory.

Remark 179.1 (Path Names with Volumes)*.* Additional syntax is needed to specify the Volume of a file.

A special instance of this situation occurs with the shared system files. Programs provided as part of the system (loaders, assemblers, compilers, utility routines, libraries, etc.) are generally defined as Files. When the appropriate commands are given, these files are read by the loader and executed. Many command interpreters simply treat such a command as the name of a file to load and execute.

The standard solution is to complicate the search procedure slightly. A special user directory is defined to contain the system files. Whenever a file name is given to be loaded, the operating system first searches the local UFD. If the file is found, it is used. If it is not found, the system automatically searches the special user directory that contains the system files.

Defn 180 (Search Path)**.** The sequence of directories searched when a file is named is called the *search path.* The search path can be extended to contain an unlimited list of directories to search when a command name is given. Systems can also be designed so that each user has their own search path.

10.5.5 Tree-Structured Directory

The natural generalization of the Two-Level Directory is to extend the directory structure to a tree of arbitrary height. This generalization allows users to create their own subdirectories and to organize their files accordingly. The tree has a root directory, and every file in the system has a unique Path Name.

A directory contains a set of files and/or subdirectories. A directory is another file, but treated in a special way. All directories have the same internal format. One bit in each directory entry defines the entry as a file (0) or as a subdirectory (1), a crude magic number. Special System Calls are used to create and delete directories.

In normal use, each process has a current directory. The current directory should contain most of the files that are of current interest to the process. When reference is made to a file, the current directory is searched. If a file is needed that is not in the current directory, then the user usually must either specify a path name or change the current directory to be the directory holding that file.

The initial current directory of a user's login shell is designated when the user job starts or the user logs in. The operating system searches the accounting file to find an entry for this user. In the accounting file is a pointer to (or the name of) the user's initial directory. This pointer is copied to a local variable for this user that specifies the user's initial current directory. From there, other processes can be spawned. The current directory of any subprocess is usually the current directory of the parent when it was spawned.

An interesting decision in this setup how to delete a directory.

- If a directory is empty, its entry in the directory that contains it can simply be deleted.
- If the directory is not empty (Some systems will not delete a directory unless it is empty), one of two approaches can be taken.
    1. the user must first delete all the files in that directory. If any subdirectories exist, this procedure must be applied recursively to them, so that they can be deleted also. This approach can result in a substantial amount of work.
    2. An alternative, such as that taken by the UNIX `rm` command, is to use an option. When a request is made to delete a directory, all that directory's files and subdirectories are also to be deleted.

With a tree-structured directory system, users can be allowed to access the files of other users. This can be done with either an absolute or a relative Path Name. It could also be done with one user changing their current directory.

10.5.6 Acyclic-Graph Directory

A tree structure prohibits the sharing of files or directories. An acyclic graph allows directories to share subdirectories and files. The same file or subdirectory may be in two different directories. The acyclic graph is a further generalization of the tree-structured directory scheme.

A shared file is not the same as two copies of the file.

- **Two copies**. Each programmer can view the copy rather than the original. But if one programmer changes the file, the changes will not appear in the other's copy.
- **Shared File**. Only one file exists, so any changes made by one person are immediately visible to the other.

A common way is to create a new directory entry called a link (soft-link or symlink on Linux). A link is effectively a pointer to another file or subdirectory. A link may be implemented as an absolute or a relative Path Name.

When a reference to a file is made, we search the directory. If the directory entry is marked as a link, then the name of the real file is included in the link information. We resolve the link by using that path name to locate the real file. Links are effectively indirect pointers. The operating system ignores these links when traversing directory trees to preserve the acyclic structure of the system.

An acyclic-graph directory structure is more flexible than a simple tree structure, but it is also more complex. Several problems must be considered carefully.

- A file may now have multiple absolute path names. We do not want to traverse shared structures more than once.
- When can the space allocated to a shared file be deallocated and reused? One possibility is to just remove the file, potentially leaving dangling pointers to the now-nonexistent file.
  Another is adding a reference count to the original file. Adding a new link or directory entry increments the reference count. Deleting a link or entry decrements the count. When the count is 0, the file can be deleted; there are no remaining references to it.

10.5.7 General Graph Directory

Simply adding new files and subdirectories to an existing tree-structured directory preserves the tree-structured nature. However, if we allow links to directories rather than just to files, the tree (and even acyclic graph) structure is destroyed, resulting in a simple graph structure

The primary advantage of an acyclic graph is the relative simplicity of the algorithms to traverse the graph and to determine when there are no more references to a file. We want to avoid traversing shared sections of an acyclic graph twice, mainly for performance reasons. If cycles are allowed to exist in the directory, we likewise want to avoid searching any component twice, for reasons of correctness as well as performance.

This anomaly results from the possibility of self-referencing (or a cycle) in the directory structure. In this case, we generally need to use a garbage collection scheme to determine when the last reference has been deleted and the disk space can be reallocated. Garbage collection involves traversing the entire file system, marking everything that can be accessed. Garbage collection is necessary only because of possible cycles in the graph. Thus, an Acyclic-Graph Directory is much easier to work with.

There are algorithms to detect cycles in graphs. However, they are computationally expensive, especially when the graph is on disk storage. A simpler algorithm in the special case of directories and links is to bypass links during directory traversal. Cycles are avoided, and no extra overhead is incurred.

10.6 File System Mounting

Just as a File must be opened before it is used, a File System must be mounted before it can be available to Processes on the system. Specifically, the directory structure may be built out of multiple Volumes, which must be mounted to make them available within the file-system name space.

Defn 181 (Mount Point)**.** A *mount point* is a location within the file structure where the file system will be attached.

The general steps to mount a File System are shown below. This scheme enables the Operating System to traverse its directory structure, switch among file systems (possibly of various types), as appropriate.

1. The operating system is given the name of the device and the Mount Point.
   - Some operating systems require that a file system type be provided when mounting; others inspect the structures of the device and determine the type of file system.
   - Typically, a mount point is an empty directory.
2. The operating system verifies that the device contains a valid File System.
   - It does so by asking the device driver to read the device directory and verifying that the directory has the expected format.
3. The operating system notes in its directory structure that a file system is mounted at the specified mount point.

Operating systems impose semantics on file system mounting to clarify functionality.

- What if a Directory already contains Files?
  - A system may disallow a mount over a directory that contains files.
  - A system may make the mounted file system available at that directory and obscure the directory's existing files until the file system is unmounted. When unmounting occurs, the use of the file system and allowing access to the original files in that directory.

- Can a File System be mounted multiple times at more than one Mount Point?
  - A system may allow the same file system to be mounted repeatedly, at different mount points.
  - A system may only allow one mount per file system.

10.7 File Sharing

File sharing is very desirable for users who want to collaborate and to reduce the effort required to achieve a computing goal. Therefore, user-oriented operating systems must accommodate the need to share files in spite of the inherent difficulties.

10.7.1 Multiple Users

Given a directory structure that allows files to be shared by users, the system must mediate the file sharing. The system can either allow a user to access the files of other users by default or require that a user specifically grant access to the files. To implement sharing and protection, the system must maintain more file and directory attributes than are needed on a single-user system. Typically, this involves recording the Owner and the Group to determine access.

This is discussed more in Section 10.8.

10.7.2 Remote File Systems

With the advent of networks, communication among remote computers became possible. Networking allows the sharing of resources spread over a distance. One obvious resource to share is data in the form of files.

There are 2 main methods for transferring files between computing systems.

1. Manual programs, like `ftp`. The World Wide Web falls into this category too.
2. Distributed File Systems. There are 2 main models and 1 main concern.
   (a) Client-Server Model.
   (b) Distributed Information Systems.

   (a) Failure Modes.

Defn 182 (Distributed File System)**.** A *Distributed File System* (*DFS*) is where remote directories are visible from a local machine, as if the file storage were directly attached to the computer.

10.7.2.1 Client-Server Model The machine containing the files is the server, and the machine seeking access to the files is the client. Generally, the server declares that a resource is available to clients and specifies exactly which resource and exactly which clients. A server can serve multiple clients, and a client can use multiple servers, depending on the implementation details of a given client–server facility.

Client identification is more difficult. A client can be specified by a network name or other identifier, such as an IP address, but these can be spoofed. More secure solutions include secure authentication of the client via encrypted keys. Unfortunately, with security come many challenges, including ensuring compatibility of the client and server and security of key exchanges.

10.7.2.2 Distributed Information Systems Distributed information systems, also known as distributed naming services, provide unified access to the information needed for remote computing. The Domain Name System (DNS) is one example of this type of information system.

Other distributed information systems provide user name/password/user ID/group ID space for a distributed facility. This allows all computer-related information to be tracked and stored in a single central place and information be shared out on an as-needed basis.

10.7.2.3 Failure Modes Local file systems can fail for a variety of reasons, including:

- Failure of the disk containing the file system.
- Corruption of the directory structure or other disk-management information (collectively called metadata).
- Disk-controller failure.
- Cable failure.
- Host-adapter failure.
- User failure can also cause files to be lost or entire directories or volumes to be deleted.
- System-Administrator can cause files to be lost or entire directories or volumes to be deleted.

Many of these failures will cause a host to crash and an error condition to be displayed, and human intervention will be required to repair the damage.

Remote file systems have even more failure modes. Because of the complexity of network systems and the required interactions between remote machines, many more problems can interfere with the proper operation of remote file systems.

For example, what would happen if the remote file system became no longer reachable? This scenario is rather common, so it would not be appropriate for the client system to act as it would if a local file system were lost. Instead, the system can either terminate all operations to the lost server or delay operations until the server is again reachable.

10.7.3 Consistency Semantics

Consistency semantics represent an important criterion for evaluating any file system that supports file sharing. These semantics specify how multiple users of a system are to access a shared file simultaneously.

Consistency semantics are directly related to Process Process/Thread Synchronization algorithms. However, those complex algorithms tend not to be implemented in the case of file I/O because of the great latencies and slow transfer rates of disks and networks.

For the following discussion, we assume that a series of file accesses attempted by a user to the same file is always enclosed between the `open()` and `close()` operations. The accesses between the `open()` and `close()` operations makes up a file session.

10.7.3.1 unix Semantics

UNIX uses the following consistency semantics:

- Writes to an open file by a user are visible immediately to other users who have this file open.
- UNIX had a mode of sharing that allows users to share the pointer of current location into the file. Thus, the advancing of the pointer by one user affects all sharing users. Here, a file has a single image that interleaves all accesses, regardless of their origin.

10.7.3.2 Immutable-Shared-Files Semantics

A unique approach is that of immutable shared files. Once a file is declared as shared by its creator, it cannot be modified. An immutable file has two key properties: its name may not be reused, and its contents may not be altered. Thus, the name of an immutable file signifies that the contents of the file are fixed. The implementation of these semantics in a distributed system is simple, because the sharing is disciplined.

10.8 Protection

When information is stored in a computer system, we want to keep it safe from improper access.

Most systems have evolved to use the concepts of file Owner and Group.

10.8.1 Types of Access

The need to protect files is a direct result of the ability to access files. Systems that do not permit access to the files of other users do not need protection. Protection mechanisms provide controlled access by limiting the types of file access that can be made. Access is permitted or denied depending on several factors, one of which is the type of access requested. Several different types of operations may be controlled:

- **Read**. Read from the file.
- **Write**. Write or rewrite the file.
- **Execute**. Load the file into memory and execute it.
- **Append**. Write new information at the end of the file.
- **Delete**. Delete the file and free its space for possible reuse.
- **List**. List the name and attributes of the file.

Other, higher-level, operations, such as renaming, copying, and editing the file, may also be controlled. For many systems, however, these functions may be implemented by a program that makes lower-level system calls. File protection is provided at only the lower level.

10.8.2 Access Control

The most common approach to the protection problem is to make access dependent on the identity of the user. Different users may need different types of access to a file or directory. The most general scheme to implement identity-dependent access is to associate with each file and directory an access-control list (ACL) specifying user names and the types of access allowed for each user. This allows for complex access methodologies, however:

- The ACL would get too long if we needed a rule for every possible user on the system.

- Constructing such a list may be a tedious and unrewarding task, especially if we do not know in advance the list of users in the system.
- The directory entry, previously of fixed size, now must be of variable size, resulting in more complicated space management.

Thus, the entries in the ACL are usually Owner, Group, and Universe.

Defn 183 (Owner)**.** The *owner* is the user who can change attributes and grant access and has the most control over the file. They are the creator of the file. The owner's User ID (UID) of a given File (or Directory) is stored with the other File Attributes.

Defn 184 (Group)**.** The *group* attribute defines a subset of users who can share access to the file and require similar access levels. The Group ID (GID) of a given File (or Directory) is stored with the other File Attributes.

Defn 185 (Universe)**.** The *universe* attribute are all other possible users in the system that are not already the Owner or part of the Group.

The most common recent approach is to combine access-control lists with the more general Owner/Group/Universe access-control scheme

For this scheme to work properly, permissions and access lists must be controlled tightly. This control can be accomplished in several ways. For example, in the UNIX system, Groups can be created and modified only by the manager of the facility (or by any superuser).

Another difficulty is assigning precedence when permission and ACLs conflict. Solaris gives ACLs precedence (as they are more fine-grained and are not assigned by default). This follows the general rule that specificity should have priority.

10.8.3 Other Protection Approaches

Another approach to the protection problem is to associate a password with each file.

- Advantages
  - If the passwords are chosen randomly and changed often, this scheme may be effective in limiting access to a file.
- Disadvantages
  - First, the number of passwords that a user needs to remember may become large, making the scheme impractical.
  - If only one password is used for all the files, then once it is discovered, all files are accessible; protection is on an all-or-none basis.
  - Some systems allow a user to associate a password with a directory, rather than with an individual file, to address this problem.

10.8.3.1 Directory Operations The directory operations that must be protected are somewhat different from the file operations. We want to control the creation and deletion of files in a directory. In addition, we probably want to control whether a user can determine the existence of a file in a directory. Sometimes, knowledge of the existence and name of a file is significant in itself; thus, listing the contents of a directory must be a protected operation. Similarly, if a path name refers to a file in a directory, the user must be allowed access to both the directory and the file. In systems where files may have numerous path names (such as acyclic and general graphs), a given user may have different access rights to a particular file, depending on the path name used.

11 File-System Implementation

To improve I/O efficiency, I/O transfers between memory and disk are performed in units of blocks. Each block has one or more sectors. Usually, the sector size is 512 bytes, but can vary from 32 bytes to 4,096 bytes.

Defn 186 (File System)**.** *File systems* provide efficient and convenient access to the disk by allowing data to be stored, located, and retrieved easily.

The *file system* (*filesystem*, *FS*) consists of two parts:

1. A collection of Files, each storing related data.
2. A directory structure, which organizes and provides information about all the files in the system.

A file system has two quite different design problems.

1. How the file system should look to the user.
   - This task involves defining a file and its attributes, the operations allowed on a file, and the directory structure for organizing files.
2. Creating algorithms and data structures to map the logical file system onto the physical secondary-storage devices.

11.1 File System Structure

The file system itself is generally composed of many different levels. The levels are listed below, from highest to lowest.

- Logical File System Module
- File Organization Module
- Basic File System Module
- I/O Control Module

Each level in the design uses the features of lower levels to create new features for use by higher levels. This layered structure is useful for minimizing the duplication of code. The I/O control and sometimes the basic file-system code can be used by multiple file systems. Each file system can then have its own logical file-system and file-organization modules. However, each layer introduces more overhead.

11.1.1 Logical File System Module

The logical file system manages Metadata information.

Defn 187 (Metadata)**.** *Metadata* includes all of the file-system structure except the actual data (or contents of the files).

The logical file system manages the directory structure to provide the file-organization module with the information it needs, when given a symbolic file name. It does this by maintaining file structure via File-Control Blocks.

Defn 188 (File-Control Block)**.** A *File-Control Block* (*FCB*) (inode in UNIX) contains information about the File, including ownership, permissions, and location of the file contents.

11.1.2 File Organization Module

The file-organization module knows about files and their logical blocks, as well as physical blocks. By knowing the type of file allocation used and the location of the file, the file-organization module can translate logical block addresses to physical block addresses for the basic file system to transfer.

This module also includes the free-space manager, which tracks unallocated blocks and provides these blocks to the file-organization module when requested.

11.1.3 Basic File System Module

The basic file system only issues generic commands to the appropriate device driver to read and write physical blocks on the disk. Each physical block is identified by its numeric disk address (Drive 1, Cylinder 73, Track 2, Sector 10). This layer also manages the memory buffers and caches that hold various file-system, directory, and data blocks. A block in the buffer is allocated before the transfer of a disk block can occur. When the buffer is full, the buffer manager must find more buffer memory or free up buffer space to allow a requested I/O to complete.

Caches are used to hold frequently used file-system metadata to improve performance, so managing their contents is critical for optimum system performance.

11.1.4 I/O Control Module

The I/O control level consists of device drivers and interrupt handlers to transfer information between the main memory and the disk system. Its input consists of high-level commands such as "retrieve block 123." Its output consists of low-level, hardware-specific instructions that are used by the hardware controller, which interfaces the I/O device to the rest of the system. The device driver writes specific bit patterns to special locations in the I/O controller's memory (likely using Memory Mapped I/O) to tell the controller which device location to act on and what actions to take.

11.2 File System Implementation

Several on-disk and in-memory structures are used to implement a File System. These structures vary depending on the operating system and the file system, but some general principles apply.

- Boot Control Block (per volume, if needed). Contains information needed by the system to boot an operating system from that volume. If the disk does not contain an operating system, this block can be empty. It is typically the first block of a volume.
  - In UFS, it is the boot block.
  - In NTFS, it is the boot sector.
- Volume Control Block (per volume). contains volume (or partition) details, such as:

  - Number of blocks in the partition,
  - Size of the blocks,
  - Free-block count
  - Free-block pointers
  - Free-File-Control Block count
  - FCB pointers

  - In UFS, this is called a superblock.
  - In NTFS, it is stored in the master file table.

- Directory Structure (per file system) is used to organize the files.
- Per-file File-Control Block. Contains many details about the file. It has a unique identifier number to allow association with a directory entry.

In-memory information is used for both file-system management and performance improvement via caching. The data is loaded at mount time, updated during file-system operations, and discarded at dismount.

- An in-memory mount table contains information about each mounted volume.
- An in-memory directory-structure cache holds the directory information of recently accessed directories. (For mount directories, it can contain a pointer to the volume table.)
- The system-wide open-file table has a copy of the FCB of each open file, as well as other information.
- The per-process open-file table contains a pointer to the appropriate entry in the system-wide open-file table, as well as process-dependent information.
- Buffers hold file-system blocks when they are being read from disk or written to disk.

11.2.1 File Creation

To create a new file, an application program calls the logical file system. The logical file system knows the format of the directory structures.

1. To create a new file, it allocates a new File-Control Block.
   - If the file-system implementation creates all FCBs at file-system creation time, an FCB is allocated from the set of free FCBs.
2. The system then reads the appropriate directory into memory, updates it with the new file name and FCB
3. Writes it back to the disk.

11.2.2 File Opening

Now that a file has been created, it can be used for I/O.

1. First, it must be opened. The `open()` call passes a file name to the logical file system.
2. The `open()` system call first searches the system-wide open-file table to see if the file is already in use by another process.
   - If it is, a per-process open-file table entry is created pointing to the existing system-wide open-file table.
     - This algorithm can save substantial overhead.
   - If the file is not already open, the directory structure is searched for the given file name.
     - Parts of the directory structure are usually cached in memory to speed directory operations.
3. Once the file is found, the FCB is copied into a system-wide open-file table in memory.
   - This table tracks the File-Control Block and the number of processes that have the file open.
4. An entry is made in the per-process open-file table, with a pointer to the entry in the system-wide open-file table and some other fields.
   - These other fields may include a pointer to the current location in the file (for the next `read()` or `write()` operation) and the access mode in which the file is open.
   - The `open()` call returns a pointer to the appropriate entry in the per-process file-system table.
   - All file operations are then performed via this pointer.
   - The file name may not be part of the open-file table, as the system has no use for it once the appropriate FCB is located on disk.
   - It could be cached, though, to save time on subsequent opens of the same file.
   - The name given to the entry varies.
   - UNIX systems refer to it as a file descriptor; Windows refers to it as a file handle.

5. When a process closes the file, the per-process table entry is removed, and the system-wide entry's open count is decremented.
6. When all users that have opened the file close it, any updated Metadata is copied back to the disk-based directory structure, and the system-wide open-file table entry is removed.

11.2.3 Partitions and Mounting

11.2.3.1 Raw Partitions Each partition can be either "raw," containing no file system, or "cooked," containing a file system. A raw disk is used where no file system is appropriate. UNIX swap space can use a raw partition, since it uses its own format on disk and does not use a file system.

11.2.3.2 Boot Partitions Boot information can be stored in a separate partition. Again, it has its own format, because at boot time the system does not have the file-system code loaded and cannot interpret the file-system format. Rather, boot information is usually a sequential series of blocks, loaded as an image into memory. Execution of the image starts at a predefined location.

This Bootloader in turn knows enough about the File System structure to be able to find and load the Kernel and start its execution. The bootloader can contain more than just the instructions required to boot a specific Operating System.

11.2.3.3 The Root Partition The root partition, which contains the Operating System Kernel and other system files, is mounted at boot. Other volumes can be automatically mounted at boot or manually mounted later.

As part of a successful mount operation, the operating system verifies that the device contains a valid file system. It does so by asking the device driver to read the device directory and verifying that the directory has the expected format. If the format is invalid, the partition must have its consistency checked and possibly corrected, either with or without user intervention. Finally, the operating system notes in its in-memory mount table that a file system is mounted, along with the type of the file system.

11.2.4 Virtual File Systems

Most operating systems, use object-oriented techniques to simplify, organize, and modularize the implementation of File Systems. The use of these methods allows very dissimilar file-system types to be implemented within the same structure, including network file systems. Data structures and procedures are used to isolate the basic System Call functionality from the implementation details. Thus, the file-system implementation consists of three major layers:

1. The File System interface, based on the `open()` , `read()` , `write()` , and `close()` calls and on file descriptors.
2. The Virtual File System layer.
3. The layer implementing the actual file-system type or the remote-file-system protocol.

Defn 189 (Virtual File System)**.** A *Virtual File System* (*VFS*) separates file-system-generic operations from their implementation. The VFS activates file-system-specific operations to handle local requests according to their file-system types.

Multiple VFS interface may coexist on the same machine, allowing transparent access to different types of file systems mounted locally. It provides a mechanism for uniquely representing a file throughout a network, the vnode.

The are four main object types defined by the Linux Virtual File System. For each of which, the VFS defines a set of operations that may be implemented.

1. The *inode object*, which represents an individual file
2. The *file object*, which represents an open file
3. The *superblock object*, which represents an entire file system
4. The *dentry object*, which represents an individual directory entry

Every object of one of these types contains a pointer to a function table. The function table lists the addresses of the actual functions that implement the defined operations for that particular object:

Defn 190 (vnode)**.** A *vnode* contains a numerical designator for a network-wide unique file.

Remark 190.1 (vnode vs. inode)*.* UNIX inodes are unique within only a **single** File System. This network-wide uniqueness is required for support of network file systems. The kernel maintains one vnode structure for each active node (File or Directory).

11.3 Directory Implementation

The selection of directory-allocation and directory-management algorithms significantly affects the efficiency, performance, and reliability of the file system.

11.3.1 Linear List

The simplest method of implementing a directory is to use a linear list of file names with pointers to the data blocks. This method is simple to program but time-consuming to execute.

- To create a new file, we must first **search** the directory to be sure that no existing file has the same name. Then, we add a new entry at the end of the directory.
- To delete a file, we **search** the directory for the named file and then release the space allocated to it.
- To reuse the directory entry, we can do one of several things:
  1. Mark the entry as unused (by assigning it a special name, or by including a used/unused bit).
  2. Attach it to a list of free directory entries.
  3. Copy the last entry in the directory into the freed location and to decrease the length of the directory.

The real disadvantage of a linear list of directory entries is that finding a file requires a linear search. Directory information is used frequently, and users will notice if access to it is slow.

We can alleviate this problem by using a modification of a linear list. A sorted list allows a binary search and decreases the average search time. However, the requirement that the list be kept sorted may complicate creating and deleting files, since we may have to move substantial amounts of directory information to maintain a sorted directory. An advantage of the sorted list is that a sorted directory listing can be produced without a separate sort step. A more sophisticated tree data structure, such as a balanced tree, might help here.

11.3.2 Hash Table

A linear list still stores the directory entries, but a hash data structure is also used to find a file. The hash table takes a value computed from the file name and returns a pointer to the file name in the linear list. Therefore, it can greatly decrease the directory search time. Insertion and deletion are also fairly straightforward, although some provision must be made for collisions—situations in which two file names hash to the same location.

The major difficulties with a hash table are its generally fixed size and the dependence of the hash function on that size. If we reach the hash table's maximum size and want to add a new file, we would have to rehash the whole table to a larger size.

One solution to this is to use a chained-overflow hash table. Each hash entry can be a linked list instead of an individual value, resolving collisions by adding the new entry to the linked list. Lookups may be slowed, because searching for a name might require stepping through a linked list of colliding table entries. Still, this method is likely to be much faster than a linear search through the entire directory.

11.4 File Allocation Methods

The direct-access nature of disks gives us flexibility in the implementation of files. In almost every case, many files are stored on the same disk. The main problem is how to allocate space to these files so that disk space is utilized effectively while allowing for quick access to files.

11.4.1 Contiguous File Allocation

Contiguous allocation requires that each file occupy a set of contiguous blocks on the disk. Disk addresses define a linear ordering on the disk.

Contiguous allocation of a file is defined by the disk address of the first block and length (in blocks). If the file is n blocks long and starts at location b, then it occupies blocks $b, b+1, \ldots, b+n-1$. The directory entry for each file indicates the address of the starting block and the length of the area allocated for this file.

11.4.1.1 Advantages of Contiguous Allocation Accessing a file that has been allocated contiguously is easy.

- **Sequential Access**. File System remembers the disk address of the last block referenced and reads the next block.
- **Direct Access** to block i of a file that starts at block b, we can immediately access block $b+i$.

11.4.1.2 Disadvantages of Contiguous Allocation However, this allocation methods has some problems. One difficulty is finding space for a new file. The system chosen to manage free space determines how this task is accomplished. This is another case of the Allocation Problem.

Defn 191 (Allocation Problem)**.** The *Allocation Problem* involves how to satisfy a request of size n from a list of free holes. If the holes are not organized, i.e. there are enough blocks but they are not contiguous, then the request cannot be serviced.

First-Fit and Best-Fit are the most common strategies used to select a free hole from the set of available holes, however, Worst-Fit is also possible. Simulations have shown that both first fit and best fit are more efficient than worst fit in terms of time and storage utilization. However, **all these algorithms** suffer from the problem of External Fragmentation. As files are allocated and deleted, the free disk space is broken into little pieces. External fragmentation exists whenever free space is broken into chunks. Fixing this problem is only solvable by garbage collection, in this case means moving all data to another disk then copying it back.

Another problem is determining how much space is needed for a file. When the file is created, the total amount of space it will need must be found and allocated.

- If we allocate too little space to a file, we may find that the file cannot be extended.
- If the total amount of space needed for a file is known in advance, preallocation may be inefficient.

To minimize these drawbacks, some operating systems use a modified contiguous-allocation scheme. Here, a contiguous chunk of space is allocated initially. Then, if that amount proves not to be large enough, another chunk of contiguous space, known as an Extent, is added. The location of a file's blocks is then recorded as a location and a block count, plus a link to the first block of the next extent.

Defn 192 (Extent)**.** An *extent* is used in a Contiguous File Allocation scheme, and is just another contiguous block(s) of storage that has been given to a file for use. Extents are allocated on an as-needed basis.

11.4.2 Linked File Allocation

Linked allocation solves all problems of Contiguous File Allocation (Paragraph 11.4.1.2). With linked allocation, each File is a linked list of disk blocks; the disk blocks may be scattered anywhere on the disk. The Directory contains a pointer to the first and last blocks of each file entry. Each block contains a pointer to the next block. These pointers are not made available to the user. Thus, if each block is 512 bytes in size, and a disk address (the pointer) requires 4 bytes, then the user sees blocks of 508 bytes.

To create a new File, we simply create a new entry in the Directory. With linked allocation, each directory entry has a pointer to the first disk block of the file, which is initialized to `null` (or the end-of-list pointer value), signifying an empty file. The size field is also set to 0. A subsequent `write()` to the file causes the free-space management system to find a free block, write to this new block, and link it to the end of the file. To read a file, we simply read blocks by following the pointers from block to block.

11.4.2.1 Advantages of Linked Allocation There is no External Fragmentation with linked allocation, and any free block on the free-space list can be used to satisfy a request. However, minor Internal Fragmentation can occur when a file's last block is only partly used; but there is little that can be done about that.

The size of a file need not be declared when the file is created. A file can continue to grow as long as free blocks are available. Consequently, it is never necessary to compact disk space.

11.4.2.2 Disadvantages of Linked Allocation The major problem is that it can be used effectively only for Sequential Access files. To find the ith block of a file, we must start at the beginning of that file and follow the pointers until we get to the ith block. Each access to a pointer requires a disk read, and some require a disk seek. Consequently, it is inefficient to support a Direct Access capability for linked-allocation files.

Another disadvantage is the space required for the pointers. If a pointer requires 4 bytes out of a 512-byte block, then 0.78 % percent of the disk is being used for pointers, rather than for information. Thus, each file requires slightly more blocks than it would otherwise. The usual solution to this problem is to collect blocks into multiples, called Clusters, and to allocate clusters rather than blocks. For instance, the file system may define a cluster as four blocks and operate on the disk only in cluster units. Then, the pointers use a much smaller percentage of the file's disk space.

Defn 193 (Cluster)**.** A *cluster* is a collection of blocks used in a Linked File Allocation scheme. Using a cluster in this scheme allows for more data to be addressed by a single pointer in the cluster. Meaning, the average utilization of the disk to other cluster pointers is minimized.

Using Clusters has the cost of increasing Internal Fragmentation, because more space is wasted when a cluster is partially full than when a block is partially full. Clusters can be used to improve the disk-access time for many other algorithms as well, so they are used in most file systems.

Another problem of linked allocation is reliability. Since files are linked together by pointers scattered all over the disk, consider what would happen if just a single file pointer were lost or damaged. A bug in the operating-system software or a disk hardware failure might result in picking up the wrong pointer. This error could in turn result in linking into the free-space list or into another file.

Some partial solutions are:

- Use doubly linked lists
- Store the file name and relative block number in each block.

However, these solutions require even more overhead for each file.

11.4.2.3 File-Allocation Table

File-Allocation Table (FAT) is a simple and efficient method of disk-space allocation that was used by the MS-DOS operating system. FAT is still commonly used today in external flash media, like flash drives.

In this system, there are 3 major disk components:

1. The Directory.
   - Contains one entry for every File in that directory, including subdirectories.
   - Stores the name and the starting block of the file.
   - May contain additional information about the file here too.
2. The File Allocation Table itself.
   - There is one entry in this table for **EACH** data block on this disk's File System.
   - The index of each entry corresponds to that same numbered block in the data blocks.
   - Each entry here **MAY** also contain a pointer to the next data block this file inhabits.
     - The maximum size of this pointer determines how big the biggest file may be.
     - In the original FAT, this pointer was 12 bytes.
     - In the more common FAT32, this pointer is 32 bytes, making the largest possible single file 4 GiB.
   - The existence of this block in this chain means this file **USES** these data blocks.
   - This table is small enough to be cached in memory for quick file lookups.
3. The Data blocks.
   - These are just the data blocks.
   - They are not cached in any way.
   - They are fetched when the Operating System traverses the FAT.

The use of the File Allocation Table to find a set of blocks on-disk is shown in Figure 11.1.

11.4.3 Indexed File Allocation

Indexed allocation solves the problem of pure Linked File Allocation by bringing all the pointers together into one location: the index block. In the absence of a File-Allocation Table, linked allocation cannot support efficient direct access. The pointers to the blocks are scattered with the blocks themselves all over the disk and must be retrieved in order. Linked allocation solves the External Fragmentation and size-declaration problems of Contiguous File Allocation.

Each file has its own index block, which is an array of disk-block addresses. The ith entry in the index block points to the ith block of the file. The directory contains the address of the index block. To find and read the ith block, we use the pointer in the ith index-block entry. This is similar to the Paging scheme discussed in Section 7.8.

When the file is created, all pointers in the index block are set to `null`. When the ith block is first written, a block is obtained from the free-space manager, and its address is put in the ith index-block entry.

11.4.3.1 Advantages of Indexed Allocation

Indexed allocation supports direct access, without suffering from External Fragmentation, because any free block on the disk can satisfy a request for more space.

11.4.3.2 Disadvantages of Indexed Allocation

Indexed-allocation schemes suffer from some of the same performance problems as does linked allocation. Specifically, the index blocks can be cached in memory, but the data blocks may be spread all over a volume.

Indexed allocation does still suffer from wasted space. The pointer overhead of the index block is generally greater than the pointer overhead of linked allocation. This is especially true when a file requires fewer blocks than an index block can address. This raises the question of how large the index block should be. Every file must have an index block, so we want the index block to be as small as possible. If the index block is **too** small, it will not be able to hold enough pointers for a large file.

To handle this, there are 3 common mechanisms:

1. **Linked scheme**.
   - An index block is normally one disk block. Thus, it can be read and written directly itself.
   - To allow for large files, link together several index blocks.
   - The last address-sized hole in the index block is `null` for small files, or is a pointer to another index block, for a large file.

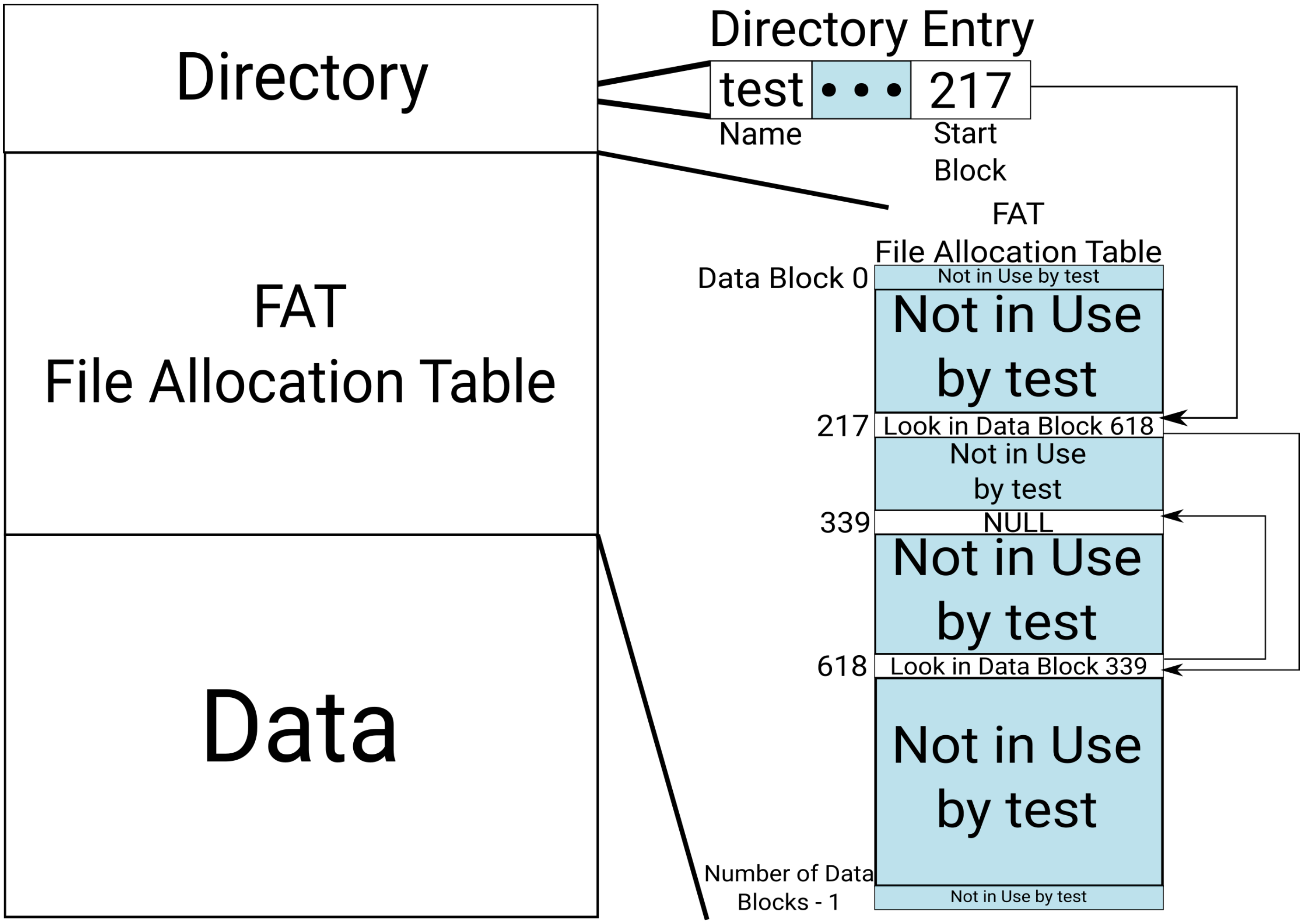


Figure 11.1: File Allocation Table

2. **Multilevel index**. A variant of linked representation uses a first-level index block to point to a set of second-level index blocks, which in turn point to the file blocks. To access a block, the operating system uses the first-level index to find a second-level index block and then uses that block to find the desired data block. This approach could be continued to a third or fourth level, depending on the desired maximum file size.
3. **Combined scheme**. This forms the basis of a UNIX UNIX `inode`.

11.4.3.3 unix `inode` The `inode` is used in UNIX-based file systems. The `inode` keeps the first 15 pointers of the index block in the `inode`.

- The `inode` does contain a little bit of data within itself.
- The first 12 of these pointers point directly to data blocks (they contain addresses of blocks that contain data of the file). Thus, the data for small files does not need a separate index block.
- The 13th points to a single indirect block.
  - This is an index block containing the addresses of blocks that contain data.
  - The redirection index block (the one from dereferencing the single indirect in the `inode`) can have as many pointer to data blocks as a block allows.
- The 14th points to a double indirect block, which contains the address of a block that contains the addresses of blocks that contain pointers to the actual data blocks.
  - Each of the redirection index blocks (the one from dereferencing an indirection) can have as many pointer to data blocks as a block allows.
- The last pointer contains the address of a triple indirect block.
  - Like the other indirect blocks, it must be dereferenced multiple times to get to the actual data.
  - Each of the redirection index blocks (the one from dereferencing an indirection) can have as many pointer to data blocks as a block allows.

A visualization of the UNIX `inode` is shown in Figure 11.2.

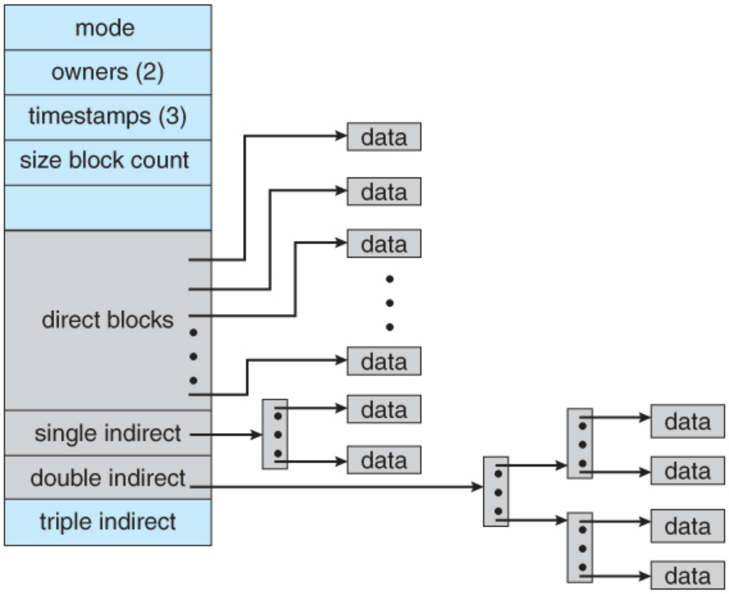


Figure 11.2: UNIX `inode`

As an illustration of the addressing power of the `inode`, **IN TERMS OF THE MAXIMUM SIZE OF A FILE IN**, the below equations are useful. First, we need to know the number of pointers possible in a single data block, seen in Equation (11.1).

$$\text{NPB} = \left\lfloor \frac{\text{Block Size}}{\text{Pointer Size}} \right\rfloor \tag{11.1}$$

Then, we have to find the size of each possible redirection.

$$\text{DBS} = \text{NDB} \times \text{Block Size} \tag{11.2a}$$

$$\text{SIPS} = \text{NSI} \times \text{NPB} \times \text{Block Size} \tag{11.2b}$$

$$\begin{aligned}\text{DIPS} &= \text{NDI} \times (\text{NPB} \times \text{NPB}) \times \text{Block Size} \\ &= \text{NDI} \times \text{NPB}^2 \times \text{Block Size}\end{aligned} \tag{11.2c}$$

$$\begin{aligned}\text{TIPS} &= \text{NTI} \times (\text{NPB} \times \text{NPB} \times \text{NPB}) \times \text{Block Size} \\ &= \text{NTI} \times \text{NPB}^3 \times \text{Block Size}\end{aligned} \tag{11.2d}$$

SIPS: Single Indirection Pointing Size. The maximum size of the blocks that the set of single indirection pointers can point to.

DIPS: Double Indirection Pointing Size. The maximum size of the blocks that the set of double indirection pointers can point to.

TIPS: Triple Indirection Pointing Size. The maximum size of the blocks that the set of triple indirection pointers can point to.

NDB: The number of Direct Pointers in the `inode`. In the UNIX definition of `inode`, this is 12.

NSB: The number of Single Indirection Pointers in the `inode`. In the UNIX definition of `inode`, this is 1 (**IF NEEDED**, otherwise NSI = 0).

NDI: The number of Double Indirection Pointers in the `inode`. In the UNIX definition of `inode`, this is 1 (**IF NEEDED**, otherwise NDI = 0).

NTI: The number of Triple Indirection Pointers in the `inode`. In the UNIX definition of `inode`, this is 1 (**IF NEEDED**, otherwise NTI = 0).

Lastly, we sum all the equations Equations (11.2a) to (11.2d) to get the maximum file size that a UNIX `inode` can handle, Equation (11.3).

$$\text{FS}_{\text{max}} = \text{SIPS} + \text{DIPS} + \text{TIPS} \tag{11.3}$$

11.4.4 Performance

The allocation methods that we have discussed vary in their storage efficiency and data-block access times. Both are important criteria in selecting the proper method or methods for an operating system to implement. Before selecting an allocation method, we need to determine how the systems will be used. A system with mostly sequential access should not use the same method as a system with mostly random access.

11.4.4.1 Contiguous Allocation Performance For any type of access, contiguous allocation requires only one access to get a disk block. We can keep the initial address of the file in memory and can immediately calculate the disk address of the ith block and read it.

11.4.4.2 Linked Allocation Performance For linked allocation, we can also keep the address of the next block in memory and read it directly. This method is fine for sequential access. For direct access, an access to the ith block might require i disk reads.

Some systems support direct-access files by using contiguous allocation **AND** sequential-access files by using linked allocation. For these systems, the type of access to be made must be declared when the file is created.

- A file created for sequential access will be linked and cannot be used for direct access.
- A file created for direct access will be contiguous and can support both direct access and sequential access, but its maximum length must be declared when it is created.

In this case, the operating system must have appropriate data structures and algorithms to support both allocation methods.

11.4.4.3 Indexed Allocation Performance If the index block is already in memory, then the access can be made directly. However, keeping the index block in memory requires considerable space.

If this memory space is not available, then we may have to read first the index block and then the desired data block. For a multi-level index, multiple index-block reads might be necessary. For an extremely large file, accessing a block near the end of the file would require reading in all the index blocks before the needed data block finally could be read. Thus, the performance of indexed allocation depends on the index structure, on the size of the file, and on the position of the block desired.

11.5 Free-Space Management

Since disk space is limited, we need to reuse the space from deleted files for new files, if possible. To keep track of free disk space, the system maintains a free-space list (which may not be implemented as a list). The free-space list records all free disk blocks—those not allocated to some file or directory. To create a file, we search the free-space list for the required amount of space and allocate that space to the new file. This space is then removed from the free-space list. When a file is deleted, its disk space is added back to the free-space list.

11.5.1 Bit Vector

Frequently, the free-space list is implemented as a bit map or bit vector. Each block is represented by 1 bit.

- If block **free**, the bit is 1.
- If block **allocated**, the bit is 0.

11.5.1.1 Advantages of Bit Vector The main advantages are:

- The relative **simplicity** in finding the first free block or n consecutive free blocks on the disk.
- The relative **efficiency** in finding the first free block or n consecutive free blocks on the disk.

11.5.1.2 Disadvantages of Bit Vector Bit vectors are inefficient unless the **entire** vector is kept in main memory. Keeping it in main memory is possible for smaller disks but not larger ones.

A 1.3 GiB disk with 512 byte blocks would need a bit map of over 332 KiB to track its free blocks. Clustering the blocks in groups of four (making a cluster 2048 bytes) reduces the bit vector size to around 83 KiB.

11.5.2 Linked List

Another approach to Free-Space Management is to link together all the free disk blocks, keeping a pointer to the first free block in a special location on the disk and caching it in memory. This first block contains a pointer to the next free disk block, and so on. The user is unable to see these free blocks.

This scheme is not efficient; to traverse the list, we must read each block, which requires substantial I/O time. However, traversing the free list is not a frequent action. Usually, the operating system simply needs a few free blocks so to allocate to a file.

11.5.2.1 File Allocation Table The File-Allocation Table method incorporates free-block accounting into the allocation table (which is already cached too). No separate method is needed.

11.5.3 Grouping

A modification of the Linked List approach mirrors the use of an Indexed File Allocation method. In this case, the first free block stores the addresses of the next $n-1$ free blocks. The last block contains the address of another free-block index. This way, a large number of free blocks can be found quickly.

11.5.4 Counting

Another method of tracking the free blocks mirrors the Contiguous File Allocation method with Extents. Generally, several contiguous blocks may be allocated or freed simultaneously, particularly when space is allocated with the contiguous-allocation algorithm or through Clustering. Rather than keeping a list of n free disk addresses, we can keep the address of the first free block and the number of contiguous blocks that are free that follow the first block. Each entry in the free-space list then consists of a disk address and a count. These entries can be stored in a balanced tree (or other structure), for efficient lookup, insertion, and deletion.

11.6 Efficiency and Performance

Disks are the major bottleneck in local system performance, since they are the slowest main computer component.

11.6.1 Efficiency

The efficient use of disk space depends on the disk-allocation and directory algorithms. For example, UNIX UNIX `inode`s are preallocated on and spread across the volume. Thus, even an empty disk has a percentage of its space lost to `inode`s. However, preallocating the `inode`s improves the File System's performance. This comes from the allocation and free-space algorithms, which try to keep a file's data blocks near that file's `inode` block to reduce seek time.

The Metadata normally kept in a File's Directory (or UNIX `inode`) entry also requires consideration. Normally, a "last write date" is recorded. Some systems also keep a "last access date", so that when the file was last read can be determined. The result of keeping this information is, whenever the file is read, a field in the directory must be written. This means the directory block must be read into memory, a changed, and written back out to disk, because operations on disks occur only in block (or Cluster) chunks.

Consider how efficiency is affected by the size of the pointers used to access data. Most Operating Systems use either 32-bit or 64-bit pointers throughout their code. Using 32-bit pointers for Files limits the size of a file to 2^{32}, or 4 GiB. Using 64-bit pointers allows very large file sizes, but require double the space to store.

11.6.2 Performance

Even after the basic file-system algorithms have been selected, we can still improve performance in several ways. Most disk controllers include an on-board cache large enough to store entire tracks at a time. When a seek is performed, the track is read into the disk's cache starting at the sector under the disk head (reducing latency time). The disk controller then transfers any sector requests to the operating system. Once blocks make it from the disk controller into main memory, the operating system may cache the blocks there.

11.6.2.1 Unified Virtual Memory Some systems cache file data using a Page Cache to create *Unified Virtual Memory*.

Defn 194 (Page Cache)**.** A *page cache* uses virtual memory techniques to cache file data as pages in a Paging system. They are cached as pages rather than as file-system blocks, meaning they have a Virtual Address Space. Caching file data using virtual addresses is far more efficient than caching through physical disk blocks, as accesses interface with Virtual Memory rather than the File System.

This can be done with a Unified Buffer Cache or without one. However, not using the unified buffer cache means you are Double Caching.

Defn 195 (Unified Buffer Cache)**.** A *Unified Buffer Cache* relies on using a Page Cache correctly, if it is used. Here, all I/O, whether done between Memory Mapped I/O or traditional I/O using `read()` and `write()` goes through the same buffer cache. This prevents the issue of Double Caching and allows for an even more general interface to I/O.

Defn 196 (Double Caching)**.** *Double Caching* is the process of caching the same piece of data twice. This may happen at the same tiem, or it may happen at different times (if something is moved **between** caches).

11.6.2.2 Synchronous/Asyncronous I/O Another issue that can affect the performance of I/O is whether writes to the file system occur synchronously or asynchronously.

- Synchronous writes occur in the order in which the disk subsystem receives them, and the writes are not buffered. Meaning, the calling routine **must** wait for the data to reach the disk drive before it can proceed.
- In an asynchronous write, the data is stored in the cache, and control returns to the caller.

Most writes are asynchronous. However, they can be made synchronous with a flag.

11.7 Recovery

Files and directories are kept both in main memory and on disk, and care must be taken to ensure that a system failure does not result in loss of data or in data inconsistency. A system crash can cause inconsistencies among on-disk file-system data structures, such as Directory structures, free-block pointers, and free File-Control Block pointers. Many file systems apply changes to these structures in place. These changes can be interrupted by a crash, and inconsistencies among the structures can result.

A typical operation, such as creating a file, can involve many structural changes within the File System on-disk. Compounding this is the caching that operating systems do to optimize I/O performance. Some changes may go directly to disk, while others may be cached. If the cached changes do not reach disk before a crash occurs, more corruption is possible.

11.7.1 Consistency Checking

A file system must first detect the problems and then correct them. For detection, a scan of all the Metadata on each file system can confirm or deny the consistency of the system. This scan can take minutes or hours and should occur **every time** the system boots.

Alternatively, a File System can record its state within the file-system metadata. Before any Metadata change, a status bit is set to indicate that the metadata is in-flux. If all changes to the metadata are successful, the file system can clear that bit. However, if the status bit remains set, a consistency checker is run.

The consistency checker (System Programs such as `fsck` in UNIX) compare the data in the directory structure with the data blocks on disk and **tries** to fix any inconsistencies it finds. The File Allocation Methods and Free-Space Management algorithms dictate what types of problems the checker can find and how successful it will be in fixing them.

11.7.2 Journaling

This is technically called a *Log-Based Transaction-Oriented File System*. However, most people today call them journaling file systems, so I went with that.

All Metadata changes are written sequentially to a log which is a circular buffer. Each set of operations for performing a specific task is a **transaction**. Once the changes are written to this log, they are considered a **committed transaction**, and the System Call will return to the user process, allowing it to continue execution. Meanwhile, these log entries are replayed, in the background, across the actual File System structures. As the changes are made, a pointer is updated to indicate which actions have completed and which are still incomplete. When a committed transaction is completed, it is removed from the log file.

The log may be in a separate section of the file system or a separate disk. It is more efficient, but more complex, to have it under separate read and write heads, thereby decreasing head contention and seek times.

If the system crashes, the log file will contain zero or more transactions. Any transactions it contains were not completed to the file system, so they must now be completed. The transactions can be executed from the pointer until the work is complete. The only problem occurs when a transaction was stopped before it was committed.

A side benefit of using logging on Metadata updates is that the updates proceed much faster than usual. The reason is the performance advantage of sequential I/O over random I/O. The costly synchronous on-demand random metadata writes are turned into less costly synchronous sequential writes to the journal. Those changes, in turn, are replayed asynchronously via random writes, in the background, to the appropriate structures. The overall result is a significant gain in performance of Metadata-oriented operations, such as file creation and deletion.

11.7.3 Other Solutions

Copy-on-Write for disks is starting to become a big thing now. This is quite similar to memory's Copy-on-Write functionality, just a different storage medium. When the updates are made on the disk in a physically separate location, asynchronously. Then the pointer to the original block is moved to the new one, synchronously. This way, if the data is committed to the disk correctly, the pointer is moved automatically, nearly without fail.

This allows for snapshots to be made.

11.7.4 Backup and Restore

Sometimes data from one disk is backed up to another storage device. This way if there is a catastrophic failure of the original, the secondary can restore what was lost.

12 I/O Systems

Because I/O devices vary so widely in their function and speed, varied methods are needed to control them. These methods form the I/O subsystem of the kernel, which separates the rest of the kernel from the complexities of managing I/O devices.

To encapsulate the details and oddities of different devices, the kernel of an operating system is structured to use Device Driver modules.

Defn 197 (Device Driver)**.** *Device Driver*s present a uniform device-access interface to the I/O subsystem. Every device requires a device driver (though certain devices can reuse another device's driver). The device driver hides the device-specific implementation details from the Operating System and I/O subsystem, and only showing a standard, uniform interface. The type of interface exported depends on the nature of the device itself.

This is analogous to System Calls providing a standard interface between the application and the Operating System.

Despite the incredible variety of I/O devices, though, we need only a few concepts to understand how the devices are attached and how the software can control the hardware.

12.1 I/O Hardware

The device communicates with the machine via a connection point, a port. If devices share a common set of wires, the connection is called a Bus. Buses are used widely in computer architecture and vary in their signaling methods, speed, throughput, and connection methods.

Defn 198 (Bus)**.** A *bus* is a set of wires and a rigidly defined protocol that specifies a set of messages that can be sent on the wires.

When device A plugs into device B, and device B plugs into device C, and device C plugs into a port on the computer, this arrangement is called a daisy chain. A daisy chain usually operates as a Bus.

All of these may be controlled by a Controller.

Defn 199 (Controller)**.** A *controller* is a collection of electronics that can operate a port, a Bus, or a device.

Because some protocols are complex, their Bus Controller is often implemented as a separate circuit board (or a host adapter) that plugs into the computer. It typically contains a processor, microcode, and some private memory to enable it to process the protocol messages. Some devices have their own built-in controllers. They can receive commands in 2 ways (some support both, some do not):

1. The Controller has one or more registers for data and control signals. The processor communicates with the controller by reading and writing bit patterns in these registers. This communication can occur through the use of special I/O instructions that specify the transfer of a byte or word to an I/O port address. The I/O instruction triggers bus lines to select the proper device and to move bits into or out of a device register.
2. The device Controller can support Memory Mapped I/O. In this case, the device-control registers are mapped into the address space of the processor. The CPU executes I/O requests using the standard data-transfer instructions to read and write the device-control registers at their mapped locations in physical memory.

For example, a graphics controller supports both of these methods of control.

- The graphics controller has I/O ports for basic control operations.
- The controller has a large memory-mapped region to hold screen contents. The process sends output to the screen by writing data into the memory-mapped region. The controller generates the screen image based on the contents of this memory.

The ease of writing to a Memory Mapped I/O Controller is offset by the disadvantage of being vulnerable to accidental modification by an incorrect pointer to an unintended region of memory. Memory protection helps reduce this risk.

12.1.1 I/O Ports

An I/O port typically consists of four registers, called the status, control, data-in, and data-out registers.

1. The `data-in` **register** is read by the host to get input.
2. The `data-out` **register** is written by the host to send output.
3. The `status` **register** contains bits that can be **read by the host**. These bits indicate states, such as:
   - Whether the current command has completed.
   - Whether a byte is available to be read from the data-in register.
   - Whether a device error has occurred.
4. The `control` **register** can be **written by the host** to start a command or to change the mode of a device. For instance:
   - One bit in a register of a serial port chooses between full-duplex and half-duplex communication.
   - Another bit enables parity checking.
   - A third bit sets the word length to different bit lengths.
   - Other bits select one of the speeds supported by the serial port.

12.1.2 Polling

The controller indicates its state through the `busy` bit in the `status` register. The controller sets the `busy` bit when it is busy working and clears it when the controller is ready to accept the next command. The host signals its wishes by setting the `command-ready` bit in the `command` register when a command is available for the controller to execute.

The repeating loop of polling is described in the following steps:

1. The host repeatedly reads the `busy` bit until that bit becomes clear.
2. The host sets the `write` bit in the `command` register and writes a byte into the `data-out` register.
3. The host sets the `command-ready` bit.
4. When the controller notices that the `command-ready` bit is set, it sets the busy bit.
5. The controller reads the `command` register and sees the `write` command. It reads the `data-out` register to get the byte and does the I/O to the device.
6. The controller clears the `command-ready` bit, clears the error bit in the status register to indicate that the device I/O succeeded, and clears the `busy` bit to indicate that it is finished.

The host is **busy-waiting** or **polling** in the first step: it is in a loop, reading the status register over and over until the busy bit becomes clear. If the controller and device are fast, this is reasonable. But if the wait is long enough, the host should switch to another task.

For some devices, the host **must** service the device quickly, or data will be lost. For instance, when data are streaming in on a serial port, the small buffer on the controller will overflow and data will be lost if the host waits too long before returning to read the bytes.

The basic polling operation is instruction-efficient. In many computer architectures, just three CPU-instruction cycles are sufficient to poll a device:

1. Read a device register.
2. Logical `AND` to extract a status bit.

3. Branch if not zero.

But polling becomes inefficient when it is attempted repeatedly yet rarely finds a device ready for service, while other useful CPU processing remains undone. In those cases, it is more efficient to have the hardware controller notify the CPU when the device becomes ready again, rather than require the CPU to poll for I/O completion. The hardware mechanism that enables a device to notify the CPU is called an Interrupt.

12.1.3 Interrupts

The CPU hardware has a wire called the Interrupt-Request Line that the CPU senses after executing every instruction.

Defn 200 (Interrupt-Request Line)**.** The *interrupt-request line* is a dedicated hardware line or Bus for sending information about exceptional circumstances to the CPU. The CPU checks this line after **every** instruction.

If the line does not contain any information, the CPU continues normal execution. If it does contain some information, then the CPU performs a Context Switch. However, instead of switching to another Process, the CPU jumps to the Interrupt Handler.

When the CPU detects that a controller has asserted a signal on the interrupt-request line, the CPU performs a state save and jumps to the Interrupt Handler routine at a fixed address in memory.

Defn 201 (Interrupt Handler)**.** The *interrupt handler*:

1. Determines the cause of the interrupt.
2. Performs the necessary processing.
3. Performs a state restore.
4. Executes a return from interrupt instruction to return the CPU to the execution state prior to the interrupt.

The basic loop of an Interrupt-driven Operating System is:

1. The device controller **raises** an interrupt by asserting a signal on the Interrupt-Request Line.
2. The CPU **catches** the interrupt and **dispatches** it to the Interrupt Handler.
3. The handler **clears** the interrupt by servicing the device.
4. The CPU returns to normal execution.

The loop enables the CPU to respond to asynchronous events.

The interrupt mechanism is used to handle a wide variety of exceptions, such as:

- Dividing by 0.
- Accessing a protected or nonexistent memory address.
- Attempting to execute a privileged instruction from user mode.

The events that trigger interrupts have a common property: they are occurrences that induce the operating system to execute an urgent, self-contained routine.

12.1.3.1 Interrupts on Modern Hardware

In modern operating systems, however, we need more sophisticated interrupt-handling features, which are provided by the CPU and interrupt-controller hardware.

- We need the ability to defer interrupt handling during critical processing.
- We need an efficient way to dispatch to the proper interrupt handler for a device without first polling all the devices to see which one raised the interrupt.
- We need a priority scheme, so that the operating system can distinguish between high- and low-priority interrupts and can respond with the appropriate degree of urgency.

Most CPUs have two interrupt request lines.

1. One is for Nonmaskable Interrupts.
2. The second line is for Maskable Interrupts:

Defn 202 (Nonmaskable Interrupt)**.** *Nonmaskable interrupt*s are reserved for events such as unrecoverable memory errors. These are errors that can cause fatal computer execution.

Defn 203 (Maskable Interrupt)**.** *Maskable interrupts* are Interrupts can be turned off by the CPU before the execution of critical instruction sequences that must not be interrupted. Maskable interrupts are used by device controllers to request service. These are interrupts that should not cause computer failure.

The interrupt mechanism accepts an address—a number that selects a specific interrupt-handling routine from a small set. In most architectures, this address is an offset in a table called the Interrupt Vector. This vector contains the memory addresses of specialized Interrupt Handlers. The purpose of a vectored interrupt mechanism is to reduce the need for a single interrupt handler to **search all possible sources of interrupts** to determine which one needs service.

In practice, however, computers have more devices, thus Interrupt Handlers than they have address elements in the Interrupt Vector. A common way to solve this problem is to use Interrupt Chaining. When an interrupt is raised, the handlers on the corresponding list are called one by one, until one is found that can service the request.

Defn 204 (Interrupt Chaining)**.** *Interrupt chaining* is where each element in the Interrupt Vector points to the head of a list of Interrupt Handlers. This list is searched after being found by indexing the interrupt vector.

Remark 204.1 (Structure Compromise). The use of Interrupt Chaining is a compromise between the overhead of a huge interrupt table and the inefficiency of dispatching to a single interrupt handler.

The interrupt mechanism also implements a system of interrupt priority levels. These levels enable the CPU to defer the handling of low-priority interrupts without masking all interrupts and makes it possible for a high-priority interrupt to preempt the execution of a low-priority interrupt.

A threaded kernel architecture is well suited to implement multiple interrupt priorities and to enforce the precedence of interrupt handling over background processing in kernel and application routines.

12.1.3.2 Other Uses of Interrupts

An operating system has other uses for an efficient hardware and software mechanism that saves a small amount of processor state and then calls a privileged routine in the kernel.

Paging One way to use the interrupt mechanism is for Virtual Memory Paging. A Page Fault is an exception that raises an Interrupt. The interrupt suspends the current process and jumps to the page-fault handler in the Kernel. This handler saves the state of the Process, moves the process to the wait queue, performs page-cache management, schedules an I/O operation to fetch the page, schedules another process to resume execution, and then returns from the interrupt.

System Calls Another example is found in the implementation of system calls. Usually, a program uses library calls to issue system calls. The library routines check the arguments given by the application, build a data structure to convey the arguments to the kernel, and then execute a special instruction called a software interrupt, or Trap. This instruction has an operand that identifies the desired kernel service. When a process executes the trap instruction, the interrupt hardware saves the state of the user code, switches to kernel mode, and dispatches to the kernel routine that implements the requested service. The Trap is given a relatively low Interrupt priority compared with those assigned to device interrupts—executing a system call on behalf of an application is less urgent than servicing a device controller before its FIFO queue overflows and loses data.

Flow Control Interrupts can also be used to manage the flow of control within the kernel. Consider the processing required to complete a disk read.

1. One step is to copy data from kernel space to the user buffer.
   - This copying is time consuming but not urgent—it should not block other high-priority interrupt handling.
2. Another step is to start the next pending I/O for that disk drive.
   - This step has higher priority.
   - If the disks are to be used efficiently, we need to start the next I/O as soon as the previous one completes.
   - A pair of interrupt handlers implements the kernel code that completes a disk read.
3. The high-priority handler:
   (a) Records the I/O status.
   (b) Clears the device interrupt.
   (c) Starts the next pending I/O.
   (d) Raises a low-priority interrupt to complete the work.
4. Later, when the CPU is not occupied with high-priority work, the low-priority interrupt will be dispatched.
   - The corresponding handler completes the user-level I/O by:
     (a) Copying data from kernel buffers to the application space.
     (b) Calling the scheduler to place the application on the ready queue.

12.1.4 Direct Memory Access

For devices that do large transfers, such as disk drives, it is wasteful to use a general-purpose processor to watch status bits and feed data into a controller register one byte at a time (Programmed I/O/PIO). Many computers avoid burdening the main CPU with PIO by offloading some of this work to a special-purpose processor called a Direct-Memory-Access Controller.

Defn 205 (Direct-Memory-Access Controller)**.** A *Direct-Memory-Access controller* (*DMA controller*) is a separate processor on a CPU. A simple DMA controller is a standard component in all modern computers

To initiate a DMA transfer, the CPU writes a DMA command block into memory. This block contains:

1. A pointer to the source of a transfer.
2. A pointer to the destination of the transfer.
3. A count of the number of bytes to be transferred.

The CPU gives the address of this command block to the DMA controller, then goes on with other work. The DMA controller proceeds to operate the memory bus directly, placing addresses on the bus to perform transfers without the help of the CPU.

Handshaking between the DMA controller and the device controller is performed via a pair of wires called `DMA-request` and `DMA-acknowledge`. The **device** controller places a signal on the `DMA-request` wire when a word of data is available for transfer. This signal causes the DMA controller to seize the memory bus, place the desired address on the memory-address wires, and place a signal on the `DMA-acknowledge` wire. When the device controller receives the `DMA-acknowledge` signal, it transfers the word of data to memory and removes the `DMA-request` signal. When the entire transfer is finished, the DMA controller Interrupts the CPU.

Remark 205.1 (Cycle Stealing)*.* When the Direct-Memory-Access Controller seizes the memory bus, the CPU is momentarily prevented from accessing main memory. The CPU can still access data items in its primary and secondary caches. Although this *cycle stealing* can slow down the CPU computation, offloading the data-transfer work to a DMA controller generally improves the total system performance.

Remark 205.2 (Direct Virtual Memory Access)*.* Some computer architectures perform *Direct Virtual Memory Access* (*DVMA*), using virtual addresses that undergo translation to physical addresses. DVMA can perform a transfer between two memory-mapped devices without the intervention of the CPU or the use of main memory.

On protected-mode kernels, the operating system generally prevents processes from issuing device commands directly. This discipline protects data from access-control violations and also protects the system from erroneous use of device controllers that could cause a system crash. The operating system exports functions that a sufficiently privileged process can use to access low-level operations on the underlying hardware. On kernels without memory protection, processes can access device controllers directly. This direct access can be used to achieve high performance, since it can avoid kernel communication, context switches, and layers of kernel software.

12.2 Application I/O Interface

The Operating System wants to treat all I/O devices in a standard, uniform way. Like other complex software-engineering problems, the approach here involves abstraction, encapsulation, and software layering. Specifically, we can abstract away the detailed differences in I/O devices by identifying a few general kinds, where each is accessed through a standardized set of functions, its *interface*. The implementation differences are encapsulated in Kernel Modules called Device Drivers that internally are custom-tailored to specific devices but that export one of the standard interfaces. The software layering used is shown in Figure 12.1.

This layering methodology is used to hide differences among devices and their controllers from the Kernel's I/O subsystem. This is analogous to the I/O system calls encapsulating the behavior of devices in a few generic classes that hide hardware differences from applications.

Making the I/O subsystem independent of the hardware simplifies the job of the operating-system developer. It also benefits the hardware manufacturers. They either:

- Design new devices to be compatible with an existing host controller interface.
- Write device drivers to interface the new hardware to popular operating systems.

Thus, we (users) can attach new peripherals to a computer without waiting for the operating system to develop explicit kernel-level support code. Unfortunately for hardware manufacturers, each operating system has its own standards for the device-driver interface.

Devices can vary in many dimensions, as seen in Table 12.1.

Now, each of the entries in Table 12.1 are further explained:

- Character-stream or block.
  - Character-stream device transfers **bytes** one-by-one.

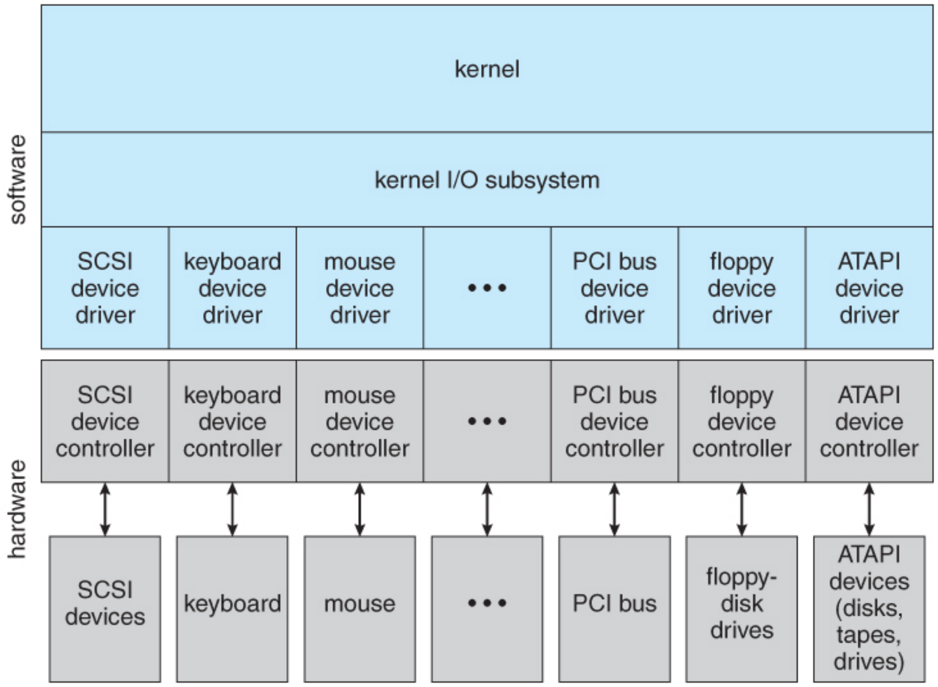


Figure 12.1: Kernel I/O Subsystem Structure

Aspect	Variation	Example
Data-Transfer Mode	Character	Terminal
	Block	Disk
Access Method	Sequential	Modem/Network
	Random	Magnetic Disk
Transfer Schedule	Synchronous	Magnetic Tape
	Asynchronous	Keyboard
Sharing	Dedicated	Magnetic Tape
	Sharable	Keyboard
Device Speed	Latency	
	Seek Time	
	Transfer Rate	
	Delay between Operations	
I/O Direction	Read-only	CD-ROM (After first write)
	Write-only	Graphics Controller
	Read-write	Disk

Table 12.1: Characteristics of I/O Devices

  - A block device transfers a block of bytes as a unit.
- Sequential or random access.
  - Sequential devices transfer data in a fixed order determined by the device
  - Random-access devices can instruct the device to seek to any of the available data storage locations.
- Synchronous or asynchronous.
  - Synchronous devices performs data transfers with predictable response times, in coordination with other aspects of the system.
  - Asynchronous devices exhibits irregular or unpredictable response times not coordinated with other computer events.
- Sharable or dedicated.
  - A sharable device can be used concurrently by several Processes or Threads.
  - Dedicated devices cannot be shared by several concurrent Processes or Threads.
- Speed of operation. Device speeds range over a wide range of speeds, from a few bytes per second to several gigabytes per second.
- Read–write, read only, or write only. Some devices perform both input and output, but others support only one data transfer direction.

For the purpose of application access, many of these differences are hidden by the operating system, and the devices are grouped into a few conventional types.

- Block I/O.
- Character-stream I/O.
- Memory-Mapped Files access.
- Network sockets.
- Operating systems also provide special system calls to access a few additional devices:
  - Time-of-day clock.
  - Timer.
- Some operating systems provide a set of System Calls for graphical display, video, and audio devices.

Most operating systems also have back door that transparently passes arbitrary commands from an application to a device driver. In UNIX, this system call is `ioctl()` (for "I/O control"). The `ioctl()` System Call enables an application to access **any** functionality that can be implemented by **any** device driver, **without** the need to invent a new system call. The ioctl() system call has three arguments.

1. File descriptor that connects the application to the driver by referring to a hardware device managed by that driver.
2. Integer that selects one of the commands implemented in the driver.
3. Pointer to an arbitrary data structure in memory that enables the application and driver to communicate any necessary control information or data.

12.2.1 Block and Character Devices

The block-device interface captures all the aspects necessary for accessing disk drives and other block-oriented devices. The Device Driver is expected to understand the commands:

1. `read()`
2. `write()`
3. `seek()`
   - Only if it is a random-access device.
   - Specifies which block to transfer next.

Applications normally access such these devices through the File-System Interface. Thus, these three functions capture the essential behaviors of block-storage devices, insulating applications from low-level differences among those devices.

The character-stream interface captures all the aspects necessary for accessing byte-by-byte generating devices. The Device Driver is expected to export the following commands:

1. `get()`
2. `put()`

This style of access is convenient for input devices (such as keyboards) that produce data for input "spontaneously"(at times that cannot necessarily be predicted by the application). This access style is also good for output devices such as printers and audio boards, which naturally fit the concept of a linear stream of bytes.

12.2.1.1 Raw I/O and Block and Character Devices The operating system itself, as well as special applications, may prefer to access a block device as a simple linear array of blocks. This mode of access is called raw I/O. To avoid conflicts, raw-device access passes control of the device directly to the application, letting the operating system step out of the way. A compromise between raw I/O and file system I/O, that is becoming common, is for the operating system to allow a mode of operation on a file that disables buffering and locking. In the UNIX world, this is called direct I/O.

12.2.1.2 Memory-Mapped Files and Block and Character Devices Memory-Mapped Files and their access can be layered on top of block-device drivers. Rather than offering read and write operations, a memory-mapped interface provides access to disk storage via an array of bytes in main memory. The System Call that maps a File into memory returns the Virtual Memory address that contains a **copy** of the file. The actual data transfers are performed only when needed to satisfy access to the memory image.

The transfers are handled by the same mechanism as that used for Demand Paging Virtual Memory access, making Memory Mapped I/O efficient.

12.2.2 Network Devices

The performance and addressing characteristics of network I/O differ significantly from those of disk I/O. Thus, most operating systems provide a network I/O interface that is different from the block device interface used for disks. One interface available in many operating systems is the network Socket interface.

Defn 206 (Socket)**.** A *socket* is an **internal** endpoint for sending or receiving data within a node on a computer network.

By analogy, the System Calls in the socket interface enable an application to:

- Create a socket
- Connect a local socket to a remote address
  - "Plugs" this application into a socket created by another application
- Listen for any remote application to plug into the local socket
- Send and receive packets over the connection.

This interface requires at least 1 interface function be defined.

1. `select()`

A call to `select()` returns information about which sockets have a packet waiting to be received and which sockets have room to accept a packet to be sent. The use of `select()` eliminates the polling and busy waiting that would otherwise be necessary for network I/O. These functions encapsulate the essential behaviors of networks, greatly facilitating the creation of distributed applications that can use any underlying network hardware and protocol stack.

12.2.3 Clocks and Timers

Most computers have hardware clocks and timers that provide three basic functions:

1. Give the current time.
2. Give the elapsed time.
3. Set a timer to trigger operation X at some later time T.

These functions are used heavily by the operating system, as well as by time-sensitive applications, but, the System Calls implementing these functions are not standardized.

The hardware to measure elapsed time and to trigger operations is called a **programmable interval timer**. It can be set to wait a certain amount of time and then generate an interrupt, and it can be set to do this once or to repeat the process to generate periodic interrupts. This has a variety of uses:

- The scheduler uses this mechanism to generate an interrupt that will preempt a process at the end of its time slice.
- The disk I/O subsystem uses it to invoke the periodic flushing of dirty cache buffers to disk.
- The network subsystem uses it to cancel operations that are proceeding too slowly because of network congestion or failures.
- The operating system may also provide an interface for user processes to use timers.

12.2.4 Nonblocking and Asynchronous I/O

Another aspect of the system-call interface relates to the choice between Blocking I/O and Nonblocking I/O.

Defn 207 (Blocking). A *blocking* System Call is one where the execution of the calling Process is stopped until the system call is completed. Note that this does not mean that the process will continue as soon as the system call returns, as the process is moved to the waiting queue after making the syscall and moved to the ready queue when it completes.

Most Operating Systems use Blocking System Calls for the application interface, because blocking application code is easier to understand than nonblocking application code.

Defn 208 (Nonblocking). A *nonblocking* System Call is one where the calling Process gets its requested information immediately, even if it is incomplete.

Remark 208.1 (Confusion between Nonblocking and Asynchronous System Calls). There is confusion between Nonblocking and asynchronous System Calls. A nonblocking System Call will return the data to the calling Process immediately, even if it is incomplete. An asynchronous System Call will schedule the system call to complete some time in the future and will return all of the data requested.

One way an application writer can overlap execution with I/O is to write a multithreaded application. Some threads can perform Blocking system calls, while others continue executing.

An alternative to a Nonblocking system call is an asynchronous system call. An asynchronous call returns immediately, without waiting for the I/O to complete. The application continues to execute its code. The completion of the I/O at some future time is communicated to the application, either:

- Through the setting of some variable in the address space of the application.
- Through the triggering of a signal or software interrupt.
- A call-back routine that is executed outside the linear control flow of the application.

Asynchronous activities occur throughout modern operating systems. Frequently, they are not exposed to users or applications but rather are contained within the operating-system operation. By default, when an application issues a network send request or a disk write request, the operating system notes the request, buffers the I/O, and returns to the application. When possible, to optimize overall system performance, the operating system completes the request.

Note that multiple Threads performing I/O to the same file might not receive consistent data, depending on how the kernel implements its I/O. In this situation, the threads may need to use locking protocols.

12.2.5 Vectored I/O

Some operating systems provide another major variation of I/O via their applications interfaces. Vectored I/O allows **one** system call to perform **multiple** I/O operations involving **multiple** locations. The same transfer could be caused by several individual invocations of system calls, but this scatter–gather method is useful for a variety of reasons.

- Multiple separate buffers can have their contents transferred via one system call, avoiding context-switching and system-call overhead.
- Without vectored I/O, the data might first need to be transferred to a larger buffer in the right order and then transmitted, which is inefficient.
- Some versions of scatter–gather provide atomicity, assuring that all the I/O is done without interruption (and avoiding corruption of data if other threads are also performing I/Oinvolving those buffers).

12.3 Kernel I/O Subsystem

Kernels provide many services related to I/O, which build on the hardware and Device Driver infrastructure, including:

- I/O Scheduling.
- Buffering.
- Caching.
- Spooling and Device Reservation.
- Error Handling.

The I/O subsystem is also responsible for protecting itself from errant processes and malicious users.

12.3.1 I/O Scheduling

To schedule a set of I/O requests means to determine a good order in which to execute them. The order in which applications issue system calls rarely is the best choice. Scheduling can improve overall system performance, can share device access fairly among processes, and can reduce the average waiting time for I/O to complete.

Operating-system developers implement scheduling by maintaining a queue of requests for each device. When an application issues a Blocking I/O system call, the request is placed on the queue for **that** device. The I/O scheduler rearranges the order of the queue to improve the overall system efficiency and the average response time experienced by applications. The operating system may also try to be fair, so that no one application receives especially poor service, or it may give priority service for delay-sensitive requests.

When a kernel supports **asynchronous** I/O, it must be able to keep track of many I/O requests at the same time. For this purpose, the operating system might attach the wait queue to a device-status table. The kernel manages this table, which contains an entry for each I/O device. Each entry indicates:

- The device's type
- Address
- State (not functioning, idle, or busy)
  - If the device is busy with a request, the type of request and other parameters will be stored in the table entry for that device.

12.3.2 Buffering

Buffering is done for three reasons.

1. One reason is to cope with a speed mismatch between the producer and consumer of a data stream.
2. A second use of buffering is to provide adaptations for devices that have different data-transfer sizes.
3. A third use of buffering is to support copy semantics for application I/O.
   - Copy semantics are such that writing to a disk will not corrupt any data.
   - The version of the data written to disk is guaranteed to be the version at the time of the application system call.

12.3.3 Caching

A cache is a region of fast memory that holds **copies** of data. Access to the cached copy is more efficient than access to the original.

The difference between a buffer and a cache is that a buffer may hold the only existing copy of a data item, whereas a cache holds a copy on faster storage of an item that resides elsewhere. However, a section of memory can sometimes be used for both purposes. For instance, to preserve copy semantics and to enable efficient scheduling of disk I/O, the operating system uses buffers in main memory to hold disk data. These buffers are also used as a cache, to improve the I/O efficiency for files that are shared by applications or that are being written and reread rapidly.

12.3.4 Spooling and Device Reservation

A spool is a buffer that holds output for a device, such as a printer, that cannot accept interleaved data streams. For example, a printer can serve only one job at a time, but several applications may wish to print their output concurrently, without having their output mixed together. The operating system solves this problem by intercepting all output to the printer. Each application's output is spooled to a separate disk file. When an application finishes printing, the spooling system queues the corresponding spool file for output to the printer. The spooling system copies the queued spool files to the printer one at a time.

12.3.5 Error Handling

An operating system that uses protected memory can guard against many kinds of hardware and application errors, so that a complete system failure is not the usual result of each minor mechanical malfunction. Devices and I/O transfers can fail in many ways, either for transient reasons, as when a network becomes overloaded, or for "permanent" reasons, as when a disk controller becomes defective. Operating systems can often compensate effectively for transient failures.

As a general rule, an I/O system call will return one bit of information about the status of the call, signifying either success or failure. In the UNIX operating system, an additional integer variable named `errno` is used to return an error code indicating the general nature of the failure.

Some hardware can provide highly detailed error information, although many current operating systems are not designed to convey this information to the application.

12.3.6 I/O Protection

To prevent users from performing illegal I/O, we define all I/O instructions to be privileged instructions requiring Kernel-level privileges. Thus, users cannot issue I/O instructions directly; they must do it through the operating system. To do I/O, a user program executes a system call to request that the operating system perform I/O on its behalf. The operating system, executing in monitor mode, checks that the request is valid and, if it is, does the I/O requested. The operating system then returns to the user.

In addition, any memory-mapped and I/O port memory locations must be protected from user access by the memory-protection system. Note that a kernel cannot simply deny all user access in these cases.

12.3.7 Kernel Data Structures

The kernel needs to keep state information about the use of I/O components. It does so through a variety of in-kernel data structures, such as the open-file table structure. The kernel uses many similar structures to track network connections, character-device communications, and other I/O activities.

UNIX provides file-system access to a variety of entities, such as user files, raw devices, and the address spaces of processes. Each of these entities supports a `read()` operation, but the semantics differ.

- To read a user file, the kernel needs to probe the buffer cache before deciding whether to perform a disk I/O.
- To read a raw disk, the kernel needs to ensure that the request size is a multiple of tthe disk sector size and is aligned on a sector boundary.
- To read a process image, it is merely necessary to copy data from memory

UNIX encapsulates these differences within a uniform structure by using an object-oriented technique.

12.4 Convert I/O Requests to Hardware Operations

Up to this point, no explanation has been given for how the Operating System connects an application's request to a set of wires or hardware.

In the case of a File lookup, there are 2 methods:

1. The Path Name also specifies the Volume or disk that the file is on. Windows/MS-DOS use this.
2. The device name space is incorporated into the regular File System namespace. UNIX uses this.

If the Path Name also specifies the Volume, then the device is easy to choose from the rest of the path. This separation makes it easy for the operating system to associate extra functionality with each device. For instance, it is easy to invoke spooling on any files written to the printer.

If the device name space is incorporated in the regular File System namespace, as it is in UNIX, the normal file-system name services are provided for free. For example, if the file system provides ownership and access control to all file names, then devices also have Owners and access control. Since files are stored on devices, such an interface provides access to the I/O system at two levels.

1. Names can be used to access the devices themselves or to access the files stored on the devices. Because there is no clear separation of the device from the path the Operating System has a mount table that associates prefixes of Path Names with specific device names. To resolve a path name, UNIX looks up the name in the mount table with the longest matching prefix; the corresponding entry in the mount table gives the device name.
2. This device name also has the form of a name in the File System namespace. When UNIX looks up this name in the file-system Directory structures, it finds not an UNIX `inode` number but a $\langle \texttt{major}, \texttt{minor} \rangle$ Device Number.

Defn 209 (Device Number)**.** The *device number* is made up of 2 parts, a `major` and `minor` number, typically represented as

$$\langle \texttt{major}, \texttt{minor} \rangle$$

The `major` device number identifies a device driver that should be called to handle I/O to this device. The `minor` device number is passed to the device driver to index into a device table. The corresponding device-table entry gives the port address or the memory-mapped address of the device controller.

Modern operating systems gain significant flexibility from the multiple stages of lookup tables in the path between a request and a physical device controller. The mechanisms that pass requests between applications and drivers are general. Thus, we can introduce new devices and drivers into a computer without recompiling the kernel.

12.4.1 Life Cycle of I/O Request

Here, we discuss the procedure for a Blocking I/O request.

1. A process issues a blocking read() system call to a file descriptor of a file that has been opened previously.
2. The system-call code in the kernel checks the parameters for correctness.
3. In the case of input, if the data are already available in the buffer cache, the data are returned to the process, and the I/O request is completed.
4. Otherwise, a physical I/O must be performed. The process is removed from the run queue and is placed on the wait queue for the device, and the I/O request is scheduled. Eventually, the I/O subsystem sends the request to the device driver.
5. The device driver allocates kernel buffer space to receive the data and schedules the I/O. Eventually, the driver sends commands to the device controller by writing into the device-control registers.
6. The device controller operates the device hardware to perform the data transfer.
7. The driver may poll for status and data, or it may have set the Direct-Memory-Access Controller up to handle the transfer into kernel memory. Assume that the transfer is managed by a DMA controller, generating an Interrupt when the transfer completes.
8. The correct interrupt handler receives the interrupt via the Interrupt Vector table, stores any necessary data, signals the Device Driver, and returns from the Interrupt.
9. The device driver receives the signal, determines which I/O request has completed, determines the request's status, and signals the kernel I/O subsystem that the request has been completed.
10. The kernel transfers data or return codes to the address space of the requesting process and moves the process from the wait queue back to the ready queue.
11. Moving the process to the ready queue unblocks the process. When the scheduler assigns the process to the CPU, the process resumes execution at the completion of the system call.

12.5 STREAMS

STREAMS enable an application to assemble pipelines of driver code dynamically. A stream is a full-duplex connection between a device driver and a user-level process. It consists of:

1. a **stream head** that interfaces with the user process
2. a **driver end** that controls the device
3. zero or more **stream modules** between the stream head and the driver end

Each of these components contains a read queue and a write queue. Message passing is used to transfer data between queues.

Kernel Modules provide the functionality of STREAMS processing; they are pushed onto a stream by use of the `ioctl()` System Call. Because messages are exchanged between queues only in adjacent modules, a queue in one module may overflow an adjacent queue. To prevent this from occurring, a queue may support flow control.

- Without flow control, a queue accepts all messages and immediately sends them on to the queue in the adjacent module without buffering them.
- A queue that supports flow control buffers messages and does not accept messages without sufficient buffer space.
  - This process involves exchanges of control messages between queues in adjacent modules.

A user process writes data to a device using either the write() or putmsg() system call.

- `write()` writes raw data to the stream
- `putmsg()` allows the user process to specify a message.

Regardless of the system call used, the stream head copies the data into a message and delivers it to the queue for the next module in line. This message passing continues until the message is copied to the driver end and hence the device. Similarly, the user process reads data from the stream head using either the read() or getmsg() system call.

- `read()` returns an unstructured byte stream to the stream head from its adjacent queue.
- `getmsg()` is used, a message is returned to the process.

STREAMS I/O is Blocking **ONLY** for the user, and only when communicating with the stream head. Otherwise, it is asynchronous (or Nonblocking). The driver end **must** respond to Interrupts. Unlike the stream head, which may block if it is unable to copy a message to the next queue in line, the driver end **must** handle all incoming data. Drivers must support flow control as well. However, if a device's buffer is full, the device typically resorts to just dropping incoming messages.

The benefit of using STREAMS is that it provides a framework for a modular and incremental approach to writing device drivers and network protocols. Modules may be used by different streams and hence by different devices. Furthermore, rather than treating character-device I/O as an unstructured byte stream, STREAMS allows support for message boundaries and control information when communicating between modules.

12.6 Performance

I/O is a major factor in system performance.

- It places heavy demands on the CPU to execute Device Driver code and to schedule Processes fairly and efficiently as they block and unblock.
  - The resulting Context Switches stress the CPU and its hardware caches.
- I/O exposes inefficiencies in the Interrupt Handler mechanisms in the Kernel.
- I/O loads down the memory bus during data copies between Controllers and Physical Memory and again during copies between kernel buffers and application data space.

Coping gracefully with all these demands is one of the major concerns of the OS designer/architect.

Interrupt handling is a relatively expensive task. Each interrupt causes the system to perform a state change, to execute the interrupt handler, and then to restore state. Network traffic can also cause a high context-switch rate (see Figure 12.2).

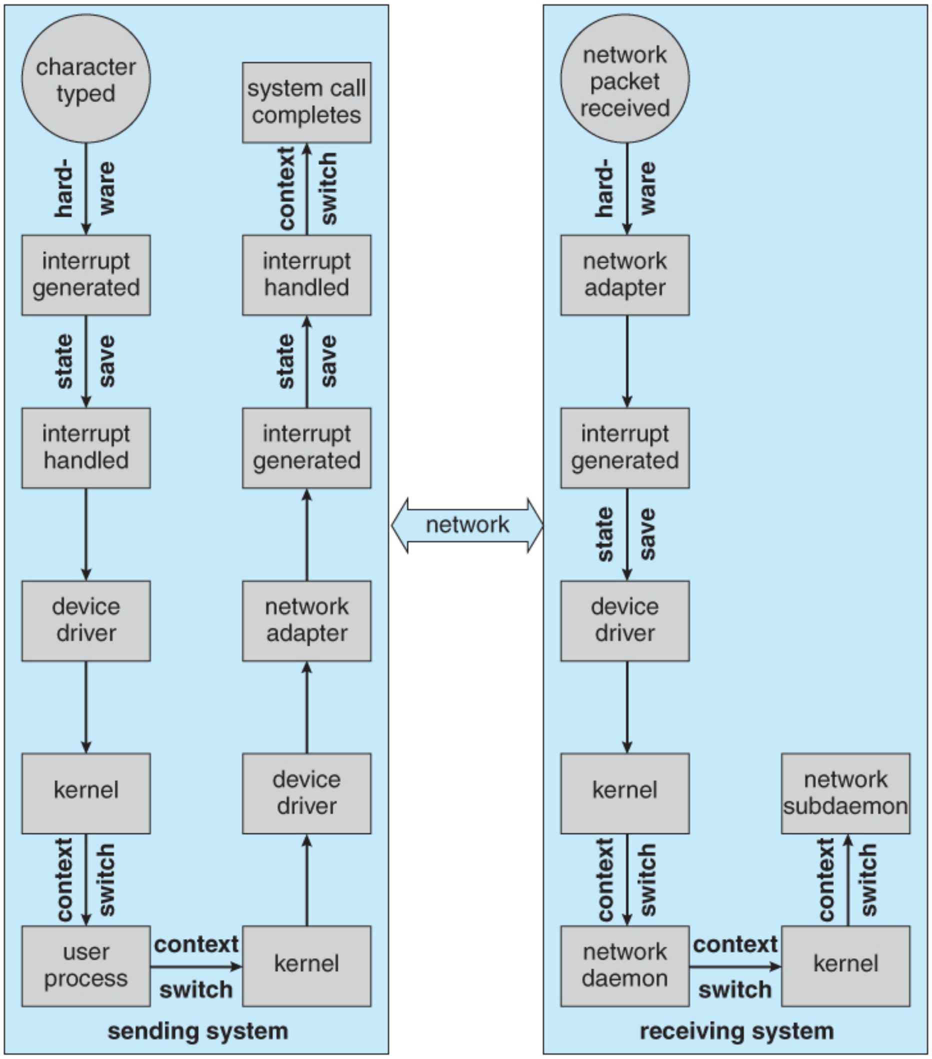


Figure 12.2: Intercomputer Communications

To help alleviate the problems of network-based interrupts:

- Reimplemented certain Daemons using in-kernel threads.
- Other systems use separate front-end processors for terminal I/O to reduce the interrupt burden on the main CPU.

- For instance, a terminal concentrator can multiplex the traffic from hundreds of remote terminals into one port on a large computer.

- An I/O channel is a dedicated, special-purpose CPU found in mainframes and in other high-end systems.
  - The job of a channel is to offload I/O work from the main CPU.
  - The idea is that the channels keep the data flowing smoothly, while the main CPU remains free to process the data.

Like device controllers and DMA controllers found in smaller computers, a channel can process more general and sophisticated programs, so channels can be tuned for particular workloads.

12.6.1 Improving Efficiency

- Reduce the number of Context Switches.
- Reduce the number of times that data must be copied in memory while passing between device and application.
- Reduce the frequency of Interrupts by using:
  - Large transfers.
  - Smart controllers.
  - Polling (if busy waiting can be minimized).
- Increase concurrency by using DMA-knowledgeable controllers or channels to offload simple data copying from the CPU.
- Move processing primitives into hardware, to allow their operation in device controllers to be concurrent with CPU and bus operation.
- Balance CPU, memory subsystem, bus, and I/O performance.
  - An overload in any one area will cause idleness in others.

13 Protection

Protection refers to a mechanism for controlling the access of Programs, Processes, or Users to the resources defined by a computer system. This must provide a means for specifying the controls to be imposed, together with a means of enforcement. Protection and security mean different things here. Security is a measure of confidence that the integrity of a system and its data will be preserved.

If system protection interferes with the ease of use of the system or significantly decreases system performance, then its use must be weighed carefully against the purpose of the system. For instance, we would want to have a complex protection system on a computer used by a university to process students' grades and also used by students for classwork. A similar protection system would not be suited to a computer being used for number crunching, in which performance is of utmost importance.

13.1 Goals of Protection

System protection was originally conceived in tandem with multiprogramming Operating Systems, so that untrustworthy Users might safely:

- Share a common logical name space
  - Share a directory of files
- Share a common physical name space
  - Such as memory.

Protection can improve reliability by detecting latent errors at the interfaces between component subsystems. Early detection of interface errors can often prevent contamination of a healthy subsystem by a malfunctioning subsystem. Also, an unprotected resource cannot defend against use (or misuse) by an unauthorized or incompetent user. A protection-oriented system provides means to distinguish between authorized and unauthorized usage.

The role of protection in a computer system is to provide a mechanism for the enforcement of the policies governing resource use.

Policies for resource use may vary by application, and they may change over time. The application programmer needs to use protection mechanisms as well, to guard resources created and supported by an application subsystem against misuse. The Operating System should provide protection mechanisms, but application designers can use them as well in designing their own protection software. Note that mechanisms are distinct from policies.

Mechanisms determine how something will be done; **policies** decide what will be done. This separation of policy and mechanism is important for system flexibility. This allows the same physical system to have as complex or as simple a protection scheme as required. This separation requires general models of protection, discussed in Section 13.5.

13.2 Principles of Protection

Principles that are used for protection allow us to make decisions about what policies to set on a system and what mechanisms enforce those policies. A key, time-tested principle for protection is the Principle of Least Privilege.

Defn 210 (Principle of Least Privilege)**.** The *principle of least privilege* states that programs, users, and even systems be given just enough privileges to perform their tasks.

An Operating System following this principle implements its features, programs, system calls, and data structures so that failure or compromise of a component does the minimum damage. The overflow of a buffer in a system Daemon might cause the daemon process to fail, but should not allow the execution of code from the daemon process's stack.

This Operating System also provides System Calls and services that allow applications to be written with fine-grained access controls. It provides mechanisms to enable privileges *when* they are needed and to disable them when they are not needed. Also, audit trails are created for all privileged function access. This allows for tracing all protection and security activities on the system.

Managing users with the Principle of Least Privilege entails creating a separate account for each user, each with just the privileges that the user needs.

13.3 Domains of Protection

A computer system is a collection of Processes and objects. Objects refer to:

- Hardware Objects
  - CPU
  - Memory Segments
  - Printers
  - Disks
  - Tape Drives
- Software Objects
  - Files
  - Programs
  - Semaphores

Each object has a unique name that differentiates it from all other objects in the system, and each can be accessed only through well-defined and meaningful operations. The operations that are possible depends on the object in question. For example, on a CPU, we can perform executions, memory can be read from and written to, etc.

A Process should be allowed to access only those resources for which it has authorization. Furthermore, at any time, a process should be able to access only those resources that it currently requires to complete its task. This second requirement, is commonly referred to as the Need-to-Know Principle.

Defn 211 (Need-to-Know Principle)**.** The *Need-to-Know principle* states that a Process should be able to access **only** those resources that it currently requires to complete its **current** task.

This is useful in limiting the amount of damage a faulty process can cause in the system.

13.4 Domain Structure

A Process operates within a Protection Domain.

Defn 212 (Protection Domain)**.** A *protection domain* specifies the resources that a Process may access. Each domain defines a set of objects and Access Rights. A domain is a collection of access rights, each of which is an ordered pair

$$\langle \text{object-name}, \text{rights-set} \rangle \tag{13.1}$$

A Protection Domain can be defined in many ways.

- Each user may be a domain. In this case, the set of objects that can be accessed depends on the identity of the user. Domain switching occurs when the user is changed —generally when one user logs out and another user logs in.
- Each process may be a domain. In this case, the set of objects that can be accessed depends on the identity of the process. Domain switching occurs when one process sends a message to another process and then waits for a response.
- Each procedure may be a domain. In this case, the set of objects that can be accessed corresponds to the local variables defined within the procedure. Domain switching occurs when a procedure call is made.

Defn 213 (Access Right)**.** The ability to execute an operation on an object is an *access right*.

Protection Domains may share Access Rights. For example, if we have three domains: D_1, D_2, and D_3 an an access right $\langle O_4, \text{print}\rangle$ that is shared by D_2 and D_3, a process executing in either of these domains can print object O_4.

The association between a Process and a Protection Domain may be either **static**, if the set of resources available to the process is fixed throughout the process's lifetime, or **dynamic**.

13.4.1 Static Domain Structure

A static association between Processes and Protection Domains is possible, but it is not a very flexible system, and makes it difficult to adhere to the need-to-know principle. To counter this, a mechanism must be available to change the content of a domain.

This mechanism is needed because a Process may execute in two different phases and may, for example, need read access in one phase and write access in another. If the Protection Domain is static, the domain must be defined to include **both** read and write access throughout the process's execution.

However, this arrangement provides more rights than are needed in each of the two phases, since we have read access in the phase where we need only write access, and vice versa.

13.4.2 Dynamic Domain Structure

A dynamic association between Processes and Protection Domains relies on a mechanism to allow Domain Switching.

Defn 214 (Domain Switching)**.** *Domain switching* is a tool that enables a Process to switch from one Protection Domain to another. We may also allow the content of a domain to be changed.

If we cannot change the content of a domain, we can provide the same effect by creating a new domain with the changed content and switching to that new domain when we want to change the domain content.

13.4.3 unix-Style Protection Domains and Schemes

In the UNIX operating system, a domain is associated with the User. Switching the domain corresponds to changing the user identification.

This change is accomplished through the File System. Each file contains a lot of metadata regarding the attributes of the file, including who owns the file and to which domain (User) that files belongs to. The first one is the file's owner identification (`userID`); the second is the `setuid` bit (the domain bit).

When the `setuid` bit is on, and a User executes that file, the process that is created has its `userID` set to the owner of the file. When the `setuid` bit is off, the `userID` does not change. For example, when a user A (that is, a user with `userID` = A) starts executing a file owned by B, whose associated domain bit is off, the `userID` of the process is set to A. When the `setuid` bit is on, the `userID` is set to that of the owner of the file: B. When the process exits, this temporary `userID` change ends.

Other methods are used to change domains in operating systems in which `userID`s are used for domain definition. This mechanism is used when an otherwise privileged facility needs to be made available to the general user population. For instance, it might be desirable to allow users to access a network without letting them write their own networking programs. On a UNIX system, the `setuid` bit on a networking program would be set, causing the `userID` to change to another `userID` that is capable of using the network when the program is run. The `userID` would change to that of a user with network access privilege (such as `root`). One problem with this method is that if a user manages to create a file with `userID` root and with its `setuid` bit on, that user can become root and do anything and everything on the system.

An alternative to this method used in some other Operating Systems is to place privileged programs in a special Directory. The operating system is designed to change the `userID` of any program run from this directory. This eliminates the security problem of when intruders create programs to manipulate the `setuid` feature and hide the programs in the system for later use. This method is less flexible than that used in UNIX, however.

Even more restrictive, and thus more protective, are systems that simply do not allow a change of `userID`. In these Operating Systems, special techniques must be used to allow users access to privileged facilities. One method, for instance, is to use a Daemon process that is started at boot and runs as a special `userID`. Regular Users then run a separate program, which sends requests to this process whenever they need to use the facility.

In any of these systems, great care must be taken in writing privileged programs. Any oversight can result in a total lack of protection on the system.

13.4.4 multics-Style Protection Domains and Schemes

In the MULTICS system, the Protection Domains are organized hierarchically into a ring structure. Each ring corresponds to a single domain, see Figure 13.1 for a visualization.

The rings are numbered from 0 to $N - 1$. Let D_i and D_j be any two domain rings. If $j < i$, then D_i is a subset of D_j, meaning a Process executing in domain D_j has more privileges than a process executing in domain D_i. A process executing in domain D_0 has the most privileges.

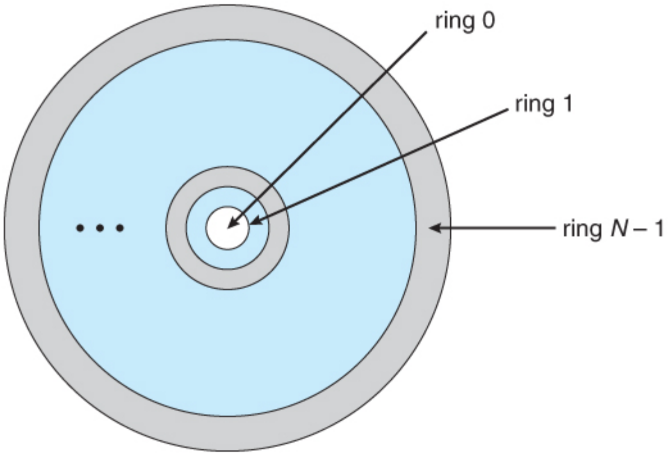


Figure 13.1: MULTICS Rings

Remark. If only two rings exist, this scheme is equivalent to the monitor–user mode of execution, where monitor-/Kernel-mode corresponds to D_0 and User-mode corresponds to D_1.

MULTICS has a segmented address space; each segment is a file, and each segment is associated with one of the rings. A segment description includes an entry that identifies the ring number that it is associated with. In addition, it includes three access bits to control reading, writing, and execution. The association between segments and rings is a policy decision.

A `current-ring-number` counter is associated with each Process, identifying the ring in which the process is executing currently. Given 3 ring domains i, j, and k, where $j < i$ and $k \geq i$, and the process is executing in ring i, the process cannot access a memory segment associated with ring j, but *can* access a segment associated with ring k. In terms of Figure 13.1, this means a process can always move outwards from the center to access memory, but never inwards. A process in ring i accessing ring k's memory segment when $i \geq k$ is restricted according to the access bits associated with that segment.

Domain switching in MULTICS occurs when a process crosses from one ring to another by calling a procedure in a different ring. This switch must be done in a controlled manner; otherwise, a process could start executing in ring 0, and no protection would be provided. To allow controlled domain switching, the ring field of the segment also includes:

- **Access bracket**. A pair of integers, $\langle b_1, b_2 \rangle$, where $b_1 \leq b_2$.
- **Limit**. An integer b_3 such that $b_3 > b_2$.
- **List of gates**. Identifies the entry points (or gates) at which the segments may be called.

If a process executing in ring i calls a procedure (or segment) with access bracket $\langle b_1, b_2 \rangle$, then the call is allowed if $b_1 \leq i \leq b_2$, and the current ring number of the process remains i. Otherwise, a Trap to the Operating System occurs, and the situation is handled.

- If $i < b_1$, then the call is allowed to occur, because we have a transfer to a ring with fewer privileges. If parameters are passed that refer to segments in a lower ring (that is, segments not accessible to the called procedure), then these segments must be copied into an area that can be accessed by the called procedure.
- If $i > b_2$, then the call is allowed to occur only if b_3 is greater than or equal to i and the call has been directed to one of the designated entry points in the list of gates. This scheme allows processes with limited access rights to call procedures in lower rings that have more access rights, but only in a carefully controlled manner.

The main disadvantage of the ring structure is that it does not allow us to enforce the Need-to-Know Principle. In particular, if an object must be accessible in domain D_j but not accessible in domain D_i, then we must have $j < i$. But this requirement means that **every** segment accessible in D_i is also accessible in D_j.

The MULTICS protection system is generally more complex and less efficient than are those used in current operating systems.

13.5 Access Matrix

A general model of protection can be viewed abstractly as a matrix, called an Access Matrix.

Defn 215 (Access Matrix)**.** An *access matrix* is a way to represent the access rights between Protection Domains and objects. The rows of the access matrix are the domains, and the columns represent objects. Each entry in the matrix consists of a set of Access Rights. The entry `access(`i`,`j`)` defines the set of operations that a process executing in domain D_i can invoke on object O_j.

Object Domain	F_1	F_2	F_3	Printer
D_1	Read		Read	
D_2				Print
D_3	Read	Execute		
D_4	Read Write		Read Write	

Table 13.1: Basic Access Matrix

Remark 215.1. Because the column defines objects explicitly, we can omit the object name from the Access Right.

Using Table 13.1, we can determine the Access Rights for various domains on various objects. A process executing in domain D_1 can read files F_1 and F_3. A process executing in domain D_4 has the same privileges as one executing in domain D_1; but in addition, it can also write onto files F_1 and F_3.

Access matrices can provide a variety of **both** mechanisms and policies for system protection. The mechanism consists of implementing the access matrix and ensuring that the semantic properties we have outlined hold. This means we must ensure that a process executing in domain D_i can access only those objects specified in row i as allowed by the access-matrix entries. The policy decisions involve which rights should be included in the (i, j)th entry. We must also decide the domain in which each process executes, which is usually decided by the operating system.

When we switch a process from one domain to another, we are executing a `switch` operation on the domain (which becomes an object). We can control Domain Switching by including domains as objects of the Access Matrix (Table 13.2).

Object Domain	F_1	F_2	F_3	Printer	D_1	D_2	D_3	D_4
D_1	Read		Read		Switch			
D_2			Print			Switch	Switch	
D_3		Read	Execute					
D_4	Read Write		Read Write		Switch Switch			

Table 13.2: Access Matrix with Domains as Objects

Similarly, when we change the content of the access matrix, we are performing an operation on an object: the access matrix. Again, we can control these changes by including the access matrix itself as an object. If we want to be pedantic, we must protect each entry in the Access Matrix because each entry can be modified individually. This requires three additional operations: `copy`, `owner`, and `control`.

The `copy` right has 3 variants.

1. Allows the access rights to be copied only within the column.
2. A right is "copied" from access(i, j) to access(k, j); it is then removed from access(i, j). This action is a `transfer` of a right, rather than a copy.
3. Propagation of the copy right may be limited. That is, when the set of rights R^* is copied from `access(`i`, `j`)` to `access(`k`, `j`)`, the rights R is created. A process executing in domain D_k cannot further copy the copy of the set of rights, R.

The `owner` right controls the addition and removal of rights. If `access(`i`, `j`)` includes the `owner` right, then a process executing in domain D_i can add and remove any right in any entry in column j. This means that there are ways to change the entries in a column.

The `control` right allows for changing the entries in a row. The `control` right is applicable only to domain objects. If `access(`i`, `j`)` includes the `control` right, then a process executing in domain D_i can remove any access right from row j.

13.5.1 Confinement Problem

The `copy` and `owner` rights provide us with a mechanism to limit the propagation of access rights. However, they do not give us the appropriate tools for preventing the propagation (or disclosure) of information. The problem of guaranteeing that no information initially held in an object can migrate outside of its execution environment is called the confinement problem. This problem is, in general, unsolvable.

13.6 Implementing Access Matrices

In general, an Access Matrix will be sparse, i.e. most of the entries in the table will be empty. Along with this, traditional sparse data structure techniques are not terribly useful for this. These are because of the way the protection facilities are used.

Most systems use a combination of Access Lists and Capability Lists. When a Process first tries to access an object, the access list is searched. If access is denied, an exception condition occurs. Otherwise, a capability is created and attached to the process. Subsequent references use the capability to quickly determine access. After the last access, the capability is destroyed.

13.6.1 Global Table

The simplest implementation of the access matrix is a global table consisting of a set of ordered tuples $\langle \text{domain}, \text{object}, \text{rights-set} \rangle$. Whenever an operation M is executed on an object O_j within domain D_i, the global table is searched for a tuple $\langle D_i, O_j, R_k \rangle$, where $M \in R_k$. If this tuple is found, the operation is allowed to continue; otherwise, an exception (or error) is raised.

This implementation suffers from several drawbacks. The table is usually large and thus cannot be kept in main memory, so additional I/O is needed. Virtual memory techniques are often used for managing this table (Memory Mapping). In addition, it is difficult to take advantage of special groupings of objects or domains.

13.6.2 Access Lists

Access Lists are created by only working with the columns of a Access Matrix.

Defn 216 (Access List)**.** An *access list* is a way for **objects** to track what domains can perform what actions on that object. The resulting list for each object consists of ordered pairs $\langle \text{domain}, \text{rights-set} \rangle$, which define all domains with a nonempty set of access rights for that object.

This can be extended to define an Access List and a default set of Access Rights. When an operation M on an object O_j is attempted in domain D_i, we search the access list for object O_j, looking for an entry $\langle D_i, R_k \rangle$ with $M \in R_k$. If the entry is found, we allow the operation; if it is not, we check the default set. If M is in the default set, we allow the access. Otherwise, access is denied, and an exception condition occurs.

Access lists correspond directly to the needs of users. When a user creates an object, they can specify which domains can access the object, as well as what operations are allowed. However, access-right information for a particular domain is not localized, making determining the set of access rights for each domain difficult. In addition, every access to an object must be checked, requiring a search of the access list. In a large system with long access lists, this search can be time consuming.

13.6.3 Capability Lists

Capability Lists are created by only working with the rows of a Access Matrix.

Defn 217 (Capability List)**.** A *capability list* is a way for **domains** to track what objects they can access and the actions the domain can perform on that object.

To execute operation M on object O_j, the process executes the operation M, specifying the capability (or pointer) for object O_j as a parameter. Just having the possession of a capability means that access to that object is allowed.

The Capability List is associated with a Protection Domain, but it is never directly accessible to a Process executing in that domain. The list itself is a protected object, maintained by the Operating System and only indirectly accessed by the user. Capability-based protection relies on the fact that the capabilities are never allowed to migrate into any space directly accessible by a user process. If all capabilities are secure, the object they protect is also secure against unauthorized access.

To provide protection, we must distinguish capabilities from other kinds of objects, and they must be interpreted for higher-level programs run. Capabilities are usually distinguished from other data in one of two ways:

1. Each object has a tag to denote whether it is a capability or accessible data. The tags themselves must not be directly accessible by an application program. Hardware or firmware support may be used to enforce this restriction. Although only one bit is necessary to distinguish between capabilities and other objects, more bits are often used. This extension allows all objects to be tagged with their types by the hardware. Thus, the hardware can distinguish integers, floating-point numbers, pointers, Booleans, characters, instructions, capabilities, and uninitialized values by their tags.
2. Alternatively, the address space associated with a Process can be split into two parts. One part is accessible to the program and contains the program's normal data and instructions. The other part, containing the capability list, is accessible only by the operating system. Segmentation (Section 7.7) is useful to support this approach.

Capability Lists do not correspond directly to the needs of Users, but they are useful for localizing information for a given Process. The process attempting access must present a capability for that access. Then, the protection system needs only to verify that the capability is valid. Revocation of capabilities, however, may be inefficient.

13.6.4 Lock-Key

The lock–key scheme is a compromise between Access Lists and Capability Lists. Each object has a list of unique bit patterns, called locks. Similarly, each domain has a list of unique bit patterns, called keys. A Process executing in a domain can access an object only if that domain has a key that matches one of the locks of the object.

As with capability lists, the list of keys for a domain must be managed by the operating system on behalf of the domain. Users are not allowed to examine or modify the list of keys (or locks) directly.

The lock–key mechanism, as mentioned, is a compromise between Access Lists and Capability Lists. The mechanism can be both effective and flexible, depending on the length of the keys. The keys can be passed freely from domain to domain. In addition, access privileges can be effectively revoked by the simple technique of changing some of the locks associated with the object.

13.7 Access Control

Similar to how we have Owner, Group, and Universe, we can extend this idea to other aspects in a system. This facility revolves around Privileges and is typically called Role-Based Access Control.

Defn 218 (Privilege)**.** A *privilege* is the right to execute a System Call or to use an option within that system call (such as opening a file with write access). Privileges can be assigned to Processes, limiting them to the access they need to perform their work. Privileges and Programs can also be assigned to roles, forming a Role-Based Access Control scheme.

Defn 219 (Role-Based Access Control)**.** *Role-Based Access Control* (*RBAC*) is a way of allocating Privileges and protections to components in a system based on roles to fulfill. Users are assigned roles or can temporarily take on certain roles based on secrets (passwords, etc.). In this way, a user can take a role that enables a Privilege, allowing the user to run a program to accomplish a specific task.

This decreases the security risk associated with superusers (`root`) and `setuid` programs.

13.8 Revoking Access Rights

In a dynamic protection system, we may sometimes need to revoke access rights to objects shared by different users. This raises various questions about revocation that must be answered. These include:

- **Immediate versus delayed**.
  - Does revocation occur immediately, or is it delayed?
  - If revocation is delayed, can we find out when it will take place?
- **Selective versus general**.
  - When an access right to an object is revoked, does it affect all the users who have an access right to that object, or can we specify a select group of users whose access rights should be revoked?
- **Partial versus total**.
  - Can a subset of the rights associated with an object be revoked, or must we revoke all access rights for this object?
- **Temporary versus permanent**.
  - Can access be revoked permanently (that is, the revoked access right will **never** again be available), or can access be revoked and later be obtained again?

With an Access List scheme, revocation is easy. The access list is searched for any Access Rights to be revoked, and they are deleted from the list. Revocation can be: immediate or delayed, general or selective, total or partial, and permanent or temporary.

Capabilities present a much more difficult revocation problem. Since the capabilities are distributed throughout the system, we must find them before we can revoke them. Schemes that implement revocation for capabilities must include the following:

- Reacquisition
- Back-pointers
- Indirection
- Keys

13.8.1 Reacquisition

Periodically, capabilities are deleted from each domain. If a Process wants to use a capability, it may find that that capability has been deleted. The process may then attempt to reacquire the capability. If access has been revoked, the process will not be able to reacquire the capability.

13.8.2 Back-pointers

A list of pointers is maintained with each object, pointing to all capabilities associated with that object. When revocation is required, we can follow these pointers, changing the capabilities as necessary. This is quite general, but its implementation is costly because of all the pointer traversal.

13.8.3 Indirection

Each capability points **indirectly** through its unique entry in the global table, and that entry points to the object. Revocation is done by searching the global table for the desired entry and deleting it. Then, when an access is attempted, the capability is found to point to an illegal table entry. Table entries can then be reused for other capabilities, since both the capability and the table entry contain the unique name of the object. The object for a capability and its table entry must match. It does not allow selective revocation.

13.8.4 Keys

A key is a unique bit pattern that can be associated with a capability. This key is defined when the capability is created, and it can be neither modified nor inspected by the Process that owns the capability. A master key is associated with each object; it can be defined or replaced with the `set-key` operation. When a capability is created, the current value of the master key is associated with the capability. When the capability is exercised, its key is compared with the master key. If the keys match, the operation is allowed to continue; otherwise, an exception condition is raised.

Revocation replaces the master key with a new value using the `set-key` operation again. This invalidates all previous capabilities for this object. This scheme does not allow selective revocation, since only one master key is associated with each object. If we associate a list of keys with each object, then selective revocation can be implemented.

Finally, we can group all keys into one global table of keys. A capability is valid only if its key matches some key in the global table. We implement revocation by removing the matching key from the table. With this scheme, a key can be associated with several objects, and several keys can be associated with each object, providing maximum flexibility.

In key-based schemes, the operations of defining keys, inserting them into lists, and deleting them from lists should not be available to all users. In particular, it would be reasonable to allow only the owner of an object to set the keys for that object. This choice, however, is a policy decision that the protection system can implement but should not define.

14 Security

Protection is an **internal** problem: How do we provide controlled access to programs and data stored in a computer system? Security, on the other hand, requires not only an adequate protection system but also consideration of the **external** environment within which the system operates. A protection system is ineffective if user authentication is compromised or a program is run by an unauthorized user. Computer resources must be guarded against unauthorized access, malicious destruction or alteration, and accidental introduction of inconsistency.

For more in-depth discussion around this topic and further consideration of closely related topics, please see EDIN01, Cryptography and EITP20, Secure Systems Engineering.

14.1 The Security Problem

In Section 13, we discussed mechanisms that the operating system can provide that allow users to protect their resources. These mechanisms work well **only** as long as the users conform to the intended use of and access to these resources.

A system is secure if its resources are used and accessed as intended under **all** circumstances. Unfortunately, total security cannot be achieved. Nonetheless, there must have mechanisms to make security breaches a rare occurrence, rather than the norm.

Security violations (or misuse) of the system can be categorized as intentional (malicious) or accidental. It is easier to protect against accidental misuse than against malicious misuse. For the most part, protection mechanisms are the core of protection from accidents.

We should note that in our discussion of security, the term:

- Intruder is for those attempting to breach security.
- A threat is the **potential** for a security violation, such as the discovery of a vulnerability.
- An attack is an attempt to break security.

The most common forms of security violations include:

- **Breach of confidentiality**. This type of violation involves unauthorized reading of data (or theft of information). Typically, a breach of confidentiality is the goal of an intruder. Capturing secret data from a system or a data stream, such as credit-card information or identity information for identity theft, can result directly in money for the intruder.

- **Breach of integrity**. This violation involves unauthorized modification of data. Such attacks can result in passing of liability to an innocent party or modification of the source code of an important commercial application.
- **Breach of availability**. This violation involves unauthorized destruction of data. Some intruders would rather wreak havoc and gain status or bragging rights than gain financially. Website defacement is a common example of this type of security breach.
- **Theft of service**. This violation involves unauthorized use of resources. For example, an intruder (or intrusion program) may install a Daemon on a system that acts as a file server.
- **Denial of service**. This violation involves preventing legitimate use of the system. Denial-of-service (DOS) attacks are sometimes accidental. The original Internet worm turned into a DOS attack when a bug failed to delay its rapid spread.

Attackers use several standard methods in their attempts to breach security. The most common is **masquerading** or **spoofing**, in which one participant in a communication pretends to be someone else (another host or another person). By masquerading, attackers breach authentication, the correctness of identification. They can then gain access that they would not normally be allowed or escalate their privileges—obtain privileges to which they would not normally be entitled.

Another common attack is to replay a captured exchange of data. A replay attack consists of the malicious or fraudulent repeat of a previously valid data transmission. Sometimes the replay comprises the entire attack. But frequently it is done along with message modification, again to escalate privileges. Consider the damage that could be done if a request for authentication had a legitimate user's information replaced with an unauthorized user's.

Yet another kind of attack is the man-in-the-middle attack, in which an attacker sits in the data flow of a communication, masquerading as the sender to the receiver, and vice versa. In a network communication, a man-in-the-middle attack may be preceded by a session hijacking, in which an active communication session is intercepted.

Absolute protection of the system from malicious abuse is not possible, but the cost to the perpetrator can be made sufficiently high to deter most intruders. In some cases, such as a denial-of-service attack, it is preferable to prevent the attack but sufficient to detect the attack so that countermeasures can be taken.

To protect a system, we must take security measures at four levels:

1. **Physical**. The site or sites containing the computer systems must be physically secured against armed or surreptitious entry by intruders. Both the machine rooms and the terminals/workstations that have access to the machines must be secured.
2. **Human**. Authorization must be done carefully to assure that only appropriate users have access to the system. Even authorized users, however, may be "encouraged" to let others use their access. They may also be tricked into allowing access via social engineering, such as:
   - **Phishing**. Here, a legitimate-looking e-mail or web page misleads a user into entering confidential information. Another
   - **Dumpster Diving**. A general term for attempting to gather information in order to gain unauthorized access to the computer (by looking through trash, finding phone books, or finding notes containing passwords, for example).
   - These security problems are management and personnel issues, not problems pertaining to operating systems.
3. **Operating system**. The system must protect itself from accidental or purposeful security breaches. A runaway process could constitute an accidental denial-of-service attack. A query to a service could reveal passwords. A stack overflow could allow the launching of an unauthorized process. The list of possible breaches is almost endless.
4. **Network**. Much computer data in modern systems travels over private leased lines, shared lines like the Internet, wireless connections, or dial-up lines. Intercepting these data could be just as harmful as breaking into a computer, and interruption of communications could constitute a remote denial-of-service attack, diminishing users' use of and trust in the system.

Physical and Human Security must be maintained if Operating System security is to be ensured. Weakness these levels of security allows for easy circumvention of strict low-level (operating system) security measures. However, all of these aspects must be addressed for security to be maintained.

14.2 Program Threats

Processes, along with the Kernel, are the only means of accomplishing work on a computer. Therefore, writing a program that creates a breach of security, or causing a normal process to change its behavior and create a breach, is a common goal of intruders. Most nonprogram security events have causing a program threat as a goal.

14.2.1 Trojan Horse

Many systems have mechanisms for allowing programs written by users to be executed by other Users. If these programs are executed in a domain that provides the Access Rights of the executing user, the other users may misuse these rights. For example, a text editing program may include code to search the file to be edited for certain keywords. If any are found, the entire file is copied to a special area accessible to the **creator** of the text editor. A code segment that misuses its environment is called a Trojan Horse.

Defn 220 (Trojan Horse)**.** A *trojan horse* or *trojan* is any malware which misleads users of its true intent. Its code segment misuses the execution environment it is given to achieve something other than what is intended.

Trojan Horses also include malware that mimics genuine software, to ensure the user is complacent and inputs secure information without realizing it is stolen/compromised.

Another variation on the Trojan Horse is Spyware. Spyware sometimes accompanies a program that the user has chosen to install.

Defn 221 (Spyware)**.** *Spyware* is malware that intentionally monitors the User's actions. The usual goal is to download ads to display on the user's system, create pop-up browser windows when certain sites are visited, or use Covert Channels.

Most frequently, Spyware comes with freeware or shareware programs, but sometimes is included with commercial software.

Defn 222 (Covert Channel)**.** *Covert channel*s are intended to capture information from the user's system and return it to a central site.

14.2.2 Trap Door

Another common, and very hard to detect type of malware is a Trap Door.

Defn 223 (Trap Door)**.** A *trap door* is a piece of malware where the designer of the program or system leaves a security hole in the software that only they are capable of using.

For instance, the code might check for a specific user ID or password, and it might circumvent normal security procedures.

Trap doors pose a difficult problem because, to detect them, we have to analyze all the source code for all components of a system. Given that software systems may consist of millions of lines of code, this analysis is not done frequently.

14.2.3 Logic Bomb

Logic Bombs is not malware, per-se; rather it is code that is executed **only** when certain conditions have been met. What that code does determines how it is classified.

Defn 224 (Logic Bomb)**.** *Logic bomb*s are programs that creates a security incident **only** under certain conditions. It would be hard to detect because under normal operations, there would be no security hole. However, when a predefined set of parameters was met, the security hole would be created.

14.2.4 Stack and Buffer Overflow

The stack- or buffer-overflow attack is the most common way for an attacker outside the system to gain unauthorized access to the target system. An authorized user of the system may also use this exploit for privilege escalation.

Essentially, the attack exploits a bug in a program. The bug can be a simple case of poor programming, in which the programmer neglected to code bounds checking on an input field. In this case, the attacker sends more data than the program was expecting. By using trial and error, or by examining the source code of the attacked program if it is available, the attacker determines the vulnerability and writes a program to do the following:

1. Overflow an input field, command-line argument, or input buffer until it writes into the stack.
2. Overwrite the current return address on the stack with the address of the exploit code loaded in step 3.
3. Write a simple set of code for the next space in the stack that includes the commands that the attacker wishes to execute.

The result of this attack program's execution will be a privileged command execution.

When a function is invoked in a typical computer architecture, the local variables defined in the function, the parameters passed to the function, and the address to which control returns once the function exits are stored in a stack frame. At the end of a stack frame, there is the return address, which specifies where to return control once the function exits. The frame pointer must be fixed on the stack, as the value of the stack pointer can vary during the function call. The saved frame pointer allows relative access to parameters and automatic variables.

Given this standard memory layout, an intruder could execute a buffer-overflow attack. The goal being to replace the return address in the stack frame so that it points to a code segment containing the attacking program.

One solution to this problem is for the CPU to have a feature that disallows execution of code in a stack section of memory. Recent versions x86 chips include the `NX` feature to prevent this type of attack. The hardware implementation involves the use of a new bit in the page tables of the CPUs. This bit marks the associated page as nonexecutable, so that instructions cannot be read from it and executed.

14.2.5 Viruses

Defn 225 (Virus)**.** A *virus* is a fragment of code embedded in a legitimate program. Viruses are self-replicating and are designed to "infect" other programs.

Viruses can wreak havoc in a system by modifying or destroying files and causing system crashes and program malfunctions. As with most penetration attacks, viruses are very specific to architectures, Operating Systems, and applications.

Once a virus reaches a target machine, a program known as a virus dropper inserts the virus into the system. The virus dropper is usually a Trojan horse, executed for other reasons but installing the virus as its core activity. Once installed, the virus may do any one of a number of things.

- **File**. A standard file Virus infects a system by appending itself to a file. It changes the start of the program so that execution jumps to its code. After it executes, it returns control to the program so that its execution is not noticed. File viruses are sometimes known as parasitic viruses, as they leave no full files behind and leave the host program still functional.
- **Boot**. A boot Virus infects the boot sector of the system, executing every time the system is booted and before the operating system is loaded. It watches for other bootable media and infects them. These viruses are also known as memory viruses, because they do not appear in the file system.
- **Macro**. Most viruses are written in a low-level language, such as assembly or C. Macro viruses are written in a high-level language. These viruses are triggered when a program capable of executing the macro is run.
- **Source code**. A source code Virus looks for source code and modifies it to include the virus and to help spread the virus.
- **Polymorphic**. A polymorphic Virus changes each time it is installed to avoid detection by antivirus software. The changes do not affect the virus's functionality but change the virus's signature. A virus signature is a pattern that can be used to identify a virus, typically a series of bytes that make up the virus code.
- **Encrypted**. An encrypted Virus includes decryption code along with the encrypted virus, again to avoid detection. The virus first decrypts and then executes.
- **Stealth**. This Virus attempts to avoid detection by modifying parts of the system that could be used to detect it.
- **Tunneling**. This Virus attempts to bypass detection by an antivirus scanner by installing itself in the interrupt-handler chain. Similar viruses install themselves in device drivers.
- **Multipartite**. A Virus of this type is able to infect multiple parts of a system, including boot sectors, memory, and files. This makes it difficult to detect and contain.
- **Armored**. An armored Virus is coded to make it hard for antivirus researchers to unravel and understand. It can also be compressed to avoid detection and disinfection. In addition, virus droppers and other full files that are part of a virus infestation are frequently hidden via file attributes or unviewable file names.

14.3 System and Network Threats

Program threats typically use a breakdown in the protection mechanisms of a system to attack programs. In contrast, system and network threats involve the abuse of services and network connections. System and network threats create a situation in which Operating System resources and User files are misused.

Sometimes, a system and network attack is used to launch a program attack, and vice versa. The more open an operating system is, the more services it has enabled and the more functions it allows, the more likely it is that a bug is available to exploit. Such changes reduce the system's Attack Surface.

Defn 226 (Attack Surface)**.** The *attack surface* of a system is the set of ways in which an attacker can try to break into the system.

It is important to note that masquerading and replay attacks are also commonly launched over networks between systems. In general, sharing secrets (to prove identity and as keys to encryption) is required for authentication and encryption, and sharing secrets is easier in environments in which secure sharing methods exist.

14.3.1 Worms

Defn 227 (Worm)**.** A *worm* is a process that uses a spawn mechanism to duplicate itself. The spawned copies use up system resources and may lock out all other Processes. The copies can also execute arbitrary code, which means they can cause other damage too.

On computer networks, worms are particularly potent, since they may reproduce themselves among systems and thus shut down an entire network.

14.3.2 Port Scanning

Port scanning is not an attack but rather a means for a cracker to detect a system's vulnerabilities to attack. Port scanning typically is automated, involving a tool that attempts to create a TCP/IP connection to a specific port or a range of ports.

One such program is `nmap` is a very versatile open-source utility for network exploration and security auditing. When pointed at a target, it will determine what services are running, including application names and versions. It can identify the host operating system. It can also provide information about defenses, such as what firewalls are defending the target. It does not exploit any known bugs.

Because port scans are detectable, they frequently are launched from zombie systems. Such systems are previously compromised, independent systems that are serving their original owners while also being used for nefarious purposes. Zombies make attackers particularly difficult to prosecute because determining the source of the attack and the person that launched it is challenging. This is one of many reasons for securing all systems, including "inconsequential" systems, not just systems containing "valuable" information or services.

14.3.3 Denial of Service

Denial-of-service attacks are aimed not at gaining information or stealing resources but rather at disrupting legitimate use of a system or facility. Most such attacks involve systems that the attacker has not penetrated. Launching an attack that prevents legitimate use is frequently easier than breaking into a machine or facility. Generally, it is impossible to prevent denial-of-service attacks. The attacks use the same mechanisms as normal operation.

Denial-of-service attacks are generally network-based. They fall into two categories:

1. The attack uses so many facility resources that no useful work can be done.
2. Disrupting the network of the facility.

Even more difficult to prevent and resolve are distributed denial-of-service (DDOS) attacks. These attacks are launched from multiple sites at once, toward a common target, typically by zombies.

14.4 Cryptography

In an isolated computer, the Operating System can reliably determine the sender and recipient of all interprocess communication, since it controls all communication channels in the computer. In a network of computers, the situation is quite different. A networked computer receives bits "from the wire" with no immediate and reliable way of determining what machine or application sent those bits. Similarly, the computer sends bits onto the network with no way of knowing who might eventually receive them. Additionally, there is no way of knowing if an eavesdropper listened to the communication.

It is generally considered infeasible to build a network of any scale in which the source and destination addresses of packets can be trusted in this sense. Therefore, the only alternative is somehow to eliminate the need to trust the network. This is the job of cryptography.

Cryptography enables a recipient of a message to verify that the message was created by some computer possessing a certain key. Similarly, a sender can encode its message so that only a computer with a certain key can decode the message. Keys are designed so that it is not computationally feasible to derive them from the messages they were used to generate or from any other public information. Thus, they provide a much more trustworthy means of constraining senders and receivers of messages.

> For a greater in-depth discussion of cryptography and the mathematics, algorithms, and theory behind what is in use, please refer to EDIN01, Cryptography.

14.4.1 Encryption

Encryption is used frequently in many aspects of modern computing. It is used to send messages securely across across a network, as well as to protect database data, files, and even entire disks from having their contents read by unauthorized entities. An encryption algorithm enables the sender of a message to ensure that only a computer possessing a certain key can read the message, or ensure that the writer of data is the only reader of that data.

An encryption algorithm consists of the following components:

- A set $\mathcal{K}$ of keys.
- A set $\mathcal{M}$ of messages.
- A set $\mathcal{C}$ of ciphertexts.
- An encrypting function $E : \mathcal{K} \to (\mathcal{M} \to \mathcal{C})$. Meaning that for each $k \in \mathcal{K}$, E_k is a function for generating ciphertexts from plaintext messages. Both E and E_k for any k should be efficiently computable functions.
- A decrypting function $D : \mathcal{K} \to (\mathcal{C} \to \mathcal{M})$. That is, for each $k \in \mathcal{K}$, D_k is a function for generating plaintext messages from ciphertexts. Both D and D_k for any k should be efficiently computable functions.

An encryption algorithm must provide this essential property:

> Given a ciphertext $c \in \mathcal{C}$, a computer can compute m such that $E_k(m) = c$ only if it possesses k.

Thus, a computer holding k can decrypt ciphertexts to the plaintexts used to produce them, but a computer not holding k cannot decrypt ciphertexts. Since ciphertexts are generally exposed (for example, sent on a network), it must be infeasible to derive k from the ciphertexts.

14.4.1.1 Symmetric Encryption

Defn 228 (Symmetric Encryption)**.** *Symmetric Encryption* uses algorithms that take in the **SAME** key for both encryption and decryption. There are 2 types of symmetric encryption algorithms: block ciphers and stream ciphers.

In a Symmetric Encryption algorithm, the same key is used to encrypt and to decrypt. Therefore, the secrecy of k must be protected. Note that the key exchange can take place directly between the two parties or via a trusted third party (such as a certificate authority).

Encryption algorithms that work on a block of bits at a time is known as a block cipher. Block ciphers are not in themselves secure encryption schemes. With block ciphers, if the same key is used for encrypting messages longer than their required block sizes extended amount of data, the encryption algorithm becomes vulnerable to attack. However, there are many modes of encryption that are based on stream ciphers, which can be used to securely encrypt longer messages.

A stream cipher is designed to encrypt and decrypt a stream of bytes or bits rather than a block. This is useful when the length of a communication would make a block cipher too slow. The key is input into a pseudo–random-bit generator, which is an algorithm that attempts to produce random bits. The output of the generator when fed a key is a keystream. A keystream is an infinite set of bits that can be used to encrypt a plaintext stream by simply XORing it with the plaintext.

14.4.1.2 Asymmetric Encryption

Defn 229 (Asymmetric Encryption)**.** *Asymmetric encryption* uses algorithms that can take in 2 keys, a public and private key. The public key is available to everyone in the world, and the private one is held by the one who generated the pair.

In an Asymmetric Encryption algorithm, there are different encryption and decryption keys. An entity preparing to receive encrypted communication creates two keys and makes one of them (called the public key) available to anyone who wants it. The private key (or "secret key") must remain secret, as anyone holding that key can decrypt any message created by the matching public key. Any sender can use that key to encrypt a communication, but only the key creator can decrypt the communication. This scheme, known as public-key encryption, was a breakthrough in cryptography. No longer must a key be kept secret and delivered securely. Instead, anyone can encrypt a message to the receiving entity, and no matter who else is listening, only that entity can decrypt the message.

Asymmetric cryptography is much more computationally expensive to execute. It is much faster for a computer to encode and decode ciphertext using symmetric algorithms than by using asymmetric algorithms. However, these algorithms are not used for general-purpose encryption of large amounts of data. They are used not only for encryption of small amounts of data but also for Authentication, confidentiality, and Key Distribution.

14.4.1.3 Authentication Constraining the set of potential senders of a message is called authentication. Authentication is thus complementary to encryption. Authentication is also useful for proving that a message has not been modified.

Note that this sort of authentication is similar to but distinct from User Authentication.

An authentication algorithm using symmetric keys consists of the following components:

- A set $\mathcal{K}$ of keys.
- A set $\mathcal{M}$ of messages.
- A set $\mathcal{A}$ of authenticators.
- A function $S : \mathcal{K} \rightarrow (\mathcal{M} \rightarrow \mathcal{A})$. That is, for each $k \in \mathcal{K}$, S_k is a function for generating authenticators from messages. Both S and S_k for any k should be efficiently computable functions.
- A function $V : \mathcal{K} \rightarrow (\mathcal{M} \times \mathcal{A} \rightarrow \{\texttt{true}, \texttt{false}\})$. That is, for each $k \in \mathcal{K}$, V_k is a function for verifying authenticators on messages. Both V and V_k for any k should be efficiently computable functions.

The critical property that an authentication algorithm must possess is this:

> For a message m, a computer can generate an authenticator $a \in \mathcal{A}$ such that $V_k(m, a) = \texttt{true}$ only if it possesses k.

Thus, a computer holding k can generate authenticators on messages so that any computer possessing k can verify them. However, a computer not holding k cannot generate authenticators on messages that can be verified using V_k. Since authenticators are generally exposed (for example, sent on a network with the messages themselves), it must not be feasible to derive k from the authenticators. Practically, if $V_k(m, a) = \texttt{true}$, then we know that m has not been modified, and that the sender of the message has k. If we share k with only one entity, then we know that the message originated from k.

All authentication algorithms rely on the proper functioning of Hash Functions.

Defn 230 (Hash Function)**.** A *hash function* $H(m)$ creates a small, fixed-sized block of data, known as a *message digest* or *hash value*, from a message m. Hash functions work by taking a message, splitting it into blocks, and processing the blocks to produce an n-bit hash. H must be collision resistant; it must be infeasible to find an $m' \neq m$ such that $H(m) = H(m')$. If $H(m) = H(m')$, we know that $m = m'$; we know that the message has not been modified.

The first main type of authentication algorithm uses symmetric encryption. In a message-authentication code (MAC), a cryptographic checksum is generated from the message using a secret key. A MAC provides a way to securely authenticate short values. If we use it to authenticate $H(m)$ for an H that is collision resistant, then we obtain a way to securely authenticate long messages by hashing them first. k is needed to compute both S_k and V_k, so anyone able to compute one can compute the other.

The second main type of authentication algorithm is a digital-signature algorithm, and the authenticators thus produced are called digital signatures. Digital signatures are very useful in that they enable anyone to verify the authenticity of the message. In a digital-signature algorithm, it is computationally infeasible to derive k_s from k_v. Thus, k_v is the public key, and k_s is the private key.

Authentication is a component of many aspects of security. Digital signatures are the core of nonrepudiation, which supplies proof that an entity performed an action. A typical example of nonrepudiation involves the filling out of electronic forms as an alternative to the signing of paper contracts. Nonrepudiation assures that a person filling out an electronic form cannot deny that he did so.

14.4.1.4 Key Distribution

The delivery of the symmetric key is a huge challenge. Sometimes it is performed out-of-band, for instance, via a paper document or a conversation. These methods do not scale well. Also consider the key-management challenge. Suppose a user wanted to communicate with N other users privately. That user would need N keys and, for more security, would need to change those keys frequently.

These are the very reasons for efforts to create asymmetric key algorithms. The keys be exchanged in public, but a given user needs only one private key, no matter how many other people they want to communicate with. There is still the matter of managing a public key for each recipient of the communication, but since public keys need not be secured, simple storage can be used for that key ring.

The problem of asymmetric public key distribution is one of authentication. What we need is proof of who owns a given public key. One way to solve that problem involves the use of digital certificates. A digital certificate is a public key digitally signed by a trusted party. The trusted party receives proof of identification from some entity and certifies that the public key belongs to that entity.

But how do we know we can trust the certifier? These certificate authorities have their public keys included within web browsers (and other consumers of certificates) before they are distributed. The certificate authorities can then vouch for other authorities (digitally signing the public keys of these other authorities), and so on, creating a **web of trust**.

14.4.2 Implementation

Network protocols are typically organized in layers, like an onion, with each layer acting as a client of the one below it. That is, when one protocol generates a message to send to its protocol peer on another machine, it hands its message to the protocol below it in the network-protocol stack for delivery to its peer on that machine.

Cryptography can be inserted at almost any layer in the OSI model. SSL provides security at the transport layer. Network-layer security generally has been standardized on IPSec, which defines IP packet formats that allow the insertion of authenticators and the encryption of packet contents. IPSec is becoming widely used as the basis for virtual private networks (VPNs), in which all traffic between two IPSec endpoints is encrypted to make a private network out of one that may otherwise be public.

More protocols benefit from protections placed lower in the stack. On the other hand, protection at lower layers in the protocol stack may give insufficient protection to higher-layer protocols.

14.5 User Authentication

If a system cannot authenticate a user, then authenticating that a message came from that user is pointless. Thus, a major security problem for operating systems is user authentication. The protection system depends on the ability to identify the programs and processes currently executing, which in turn depends on the ability to identify each user of the system.

Users normally identify themselves. So how do we determine whether a user's identity is authentic? Generally, user authentication is based on one or more of three things:

1. The user's possession of something (a key or card).

2. The user's knowledge of something (a user identifier and password).
3. An attribute of the user (fingerprint, retina pattern, or signature).

14.5.1 Passwords

The most common approach to authenticating a user identity is the use of passwords. When the user identifies themself by user ID or account name, they are asked for a password. If the user-supplied password matches the password stored in the system, the system assumes that the account is being accessed by the owner of that account. Passwords are often used to protect objects in the computer system, in the absence of more complete protection schemes. They can be treated as a special case of keys or capabilities. Different passwords may be associated with different access rights. For example, different passwords may be used for reading files, appending files, and updating files.

In practice, most systems require only one password for a user to gain full rights. Although more passwords theoretically would be more secure, such systems tend not to be implemented due to the classic trade-off between security and convenience. If security makes something inconvenient, then the security is frequently bypassed or otherwise circumvented.

14.5.2 Password Vulnerabilities

Passwords are extremely common because they are easy to understand and use. Unfortunately, passwords can often be guessed, accidentally exposed, sniffed (read by an eavesdropper), or illegally transferred from an authorized user to an unauthorized one. There are two common ways to guess a password.

1. One way is for the intruder (either human or program) to know the user or to have information about the user. All too frequently, people use personal information as their passwords.
2. The other way is to use brute force, enumerating all possible combinations of valid password characters until the password is found.

In addition to being guessed, passwords can be exposed as a result of visual or electronic monitoring.

The final type of password compromise, illegal transfer, is the result of human nature. Most computer installations have a rule that forbids users to share accounts. This rule is sometimes implemented for accounting reasons but is often aimed at improving security. Sometimes, users break account-sharing this behavior can result in a system's being accessed by unauthorized users.

Passwords can be either generated by the system or selected by a user. However, system-generated passwords may be difficult to remember. Some systems also age passwords, forcing users to change their passwords at regular intervals. This method is not foolproof either, because users can easily toggle between two passwords. The solution, as implemented on some systems, is to record a password history for each user.

14.5.3 Securing Passwords

One problem with all these approaches is the difficulty of keeping the password secret within the computer. How can the system store a password securely yet allow its use for authentication when the user presents her password? The UNIX system uses secure hashing to avoid the necessity of keeping its password list secret. Because the list is hashed rather than encrypted, it is impossible for the system to decrypt the stored value and determine the original password. When a user presents a password, it is hashed and compared against the stored encoded password. Even if the stored encoded password is seen, it cannot be decoded, so the password cannot be determined.

Systems also include a "salt," or recorded random number, in the hashing algorithm. The salt value is added to the password to ensure that if two plaintext passwords are the same, they result in different hash values.

14.5.4 One-Time Passwords

To avoid the problems of password sniffing and shoulder surfing, a system can use a set of paired passwords. When a session begins, the system randomly selects and presents one part of a password pair; the user must supply the other part. In this system, the user is challenged and must respond with the correct answer to that challenge.

This approach can be generalized to the use of an algorithm as a password. Such algorithmic passwords are not susceptible to reuse. That is, a user can type in a password, and no entity intercepting that password will be able to reuse it.

A one-time password generator that requires input by the user involves two-factor authentication. Two different types of components are needed: a one-time password generator that generates the correct response only if the PIN is valid and the PIN itself. Two-factor authentication offers far better authentication protection than single-factor authentication because it requires "something you have" as well as "something you know."

14.6 Implementing Security Defenses

14.6.1 Security Policy

The first step toward improving the security of any aspect of computing is to have a security policy. Policies vary widely but generally include a statement of what is being secured. Without a policy in place, it is impossible for users and administrators to know what is permissible, what is required, and what is not allowed.

14.6.2 Vulnerability Assessment

How can we determine whether a security policy has been correctly implemented? The best way is to execute a vulnerability assessment. Such assessments can cover broad ground, from social engineering through risk assessment to port scans.

The core activity of most vulnerability assessments is a penetration test, in which the entity is scanned for known vulnerabilities. Vulnerability scans typically are done at times when computer use is relatively low, to minimize their impact. When appropriate, they are done on test systems rather than production systems.

A scan within an individual system can check a variety of aspects of the system:

- Short or easy-to-guess passwords.
- Unauthorized privileged Programs, such as `setuid` programs.
- Unauthorized programs in system directories.
- Unexpectedly long-running Processes.
- Improper directory protections on user and system directories.
- Improper protections on system data files, such as the password file, device drivers, or the Operating System Kernel itself.
- Dangerous entries in the program search path.
- Changes to system programs detected with checksum values.
- Unexpected or hidden network Daemons.

Any problems found by a security scan can be either fixed automatically or reported to the managers of the system.

Networked computers are much more susceptible to security attacks than are standalone systems. Unfortunately for system administrators and computer-security professionals, it is frequently impossible to lock a machine in a room and disallow all remote access. Vulnerability scans can be applied to networks to address some of the problems with network security. The scans search a network for ports that respond to a request. If services are enabled that should not be, access to them can be blocked, or they can be disabled. The scans then determine the details of the application listening on that port and try to determine if it has any known vulnerabilities. Testing those vulnerabilities can determine if the system is misconfigured or lacks needed patches.

14.6.3 Intrusion Detection

Securing systems and facilities is intimately linked to intrusion detection. Intrusion detection strives to detect attempted or successful intrusions into computer systems and to initiate appropriate responses to the intrusions. Intrusion detection encompasses a wide array of techniques, including:

- The time at which detection occurs. Detection can occur in real time (while the intrusion is occurring) or after the fact.
- The types of inputs examined to detect intrusive activity. These may include User-shell commands, process System Calls, and network packet headers or contents. Some forms of intrusion might be detected only by correlating information from several such sources.
- The range of response capabilities. Simple forms of response include alerting an administrator to the potential intrusion or somehow halting the potentially intrusive activity. In a sophisticated form of response, a system might transparently divert an intruder's activity to a honeypot—a false resource exposed to the attacker. The resource appears real to the attacker and enables the system to monitor and gain information about the attack.

These degrees of freedom in the design space for detecting intrusions have yielded a wide range of solutions, known as intrusion-detection systems (IDSs) and intrusion-prevention systems (IDPs). IDS systems raise an alarm when an intrusion is detected, while IDP systems act as routers, passing traffic unless an intrusion is detected (at which point that traffic is blocked).

Automatic IDSs and IDPs today typically settle for one of two less ambitious approaches:

1. Signature-Based Detection. System input or network traffic is examined for specific behavior patterns (signatures) known to indicate attacks. For example, scanning network packets for the string `/etc/passwd/` targeted for a UNIX system. Another example is Virus-detection software, which scans binaries or network packets for known viruses.

2. Anomaly Detection. Detect anomalous behavior within computer systems. Of course, not all anomalous system activity indicates an intrusion, but the presumption is that intrusions often induce anomalous behavior. An example of anomaly detection is monitoring System Calls of a Daemon Process to detect whether the system call behavior deviates from normal patterns.

14.6.4 Virus Protection

Protection from Viruses thus is an important security concern. Antivirus programs are often used to provide this protection. Some of these programs are effective against only particular known viruses. They work by searching all the programs on a system for the specific pattern of instructions known to make up the virus. Antivirus programs may have catalogs of thousands of viruses for which they search. When they find a known pattern, they remove the instructions, disinfecting the program.

Some viruses modify themselves as they infect other software to avoid the basic pattern-match approach of antivirus programs. Antivirusb programs in turn now look for families of patterns rather than a single pattern to identify a virus.

14.6.5 Auditing, Accounting, and Logging

Auditing, accounting, and logging decrease system performance, but they are useful in several areas, including security. Logging can be general or specific. For example, all System Call executions can be logged for analysis of program behavior. More typically, only suspicious events are logged.

Authentication failures and authorization failures can tell us quite a lot about break-in attempts.

Accounting is another potential tool in a security administrator's kit. It can be used to find performance changes, which in turn can reveal security problems.

14.7 Firewalling

Now, how can a trusted computer can be connected safely to an untrustworthy network? The most common solution is the use of a Firewall to separate trusted and untrusted systems.

Defn 231 (Firewall)**.** A *firewall* is a computer, appliance, or router that sits between the trusted and the untrusted.

A network Firewall limits network access between the two security domains and monitors and logs all connections. It can also limit connections based on source or destination address, source or destination port, or direction of the connection. In fact, a network firewall can separate a network into multiple domains. A common implementation has the Internet as the untrusted domain; a semitrusted/semisecure network, called the demilitarized zone (DMZ); and the trusted computers as a third domain.

Of course, a Firewall itself must be secure and attack-proof. Otherwise, its ability to secure connections can be compromised. Furthermore, firewalls do not prevent attacks that tunnel, or travel within protocols or connections that the firewall allows. A buffer-overflow attack to a web server will not be stopped by the firewall, for example, because the HTTP connection is allowed; it is the contents of the HTTP connection that house the attack. Likewise, denial-of-service attacks can affect firewalls as much as any other machines. Another vulnerability of firewalls is spoofing, in which an unauthorized host pretends to be an authorized host by meeting some authorization criterion.

15 Virtual Machines

With a Virtual Machine, guest Operating Systems and applications run on a system utilizing Virtualization.

Defn 232 (Virtualization)**.** *Virtualization* is the act of abstracting the Hardware of a single computer into several different execution environments. Each of these execution environments operates under the illusion that they are the only environment running on its own private computer. These "computer" for these environments appears to be native hardware and things in these environments behave as native hardware would but that also protects, manages, and limits them.

This concept is similar to the Layered Approach of Operating System implementation (see Section 1.7.2). In the case of Virtualization, there is a layer that creates a virtual system on which operating systems or applications can run.

Defn 233 (Virtual Machine)**.** A *Virtual Machine* (*VM*, not to be confused with Virtual Memory's VM) is an Operating System that is running inside an execution environment provided by Virtualization. The operating system running on this virtualized hardware believes it is running on real hardware, with all of its quirks and problems. This operating system also believes it is the **only** one running, when there could be several virtual machines running on the same hardware.

Virtual Machine implementations involve several components. At the base is the Host.

Defn 234 (Host)**.** The *host* is the the underlying physical Hardware system that runs the virtual machines.

The Host runs the Virtual Machine Manager.

Defn 235 (Virtual Machine Manager)**.** The *Virtual Machine Manager* (*VMM*), also known as a *hypervisor* creates and runs virtual machines by providing an interface that is identical to the host to every guest..

Remark 235.1. This is true except in the case of Paravirtualization.

Each guest process is provided with a virtual copy of the host. Usually, the guest process is an Operating System. A single physical machine can run multiple operating systems concurrently, each in its own virtual machine.

With Virtualization, the definition of "Operating System" once again blurs. For example, consider Virtual Machine Manager software such as VMware ESX. This virtualization software:

- Is installed on the hardware
- Runs when the hardware boots
- Provides services to applications
  - CPU scheduling
  - Memory Management
  - Migration of VMs between systems.

Furthermore, the "applications" are guest Operating Systems. Is the VMware ESX VMM an operating system that, in turn, runs other operating systems? It certainly acts like an operating system.

The implementation of VMMs varies greatly. Options include the following:

- Hardware-based solutions that provide support for virtual machine creation and management via Firmware. These VMMs, which are only found in mainframes, are known as Type 0 Hypervisor. IBM LPARs and Oracle LDOMs are examples.
- Operating System-like software built to provide Virtualization, including VMware ESX, Joyent SmartOS, and Citrix XenServer. These VMMs are known as Type 1 Hypervisors.
- General-purpose Operating Systems that provide standard functions **as well as** Virtual Machine Manager functions, including Microsoft Windows Server with HyperV and Linux with the KVM feature. Because such systems have a feature set similar to Type 1 Hypervisors, they are also considered type 1.
- Regular applications that run on standard Operating Systems but provide Virtual Machine Manager features to guest operating systems. These applications, which include VMware, Parallels Desktop, and Oracle VirtualBox, are Type 2 Hypervisors.
- Paravirtualization, a technique in which the guest Operating System is modified to work in cooperation with the Virtual Machine Manager to optimize performance.
- Programming-environment virtualization, in which Virtual Machine Managers do not virtualize real hardware but instead create an optimized virtual system. This technique is used by Oracle Java and Microsoft.Net.
- Emulators that allow applications written for one hardware environment to run on a very different hardware environment, such as a different type of CPU.
- Application containment, which is not virtualization at all but rather provides virtualization-like features by segregating applications from the Operating System. Solaris Zones, BSD Jails, and Docker "contain" applications, making them more secure and manageable.

A formal definition of Virtualization helped to establish system requirements and a target for functionality. The virtualization requirements stated that:

1. A VMM provides an environment for programs that is essentially identical to the original machine.
2. Programs running within that environment show only minor performance decreases.
3. The VMM is in complete control of physical system resources.

These requirements of fidelity, performance, and safety still guide Virtualization efforts today.

15.1 Benefits and Features

Several advantages make Virtualization attractive. Most of them are related to the ability for several different execution environments (Operating Systems) to concurrently share the same Hardware.

One important advantage of Virtualization is that the host system is protected from the Virtual Machines, just as the virtual machines are protected from each other. A virus inside a guest Operating System might damage that operating system but is unlikely to affect the host or the other guests. Because each virtual machine is almost completely isolated from all other virtual machines, there are almost no protection problems. This isolation can also be a problem, because it is difficult to share legitimate resources. However, there are 2 approaches handling this problem:

1. Share a File System Volume and thus to share files.

2. Define a virtual network of Virtual Machines, each of which can send information over the virtual communications network. The network is modeled after physical communication networks but is implemented in software.

One feature common to most Virtualization implementations is the ability to **suspend**, a running Virtual Machine. Most Operating Systems provide this basic feature for Processes, but in a virtualized system, the guest operating system **is** a "process", which means it can be suspended. Virtual Machine Managers can go one step further and allow copies and **snapshots** to be made of the guest. The copy can be used to create a new VM or to move a VM from one machine to another with its current state intact. The guest can then resume where it was, as if on its original machine, creating a clone. The snapshot records a point in time, and the guest can be reset to that point if necessary. Often, VMMs allow any number snapshots to be taken, so long as storage allows. These abilities are used to good advantage in virtual environments.

A Virtual Machine system is a perfect vehicle for low-level development. For example, changing an Operating System is a difficult task. Operating systems are large and complex programs, and a change in one part may cause obscure bugs to appear in some other part. The power of the operating system makes changing it particularly dangerous. Because the operating system executes in kernel mode, a wrong change in a pointer could cause an error that would destroy the entire file system.

Another benefits is that system programmers can be given their own Virtual Machine, and development is done on the virtual machine instead of on a physical machine. When a deployment happens, normal system operation is disrupted only when a completed and tested change is ready to be put into production. Another advantage of virtual machines for developers is that multiple Operating Systems can run concurrently on the developer's workstation. This virtualized workstation allows for rapid porting and testing of programs in varying environments. In addition, multiple versions of a program can run, each in its own isolated operating system, within one system.

A major advantage of Virtual Machines in production data-center use is system Consolidation.

Defn 236 (Consolidation)**.** *Consolidation* involves taking physically separate systems and running them in Virtual Machines on one system. These physical-to-virtual conversions typically result in a maximization of resource usage, since many separate lightly used systems can be combined to create one more heavily used system.

One of the tools that make this possible is templating, where one standard Virtual Machine image, including an installed and configured guest Operating System and applications, is saved and used as a source for multiple running VMs. Other features include managing the patching of all guests, backing up and restoring the guests, and monitoring their resource use. This batch management allows a single system administrator to handle many times the regular amount of physical servers.

Some VMMs include a live migration feature that moves a running guest from one physical server to another without interrupting its operation or active network connections. If a server is overloaded, live migration can thus free resources on the source host while not disrupting the guest. Similarly, when Host Hardware must be repaired or upgraded, guests can be migrated to other servers, the evacuated host can be maintained, and then the guests can be migrated back. This operation occurs without downtime and without interruption to users.

15.2 Building Blocks

Although the virtual machine concept is useful, it is difficult to implement. Much work is required to provide an exact duplicate of the underlying machine. This is especially a challenge on dual-mode systems, where the underlying machine has only user mode and kernel mode.

Remark. Note that these building blocks are not required by Type 0 Hypervisors.

The ability to virtualize heavily depends on the hardware features provided by the CPU. If the features are sufficient, then it is possible to write a Virtual Machine Manager that provides a guest environment. Otherwise, Virtualization is impossible.

If it is possible to virtualize a system, the Virtual Machine Managers use several techniques to implement it, including Trap-and-Emulate and Binary Translation.

One important concept found in most virtualization options is the implementation of a Virtual CPU.

Defn 237 (Virtual CPU)**.** The *Virtual CPU* (*VCPU*) does not execute code. Rather, it represents the state of the guest's CPU as the guest machine believes it to be. For each guest, the VMM maintains a VCPU representing that guest's current CPU state, much like a Process Control Block. When the guest is Context Switched onto a physical CPU by the Virtual Machine Manager, information from the VCPU is used to load the right context, much as a general-purpose Operating System would use the PCB.

15.2.1 Trap-and-Emulate

On a typical dual-mode system, the virtual machine guest can execute only in user mode (unless extra hardware support is provided). The kernel, of course, runs in kernel mode, and it is not safe to allow user-level code to run in kernel mode. Just as the physical machine has two modes, however, so must the virtual machine. Consequently, we must have a virtual user mode and a virtual kernel mode, both of which run in physical user mode. Actions that cause a transfer from user mode to kernel mode on a real machine (such as a System Call, an Interrupt, or an attempt to execute a privileged instruction) must also cause a transfer from virtual user-mode to virtual kernel-mode in the Virtual Machine.

When the kernel in the guest attempts to execute a privileged instruction, that is an error (because the system is in both physical user-mode and virtual user-mode) and causes a trap to the Virtual Machine Manager in the real machine. The VMM gains control and executes (or "emulates") the action that was attempted by the guest kernel on the part of the guest. It then returns control to the Virtual Machine.

With privileged instructions, time becomes an issue. All nonprivileged instructions run natively on the Hardware, providing the same performance for guests as native applications. Privileged instructions create extra overhead, causing the guest to run more slowly than it would natively. In addition, the CPU is being multiprogrammed among many Virtual Machines, which can further slow down the virtual machines in unpredictable ways.

Only the privileged instructions (needed mainly for I/O) must be emulated and hence only these instructions execute more slowly. In general, with the evolution of hardware, the performance of trap-and-emulate functionality has been improved, and cases in which it is needed have been reduced. For example, many CPUs now have extra modes added to their standard dual-mode operation.

15.2.2 Binary Translation

Some CPUs do not have a clean separation of privileged and nonprivileged instructions. This includes the Intel x86 CPU line, which started in 1978. The chip has maintained backward compatibility throughout its lifetime, preventing changes that would have made virtualization easier through many generations.

For example, `popf` instruction loads the flag register from the contents of the stack. If the CPU is in privileged mode, **all** of the flags are replaced from the stack. If the CPU is in user mode, then only some flags are replaced, and others are ignored. Because no trap is generated if `popf` is executed in user mode, the Trap-and-Emulate procedure is rendered useless. Other x86 instructions cause similar problems. These instructions will be refered to as **special instructions**. As recently as 1998, it seemed that using the trap-and-emulate method to implement Virtualization on the x86 was considered impossible because of these special instructions.

Binary translation is fairly simple in concept but complex in implementation. The basic steps are as follows:

1. If the guest VCPU is in user mode, the guest can run its instructions natively on a physical CPU.
2. If the guest VCPU is in kernel mode, then the guest believes that it is running in kernel mode. The Virtual Machine Manager examines every instruction the guest executes in virtual kernel mode by reading the next few instructions that the guest is going to execute, based on the guest's program counter. Instructions other than special instructions are run natively. Special instructions are translated into a new set of instructions that perform the equivalent task—for example changing the flags in the VCPU.

This basic method of binary translation just described would execute correctly but perform poorly. Fortunately, the vast majority of instructions would execute natively. Caching of previously translated instructions can provide further increases to performance, particularly if the cache is large enough.

15.2.3 Hardware Assistance

Without some level of hardware support, virtualization would be impossible. The more hardware support available within a system, the more feature-rich and stable the virtual machines can be and the better they can perform.

For example, AMD Virtualization technology (AMD-V) defines two additional modes of operation: host and guest. This makes these CPUs multimode processors, rather than dual-mode. The Virtual Machine Manager can enable host mode, define the characteristics of each guest Virtual Machine, and then switch the system to guest mode, passing control of the system to a guest operating system that is running in the virtual machine. In guest mode, the virtualized operating system thinks it is running on native hardware and sees whatever devices are included in the host's definition of the guest. If the guest tries to access a virtualized resource, then control is passed to the VMM to manage that interaction.

These multimode processors, developed for Virtualization provide guest Virtual CPU state data structures to load and save guest CPU state automatically during guest context switches. In addition, virtual machine control structures (VMCSs) are provided to manage guest and host state, as well as the various guest execution controls, exit controls, and information about why guests exit back to the host.

AMD and Intel have also addressed memory management in the virtual environment. With these memory management enhancements, VMMs no longer need to implement software Nested Page Tables (NPTs). These CPUs implement nested page tables in hardware to allow the VMM to fully control paging while the CPUs accelerate the translation from virtual to physical addresses. The NPTs add a new layer, one representing the guest's view of logical-to-physical address translation. The CPU page-table walking function includes this new layer as necessary, walking through the guest table to the VMM table to find the physical address desired. This process is illustrated in Figure 15.1.

I/O is another area improved by hardware assistance. Remember that the standard Direct-Memory-Access Controller accepts a target memory address and a source I/O device and transfers data between the two without Operating System

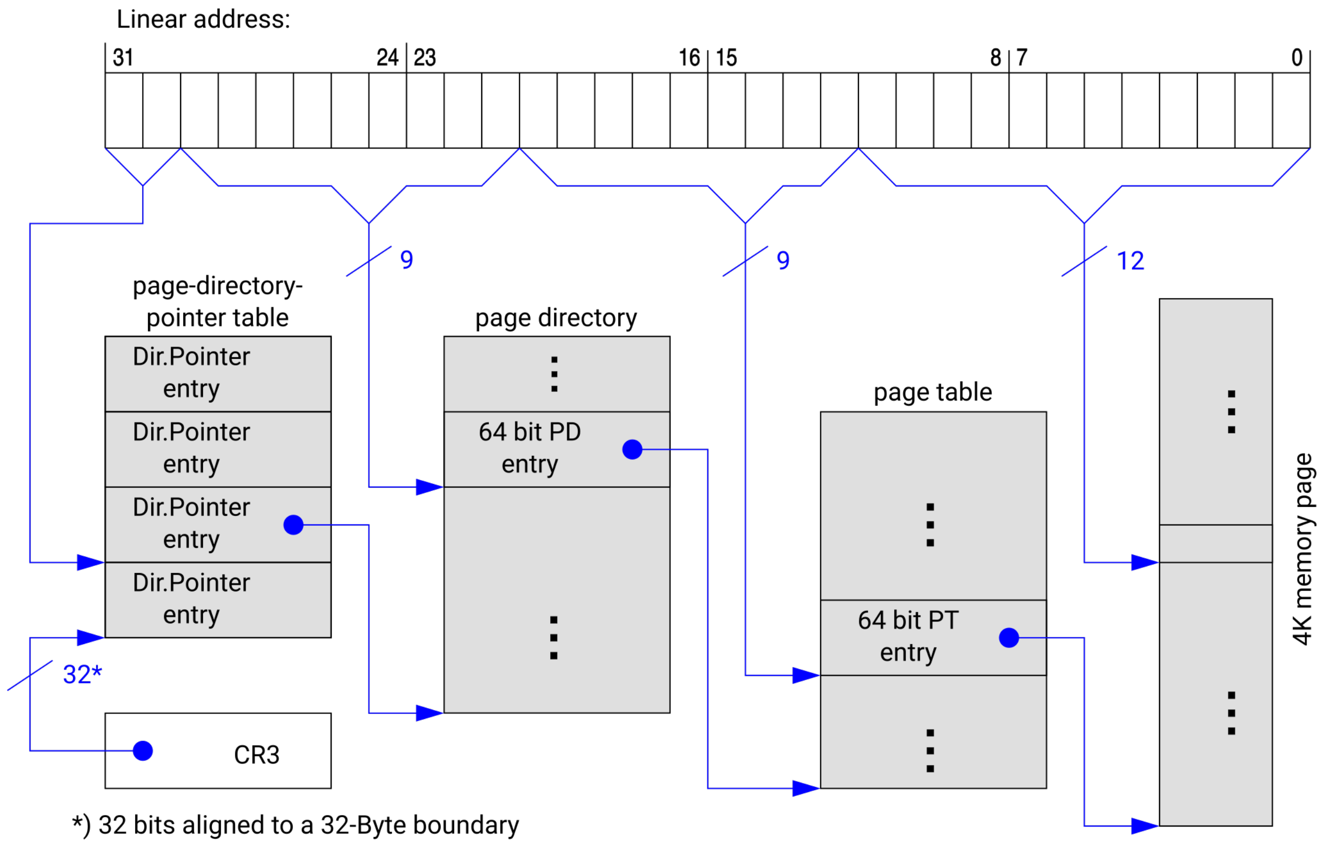


Figure 15.1: Nested Page Tables, for Virtualization

action. Without hardware assistance, a guest might try to set up a DMA transfer that affects the memory of the VMM or other guests. In CPUs that provide hardware-assisted DMA, even DMA has a level of indirection.

1. The VMM sets up protection domains to tell the CPU which physical memory belongs to each guest.
2. Assigns the I/O devices to the protection domains, allowing them direct access to those memory regions and only those regions.
3. The hardware then transforms the address in a DMA request issued by an I/O device to the host physical memory address associated with the I/O.

In this manner DMA transfers are passed through between a guest and a device without VMM interference.

Similarly, interrupts must be delivered to the appropriate guest and must not be visible to other guests. By providing an interrupt remapping feature, CPUs with virtualization hardware assistance automatically deliver an interrupt destined for a guest to a core that is currently running a thread of that guest. That way, the guest receives interrupts without the VMM's needing to intercede in their delivery. Without interrupt remapping, malicious guests can generate interrupts that can be used to gain control of the host system.

15.3 Types of Virtualization

Here, I discuss the ways that virtual environments are created using Virtualization and the Building Blocks discussed earlier. Of course, the hardware on which the virtual machines are running can cause great variation in implementation methods. Throughout this discussion, it is safe to assume that Virtual Machine Managers take advantage of hardware assistance when possible.

15.3.1 Virtual Machine Life Cycle

Whatever the hypervisor type, at the time a virtual machine is created, its creator gives the Virtual Machine Manager certain parameters. These parameters usually include:

- Number of CPUs.
- Amount of memory.
- Networking details.
- Storage details.

For example, a user might want to create a new guest with:

- Two Virtual CPUs
- 4 GiB of memory
- 10 GiB of disk space
- One network interface that gets its IP address via DHCP
- Access to the DVD drive

In the case of a Type 0 Hypervisor, the resources are usually dedicated in hardware. In this situation, if there are not two virtual CPUs available and unallocated, the creation request will fail. For other hypervisor types, the resources are dedicated or virtualized, depending on the type. Obviously, an IP address cannot be shared, but the Virtual CPUs are usually multiplexed on the physical CPUs. Similarly, memory management usually involves allocating more memory to guests than actually exists in physical memory. This is more complicated than multiplexing memory like we do the CPU.

When the Virtual Machine is no longer needed, it can be deleted. When this happens, the Virtual Machine Manager first frees up any used disk space and then removes the configuration associated with the virtual machine, essentially "forgetting" the virtual machine. These steps are quite simple compared with building, configuring, running, and removing physical machines.

15.3.2 Type 0 Hypervisor

Type 0 Hypervisors have existed for many years under many names, including "partitions" and "domains". They are a hardware feature, and that brings its own positives and negatives. The feature set of a Type 0 Hypervisor tends to be smaller than those of the other types because it is implemented in Hardware.

Defn 238 (Type 0 Hypervisor)**.** A *Type 0 Hypervisor* provides the Virtualization required to run Virtual Machines in Firmware. This means that there is **NO** abstraction required and no abstraction overhead incurred in this method. However, this type of virtualization is also relatively inflexible, as the number of virtual domains that can be created for execution is limited by firmware.

Operating Systems need do nothing special to take advantage of their features. The Virtual Machine Manager itself is encoded in the firmware and loaded at boot time. In turn, it loads the guest images to run in each partition. Each guest believes that it has dedicated hardware, because the hardware assigned to that Virtual Machine **is** dedicated, simplifying many implementation details.

I/O presents some difficulty, because it is not easy to dedicate I/O devices to guests if there are not enough. Either all guests must get their own I/O devices, or the system must provided I/O device sharing. In these cases, the Virtual Machine Manager manages shared access or grants all devices to a control partition. In the **control partition**, a guest operating system provides services (such as networking) via Daemons to other guests, and the hypervisor routes I/O requests appropriately.

Because type 0 virtualization is very close to raw hardware execution, it should be considered separately from the other Virtualization methods discussed here. A Type 0 Hypervisor can run multiple guest operating systems (one in each hardware partition). All of those guests, because they are running on a subset of the raw hardware, can in turn be Virtual Machine Managers. Because of that, each can have its own guest operating systems. Other types of hypervisors usually cannot provide this virtualization-within-virtualization functionality.

15.3.3 Type 1 Hypervisor

Type 1 Hypervisors are special-purpose Operating Systems that run natively on the hardware. But rather than providing System Calls and other interfaces for running Programs, they create, run, and manage guest operating systems.

Defn 239 (Type 1 Hypervisor)**.** A *Type 1 Hypervisor* provides the Virtualization required to run a Virtual Machine in Software. Here, the physical resources of the system are managed by the software, either a standalone Virtual Machine Manager, or a traditional Kernel with extensions for virtualization. This is the most commonly used type of hypervisor, because of its flexibility. It can run almost any number of guests, and is limited only by its ability to schedule and handle the running guests. In this case, there are overheads incurred from using this system, as there is some abstraction of hardware resources to form a virtual interface.

Remark 239.1 (Nested Virtualization)*.* Type 1 Hypervisors **cannot** be virtually nested inside another Type 1 Hypervisor.

Type 1 Hypervisors run in Kernel-mode, taking advantage of hardware protection. Where the host CPU allows, they use multiple modes to give guest Operating Systems their own control and improved performance. They implement device drivers for the hardware they run on. Because they are operating systems, they must also provide CPU Scheduling, memory management, I/O management, Protection, and even Security.

An important benefit is the ability to perform Consolidation.

15.3.3.1 Traditional OSs as VMMs

Some general-purpose Operating Systems also provide Virtual Machine Manager functionality. For example, RedHat Enterprise Linux, Windows, or Oracle Solaris can perform its normal duties as well as providing a VMM allowing other operating systems to run as guests. Because of their extra duties, these hypervisors typically provide fewer virtualization features than other Type 1 Hypervisors. In many ways, they treat a guest operating system as just another process, albeit with special handling provided when the guest tries to execute special instructions.

15.3.4 Type 2 Hypervisor

Type 2 Hypervisors are less interesting to Operating Systems, because there is very little operating-system involvement in these application-level Virtual Machine Managers. This type of VMM is simply another process run and managed by the host, and even the Host does not know Virtualization is happening within the VMM.

Defn 240 (Type 2 Hypervisor)**.** A *Type 2 Hypervisor* provides Virtualization through Software as well, however this hypervisor is running as a User-level Process on top of another Operating System. This leads to heavy levels of abstraction, thus slowing down performance significantly. However, this also allows relatively unprivileged users to create and manage Virtual Machines on their system.

Type 2 Hypervisors have limits not associated with some of the other types. For example, a user needs administrative privileges to access many of the hardware assistance features of modern CPUs. If the VMM is being run by a standard user without additional privileges, the VMM cannot take advantage of these features. This limitation, as well as the extra overhead of running the Operating System as well as guest operating systems, type 2 hypervisors tend to have poorer overall performance than type 0 or 1.

However, this is also a benefit, because Type 2 Hypervisors run on a variety of general-purpose Operating Systems, and running them requires no changes to the Host operating system.

15.3.5 Paravirtualization

Paravirtualization presents the guest with a system that is similar but not identical to the guest's preferred system. This system does not attempt to "trick" the guest Operating System that it has its own system. Instead, the guest and the host work together for a better Virtualization experience.

The guest must be modified to run on the paravirtualized virtual hardware. The gain for this extra work is more efficient use of resources and a smaller virtualization layer.

Other Virtual Machine Managers present virtual devices to guests that **appear** to be real devices. Instead of taking that approach, the paravirtualization presents clean and simple device abstractions that allow efficient I/O, as well as good communication between the guest and the VMM about device I/O. For each device used by each guest, there is a circular buffer shared by the guest and the VMM via Shared-Memory. Read and write data are placed in this buffer.

For memory management, paravirtualization does not implement nested page tables. Rather, each guest has its own set of page tables, set to read-only. The Virtual Machine Manager requires the guest to use a specific mechanism, a Hypercall from the guest to the hypervisor VMM, when a page-table change is needed.

Defn 241 (Hypercall)**.** A *hypercall* is like a traditional System Call, but instead of going to the Operating System, it the request is passed to the Host's Virtual Machine Manager.

This means that the guest Operating System's Kernel code must be changed from the default code to these paravirtualization-specific methods. To optimize performance, paravirtualization allows the guest to queue up multiple page-table changes asynchronously via Hypercalls, then check to ensure that the changes are complete before continuing operation.

15.3.6 Programming-Environment Virtualization

Another kind of Virtualization, based on a different execution model, is the virtualization of programming environments. Here, a programming language is designed to run within a custom-built virtualized environment. The Java Virtual Machine (JVM) is an example of this.

Instead, we can define a virtual environment, based on Application Programming Interfaces, that provides a set of features that we want to have available for a particular language and programs written in that language. Java programs run within the JVM environment, and the JVM is compiled to be a native program on systems on which it runs. This arrangement means that Java programs are written once and then can run on any system on which a JVM is available. The same can be said for interpreted languages, which run inside programs that read each instruction and interpret it into native operations.

15.3.7 Emulation

Virtualization is probably the most common method for running applications designed for one Operating System on a different operating system, but on the **same** CPU. Emulation is useful when the Host system has one system architecture and the guest system was compiled for a different architecture.

Programs can run in an emulator that translates each of the outdated system's instructions into the native instruction set of the new system.

As may be expected, the major challenge of emulation is performance. Instruction-set emulation can run an order of magnitude slower than native instructions, because it may take ten instructions on the new system to read, parse, and simulate an instruction from the old system. Thus, unless the new machine is ten times faster than the old, the program running on the new machine will run more slowly than it did on its native hardware. Another challenge for emulator writers is that it is difficult to create a correct emulator because, in essence, this task involves writing an entire CPU in software.

15.3.8 Application Containment

The goal of virtualization in some instances is to provide a method to segregate applications, manage their performance and resource use, and create an easy way to start, stop, move, and manage them. In such cases, full-fledged virtualization may not be needed. If the applications are all compiled for the same Operating System, then we do not need complete virtualization to provide these features. We can instead use application containment.

In this system, **only one Kernel is installed**, and the hardware is not virtualized. Rather, the Operating System and its devices are virtualized, providing Processes with a zone that gives the impression that they are the only processes on the system. One or more containers can be created, and each can have its own applications, network stacks, network address and ports, user accounts, and so on. CPU and memory resources can be divided among the zones and the system-wide processes. Each zone in fact can run its own scheduler to optimize the performance of its applications on the allotted resources.

15.4 Virtualization and OS Components

Here, I discuss how the Virtual Machine Manager provides core Operating System functions like Scheduling, I/O, and memory management.

15.4.1 CPU Scheduling

A system with Virtualization, frequently acts like a multiprocessor system. The virtualization software presents one or more Virtual CPUs to each of the Virtual Machines running on the system and then schedules the use of the physical CPUs among the virtual machines. The significant variations among virtualization technologies make it difficult to generalize the effect of virtualization on scheduling.

First, consider the general case of Virtual Machine Manager scheduling. The VMM has a number of physical CPUs available and a number of threads to run on those CPUs. The threads can be VMM threads or guest threads. The VMM itself needs some CPU cycles for guest management and I/O management and can steal cycles from the guests by scheduling its threads across all of the system CPUs, but the impact of this action is relatively minor. Guests are configured with a certain number of Virtual CPUs at creation time, and can be adjusted throughout the life of the VM.

When there are enough CPUs to allocate the requested number to each guest, the Virtual Machine Manager can treat the CPUs as dedicated and schedule only a given guest's threads on that guest's CPUs. In this situation, the guests act much like native Operating Systems running on native CPUs. In other situations, there may not be enough CPUs to go around, especially if the CPUs have Overcommitment, where the guests are configured for more CPUs than exist in the system. Then, a VMM can use standard Scheduling Algorithms to make progress on each thread but can also add a fairness aspect to those algorithms.

Defn 242 (Overcommit)**.** Virtualization systems allow the created virtual resources to *overcommit* the system's physical resources. For example, a Virtual Machine can be given 2 Virtual CPUs, when there is only 1 physical CPU. The same can happen with memory; a guest can be configured have more memory than the host system has.

Even given a Scheduler that provides fairness, any guest Operating System scheduling algorithm that assumes a certain amount of progress in a given amount of time will be negatively affected by virtualization. Within a Virtual Machine, the guest operating system is at the mercy of the Virtualization system as to what CPU resources it actually receives.

The net effect of such scheduling layering is that individual virtualized Operating Systems receive only a portion of the available CPU cycles, even though they believe they are receiving all of the cycles and that they are scheduling for all of those cycles.

15.4.2 Memory Management

Efficient memory use in general-purpose operating systems is one of the major keys to performance. In virtualized environments, there are more users of memory (the guests and their applications, as well as the VMM), leading to more pressure on memory use. Further adding to this pressure is that VMMs typically Overcommit memory. The extra need for efficient memory mean great measures are taken to ensure the optimal use of memory.

Before memory optimization can occur, the VMM must establish how much real memory each guest should use. To do that:

1. Virtual Machine Manager evaluates the maximum memory size of each guest as dictated when it is configured.
    - General-purpose operating systems do not expect the amount of memory in the system to change, so VMMs must maintain the illusion that the guest has that amount of memory.
2. Virtual Machine Manager computes a target real memory allocation for each guest based on the configured memory for that guest and other factors, such as Overcommitment and system load.
3. Then three low-level mechanisms are used to reclaim memory from the guests.
    (a) VMM Page Replacement
    (b) Guest Pseudo-Device Driver
    (c) Page Hashing and Remapping

The overall effect is to enable guests to behave and perform as if they had the full amount of memory requested although in reality they have less.

15.4.2.1 VMM Page Replacement A guest believes it controls memory allocation via its Page Table management, whereas in reality the Virtual Machine Manager maintains a nested page table that re-translates the guest page table to the real page table. The VMM can use this extra level of indirection to optimize the guest's use of memory without the guest's knowledge or help. One approach is to provide double paging, in which the VMM has its own page-replacement algorithms. The VMM can swap pages to the Backing Store pages that the guest believes are in-memory. The VMM knows less about the guest's memory access patterns than the guest does, so its paging is less efficient, creating performance problems.

VMMs use this method when other methods are not available or are not providing enough free memory. However, it is not the preferred approach.

15.4.2.2 Guest Pseudo-Device Driver A common solution is for the VMM to install in each guest a Pseudo-Device Driver or Kernel Module that it controls.

Defn 243 (Pseudo-Device Driver)**.** A *pseudo–device driver* uses device-driver interfaces, appearing to the Kernel to be a device driver, but does not actually control a device. Rather, it is an easy way to add kernel-mode code without directly modifying the kernel.

This balloon memory manager communicates with the VMM and is told to allocate or deallocate memory. If told to allocate, it allocates memory and tells the operating system to pin the allocated pages into physical memory. The guest sees memory pressure becauses of these pinned pages, decreasing the amount of physical memory it has available to use. The guest then may free up other physical memory to be sure it has a sufficient pool of free memory. Meanwhile, the VMM, knowing that the pages pinned by the balloon process will never be used, removes those physical pages from the guest and allocates them to another guest. At the same time, the guest is using its own memory-management and paging algorithms to manage the available memory, which is the most efficient option.

If memory pressure within the entire system decreases, the VMM will tell the balloon process within the guest to unpin and free some or all of the memory, allowing the guest more pages for its use.

15.4.2.3 Page Hashing and Remapping Another common method for reducing memory pressure is for the Virtual Machine Manager to determine if the same page has been loaded more than once. If this is the case, to the VMM reduces the number of copies of the page to one and maps the other users of the page to that one copy. This can be done by randomly sampling the guests' memory and creating a hash for each page sampled. The hash of every page examined is compared with other hashes already stored in a hash table. If there is a match, the pages are compared byte by byte to see if they really are identical. If they are, one page is freed, and its logical address is mapped to the other's physical address.

This technique might seem at first to be ineffective, but consider that guests run Operating Systems. If multiple guests run the same operating system, then only one copy of the active operating-system pages need be in memory.

15.4.3 I/O

In the area of I/O, Virtual Machine Managers have some leeway and can be less concerned with exactly representing the underlying hardware to their guests. Operating Systems are used to dealing with varying and flexible I/O mechanisms. Usually, device drivers can be dynamically loaded and unloaded. Virtualization takes advantage of such built-in flexibility by providing specific virtualized devices to guest operating systems.

Virtual Machine Managers vary greatly in how they provide I/O to their guests. I/O in virtual environments is complicated and requires careful VMM design and implementation. In addition to direct access, VMMs can provide shared access to devices. The VMM must provide protection while sharing the device, assuring that a guest can access only the blocks specified in the guest's configuration. In such instances, the VMM must be part of every I/O, checking it for correctness as well as routing the data to and from the appropriate devices and guests.

In the area of networking, Virtual Machine Managers also have work to do. General-purpose Operating Systems typically have one IP address. Therefore, a server running a VMM may have dozens of addresses, and the VMM acts as a virtual switch to route the network packets to the addressed guest. The guests can be "directly" connected to the network by an IP address that is seen by the broader network (this is known as bridging). Alternatively, the VMM can provide a network address translation (NAT) address.

15.4.4 Storage Management

Type 0 Hypervisors do tend to allow root disk partitioning, partly because these systems tend to run fewer guests than other systems. Alternatively, they may have a disk manager as part of the control partition, and that disk manager provides disk space (including boot disks) to the other partitions.

Type 1 Hypervisors store the guest root disk (and configuration information) in one or more files within the file systems provided by the Virtual Machine Manager. Type 2 Hypervisors store the same information within the host operating system's file systems. Both of these create a disk image, containing all of the contents of the root disk of the guest, containing one file in the VMM. Aside from the potential performance problems that causes, it is a clever solution, because it simplifies copying and moving guests.

Because of the disk images created physical-to-virtual (P-to-V) conversion can be done. Physical-to-Virtual conversion reads the disk blocks of the physical system's disks and stores them within files that the Virtual Machine Manager can access. It is also possible to go the other way, virtual-to-physical (V-to-P) conversion is a procedure for converting a virtualized guest to a physical system.

15.4.5 Live Migration

One feature found Type 0 Hypervisors and Type 1 Hypervisors is the live migration of a running guest from one system to another. Live migration is made possible because of the well-defined interfaces between guests and VMMs and the limited state the VMM maintains for the guest. The VMM migrates a guest via the following steps:

1. The source Virtual Machine Manager establishes a connection with the target VMM and confirms that it is allowed to send a guest.
2. The target creates a new guest by creating a new Virtual CPU, new nested page table, and other state storage.
3. The source sends all read-only memory pages to the target.
4. The source sends all read-write pages to the target, marking them as clean on the source.
5. The source repeats step 4, as during transmission, some pages were probably modified by the guest and are now dirty. These pages need to be sent again and marked again as clean.
6. When the cycle of steps 4 and 5 becomes very short, the source VMM freezes the guest, sends the VCPU's final state, sends other state details, sends the final dirty pages, and tells the target to start running the guest. Once the target acknowledges that the guest is running, the source terminates the guest.

Lastly, here are a few interesting details and limitations concerning live migration. First, for network connections to continue uninterrupted, the network infrastructure needs to understand that a MAC address can move between systems. Before Virtualization, this did not happen, as the MAC address was tied to physical hardware. With virtualization, the MAC must be movable for existing networking connections to continue without resetting. Modern network switches understand this and route traffic wherever the MAC address is, even accommodating a move.

A limitation of live migration is that no disk information is transferred. One reason live migration is possible is that most of the guest's state is maintained within the guest

- Open file tables
- System Call state
- Kernel state
- etc.

Because disk I/O is so much slower than memory access, and used disk space is usually much larger than used memory, disks associated with the guest cannot be reasonably be moved as part of a live migration. Rather, the disk must be remote to the guest, accessed over the network. In that case, disk access state is maintained within the guest, and network connections are all that matter to the Virtual Machine Manager. The network connections are maintained during the migration, so remote disk access continues.

16 Network

Defn 244 (Port)**.** A *port* is a single instance of a data flow. There are many different flows of data. These may be from different applications or different instances of the same application. In both TCP and UDP, flows are given unique *port numbers.*

Some of these are standard for particular applications, e.g. port 80 for HTTP (web), port 25 for SMTP (email). The transport protocol uses the port number to deliver data to the correct application.

Remark 244.1 (Port Confusion)*.* It is important to note that the Port is ***NOT*** the same thing as a Port.

A Computer Components

A.1 Central Processing Unit

Defn A.1.1 (Central Processing Unit)**.** The *Central Processing Unit*, *CPU*, is a chip that performs all actions in the computer. It calculates mathematical and logical values and acts based on them. It has several components built onto it, and can be thought of as the "brain" of the computer.

The design of a CPU determines some of the functionality it has. Therefore, more specialized processors can be made for special tasks, and more general processors can be built to handle a wide variety of calculations.

A.1.1 Registers

Defn A.1.2 (Register)**.** A *register* is a data storage mechanism built directly onto the Central Processing Unit. It is several hundred times faster than the system Memory. Registers are generally used when the currently running program is performing calculations. Since they are so fast, they are used as both source and destination operands in instructions.

Remark A.1.2.1. Depending on the Central Processing Unit architecture, there may be cases when Registers behave slightly differently between processors. This is something that can only be found by checking the Central Processing Unit manufacturer's documentation.

A.1.2 Program Counter

A.1.3 Arithmetic Logic Unit

A.1.4 Cache

A.2 Memory

Defn A.2.1 (Memory)**.** *Memory*, or *RAM* (*Random Access Memory*), is a Volatile data storage mechanism. It is directly connected to the Central Processing Unit. This is the location that the Central Processing Unit writes to when it cannot or should not store something in the Central Processing Unit's Registers.

Remark A.2.1.1 (Volatility). Memory is volatile because each of the cells is a small capacitor. In between the clock cycles on the Central Processing Unit and Memory, the capacitors discharge. On the clock cycle, the capacitors are refreshed with electrical power, which does one of 2 things:

1. Keep the data bits the same, 1 to 1.
2. Update the data bits from 0 to 1.

Defn A.2.2 (Volatile)**.** If a data storage mechanism is called *volatile*, it means that once the storage mechanism loses power, the data is lost. This is in contrast to Non-Volatile data storage mechanisms.

A.2.1 Stack

Defn A.2.3 (Call Stack)**.** The *call stack* is an imaginary construct that resembles the traditional stack data structure. It is a way to visualize and organize the way memory is used during the execution of a program and its function/methods. It is filled with Stack Frames. This **does not** hold the code that is used in the function, rather it is everything that is needed for the function to be able to run.

Defn A.2.4 (Stack Frame)**.** A *stack frame*, *activation frame*, or *activation record* are objects that represent necessary portions of a function. These include:

- A Dynamic Link
- Local Variables
- Temporary Variables
- Static Links
- Function Arguments
- Return Address

Additionally, there are 2 registers used as pointers to move around and interact with the stack frame.

1. `FP` is in register `%rbp`. It is the Frame Pointer.
2. `SP` is in register `%rsp`. It is the Stack Pointer.

Defn A.2.5 (Dynamic Link)**.** The *dynamic link* or *dynlink* is a memory address pointer and sits at the bottom of a Stack Frame. It is a pointer back to the previous function's dynamic link. This ensures that any function can find its parent/calling function.

The dynamic link also serves as a means to access any variable that might be needed by this function. To access any variable in *this* function, you can subtract a byte multiple that you need to access the proper value. To access any variable in the calling function, you can add a byte multiple that would correspond to the proper variable.

In the `x86_ 64` architecture, instruction set, and convention that we used, the register `%rbp` was the dynamic link.

Remark A.2.5.1. Note: Due to the conventions we used, when accessing arguments passed to the function, we treated them as local variables, just further down in the call stack. This also means that we need to skip over the Return Address block in memory.

Remark A.2.5.2. Because we used the `%rbp` register to store our current Dynamic Link's address, the dynamic link might also be called the *base pointer*.

Defn A.2.6 (Local Variable)**.** *Local variables* are handled very simply. They get an appropriate amount of memory allocated to them on the stack, and that is it.

There is no way to give a variable a name in assembly. (Usually. Depends on the architecture and instruction set). However, there is no way to name something in memory. But, because the size of all the objects is known at compile-time, allocating the proper amount of memory required by each variable is possible.

Remark A.2.6.1. This holds true for strongly-typed, static, compiled languages, like Java, C, C++, etc. However, Python is slightly different in this regard, and handles it differently.

Defn A.2.7 (Temporary Variable)**.** A *temporary variable* is one that is allocated on this function's Stack Frame while calculating values. Once the calculations are completed, these values are deallocated. These temporary variables can also point to objects on the Heap. When the function has finished running, then these values are deallocated, along with all other Local Variables in use.

For example, since assembly-level addition only allows for 2 operands, but in general, addition can have more than 2 operands in use, there needs to be a way to store the value used in the addition. While we can accumulate and use that value in the addition, the values being added together are *not* modified.

Defn A.2.8 (Static Link)**.** The *static link* is an implicit argument, meaning it ***ALWAYS*** gets pushed onto the stack as a Function Argument, when appropriate.

Appropriate in this context could mean several things:

- When an object is alive, and when it is being acted on by a function.
  - In this case, the static link points to an instance of a class on the Heap.
- When a language allows for nested function declarations.
  - Then the static link points to the Dynamic Link of the outer function
  - This allows access to the outer function's Local Variables like normal, and allows us to go back later.

Defn A.2.9 (Function Argument)**.** *Function arguments* are handled very simply. If a function call takes an argument, then the argument is calculated, and then that argument is pushed onto the stack in *this* Stack Frame.

Remark A.2.9.1. If more than one argument is passed to a function, there are 2 ways to push values onto the Stack Frame:

1. In the order they are passed to the function
   - Say a function with 3 arguments is called, then the stack would have arguments in this order
     (a) argument0 (Lowest memory address)
     (b) argument1
     (c) argument2 (Highest memory address)
2. In reverse order
   - Say the same function is called with the same 3 arguments, then the stack would have arguments in this order
     (a) argument2 (Lowest memory address)
     (b) argument1
     (c) argument0 (Highest memory address)

When the values that were passed need to be accessed, and if the memory sizes of things are known at compile time, then we can calculate how far down we need to go in the stack to find the value. This is done by adding a positive value to the `%rbp`

Defn A.2.10 (Return Address)**.** The *return address* is used by the `%rip` register. It is calculated and pushed onto the Stack Frame stack when the `CALL` macro is used. It is the thing that allows us to jump around in the code from the `text` area of our program.

Remark A.2.10.1. The `%rip` register is the *register instruction pointer*. It holds the value of the *next* instruction to execute. Technically, it is the Program Counter's value.

Defn A.2.11 (Garbage Collection)**.** *Garbage collection* is the act of deallocating objects that may still be on the heap and organizing the heap. Since the heap allocates continuous "blocks" of memory required by an object, the heap may have the necessary memory to allocate an object, but in discontinuous locations.

Defn A.2.12 (Frame Pointer)**.** The *frame pointer* is a pointer that ***ALWAYS*** points to the current function's Dynamic Link. The frame pointer is commonly abbreviated as *FP*. This is the thing that allows us to access Local Variables, Function Arguments, and everything else inside of the Stack Frame. The value is held in the `%rbp` register.

Defn A.2.13 (Stack Pointer)**.** The *stack pointer* is a pointer that ***ALWAYS*** points to the top of the current Stack Frame. The stack pointer is commonly abbreviated as *SP*. This value is held in the `%rsp` register. This is the pointer that allows us to push and pop onto this function's Stack Frame.

Defn A.2.14 (Class Descriptor)**.** The *class descriptor* is a portion of memory set aside for the methods that are in an object.

A.2.2 Heap

Defn A.2.15 (Heap)**.** The *heap* is a memory organization construct that helps visualize the way memory is used during the execution of a program. It is ***SIGNIFICANTLY*** larger than the Call Stack.

In an object-oriented language, this is where instances of classes exist. These objects are allocated on a first-come first-serve basis. When the object is allocated, the amount of memory that the object requires is allocated ***in a continuous block***. The problem is that if the heap has been extensively used, then there might be enough total memory required to allocate an object, but because it is not in a continuous block, the object cannot be allocated.

This makes deallocation more complex, because when they are deallocated, the program might still view the memory as in-use. Additionally, because of the continuous block allocation nature of the heap, it must be organized every once in a while. This is called Garbage Collection.

Remark A.2.15.1. In an object-oriented language, like Java, when objects are stored on the heap, **ONLY** their class fields are stored there. The class methods are stored elsewhere, in the Class Descriptor.

A.3 Disk

Defn A.3.1 (Non-Volatile)**.** If a data storage mechanism is called *non-volatile*, it means that once the storage device loses power, the data is still safely stored. This is in contrast to Volatile data storage mechanisms.

A.4 Fetch-Execute Cycle

B Complex Numbers

Defn B.0.1 (Complex Number)**.** A *complex number* is a hyper real number system. This means that two real numbers, $a, b \in \mathbb{R}$, are used to construct the set of complex numbers, denoted mathbbC.

A complex number is written, in Cartesian form, as shown in Equation (B.1) below.

$$z = a \pm ib \tag{B.1}$$

where

$$i = \sqrt{-1} \tag{B.2}$$

Remark (i vs. j for Imaginary Numbers)*.* Complex numbers are generally denoted with either i or j. Electrical engineering regularly makes use of j as the imaginary value. This is because alternating current i is already taken, so j is used as the imaginary value instad.

B.1 Parts of a Complex Number

A Complex Number is made of up 2 parts:

1. Real Part
2. Imaginary Part

Defn B.1.1 (Real Part)**.** The *real part* of an imaginary number, denoted with the Re operator, is the portion of the Complex Number with no part of the imaginary value i present.

If $z = x + iy$, then

$$\text{Re}\{z\} = x \tag{B.3}$$

Remark B.1.1.1 (Alternative Notation)*.* The Real Part of a number sometimes uses a slightly different symbol for denoting the operation. It is:

$$\mathfrak{Re}$$

Defn B.1.2 (Imaginary Part)**.** The *imaginary part* of an imaginary number, denoted with the Im operator, is the portion of the Complex Number where the imaginary value i is present.

If $z = x + iy$, then

$$\text{Im}\{z\} = y \tag{B.4}$$

Remark B.1.2.1 (Alternative Notation)*.* The Imaginary Part of a number sometimes uses a slightly different symbol for denoting the operation. It is:

$$\mathfrak{Im}$$

B.2 Binary Operations

The question here is if we are given 2 complex numbers, how should these binary operations work such that we end up with just one resulting complex number. There are only 2 real operations that we need to worry about, and the other 3 can be defined in terms of these two:

1. Addition
2. Multiplication

For the sections below, assume:

$$z = x_1 + iy_1$$
$$w = x_2 + iy_2$$

B.2.1 Addition

The addition operation, still denoted with the + symbol is done pairwise. You should treat i like a variable in regular algebra, and not move it around.

$$z + w \coloneqq (x_1 + x_2) + i(y_1 + y_2) \tag{B.5}$$

B.2.2 Multiplication

The multiplication operation, like in traditional algebra, usually lacks a multiplication symbol. You should treat i like a variable in regular algebra, and not move it around.

$$\begin{aligned} zw &\coloneqq (x_1 + iy_1)(x_2 + iy_2) \\ &= (x_1x_2) + (iy_1x_2) + (ix_1y_2) + (i^2y_1y_2) \\ &= (x_1x_2) + i(y_1x_2 + x_1y_2) + (-1y_1y_2) \\ &= (x_1x_2 - y_1y_2) + i(y_1x_2 + x_1y_2) \end{aligned} \tag{B.6}$$

B.3 Complex Conjugates

Defn B.3.1 (Complex Conjugate)**.** The conjugate of a complex number is called its *complex conjugate*. The complex conjugate of a complex number is the number with an equal real part and an imaginary part equal in magnitude but opposite in sign. If we have a complex number as shown below,

$$z = a \pm bi$$

then, the conjugate is denoted and calculated as shown below.

$$\overline{z} = a \mp bi \tag{B.7}$$

The Complex Conjugate can also be denoted with an asterisk ($*$). This is generally done for complex functions, rather than single variables.

$$z^* = \overline{z} \tag{B.8}$$

B.3.1 Notable Complex Conjugate Expressions

There are 2 interesting things that we can perform with *just* the concept of a Complex Number and a Complex Conjugate:

1. $z\overline{z}$
2. $\frac{z}{\overline{z}}$

The first is interesting because of this simplification:

$$\begin{aligned} z\overline{z} &= (x + iy)(x - iy) \\ &= x^2 - xyi + xyi - i^2y^2 \\ &= x^2 - (-1)y^2 \\ &= x^2 + y^2 \end{aligned}$$

Thus,

$$z\overline{z} = x^2 + y^2 \tag{B.9}$$

which is interesting because, in comparison to the input values, the output is completely real.

The other interesting Complex Conjugate is dividing a Complex Number by its conjugate.

$$\frac{z}{\overline{z}} = \frac{x + iy}{x - iy}$$

We want to have this end up in a form of $a + ib$, so we multiply the entire fraction by z, to cause the denominator to be completely real.

$$z\left(\frac{z}{\overline{z}}\right) = \frac{z^2}{z\overline{z}}$$

Using our solution from Equation (B.9):

$$\begin{aligned} &= \frac{(x + iy)^2}{x^2 + y^2} \\ &= \frac{x^2 + 2xyi + i^2y^2}{x^2 + y^2} \end{aligned}$$

By breaking up the fraction's numerator, we can more easily recognize this to be teh Cartesian form of the Complex Number.

$$
\begin{aligned}
&= \frac{\left(x^2 - y^2\right) + 2xyi}{x^2 + y^2} \\
&= \frac{x^2 - y^2}{x^2 + y^2} + \frac{2xyi}{x^2 + y^2}
\end{aligned}
$$

This is an interesting development because, unlike the multiplication of a Complex Number by its Complex Conjugate, the division of these two values does **not** yield a purely real number.

$$\frac{z}{\overline{z}} = \frac{x^2 - y^2}{x^2 + y^2} + \frac{2xyi}{x^2 + y^2} \tag{B.10}$$

B.3.2 Properties of Complex Conjugates

Conjugation follows some of the traditional algebraic properties that you are already familiar with, namely commutativity.

First, start by defining some expressions so that we can prove some of these properties:

$$
\begin{aligned}
z &= x + iy \\
\overline{z} &= x - iy
\end{aligned}
$$

(i) The conjugation operation is commutative.
(ii) The conjugation operation can be distributed over addition and multiplication.

$$
\begin{aligned}
\overline{z + w} &= \overline{z} + \overline{w} \\
\overline{zw} &= \overline{zw}
\end{aligned}
$$

Property **(ii)** can be proven by just performing a simplification.

*Prove Property **(ii)**.* Let z and w be complex numbers ($z, w \in \text{mathbbC}$) where $z = x_1 + iy_1$ and $w = x_2 + iy_2$. Prove that $\overline{z + w} = \overline{z} + \overline{w}$.

We start by simplifying the left-hand side of the equation ($\overline{z + w}$).

$$
\begin{aligned}
\overline{z + w} &= \overline{(x_1 + iy_1) + (x_2 + iy_2)} \\
&= \overline{(x_1 + x_2) + i(y_1 + y_2)} \\
&= (x_1 + x_2) - i(y_1 + y_2)
\end{aligned}
$$

Now, we simplify the other side ($\overline{z} + \overline{w}$).

$$
\begin{aligned}
\overline{z} + \overline{w} &= \overline{(x_1 + iy_1)} + \overline{(x_2 + iy_2)} \\
&= (x_1 - iy_1) + (x_2 - iy_2) \\
&= (x_1 + x_2) - i(y_1 + y_2)
\end{aligned}
$$

We can see that both sides are equivalent, thus the addition portion of Property **(ii)** is correct.

Remark. The proof of the multiplication portion of Property **(ii)** is left as an exercise to the reader. However, that proof is quite similar to this proof of addition.

■

B.4 Geometry of Complex Numbers

So far, we have viewed Complex Numbers only algebraically. However, we can also view them geometrically as points on a 2 dimensional Argand Plane.

Defn B.4.1 (Argand Plane)**.** An *Argane Plane* is a standard two dimensional plane whose points are all elements of the complex numbers, $z \in \text{mathbbC}$. This is taken from Descarte's definition of a completely real plane.

The Argand plane contains 2 lines that form the axes, that indicate the real component and the imaginary component of the complex number specified.

A Complex Number can be viewed as a point in the Argand Plane, where the Real Part is the "x"-component and the Imaginary Part is the "y"-component.

By plotting this, you see that we form a right triangle, so we can find the hypotenuse of that triangle. This hypotenuse is the distance the point p is from the origin, refered to as the Modulus.

Remark. When working with Complex Numbers geometrically, we refer to the points, where they are defined like so:

$$z = x + iy = p(x, y)$$

Note that p is **not** a function of x and y. Those are the values that inform us **where** p is located on the Argand Plane.

B.4.1 Modulus of a Complex Number

Defn B.4.2 (Modulus)**.** The *modulus* of a Complex Number is the distance from the origin to the complex point p. This is based off the Pythagorean Theorem.

$$\begin{aligned} |z|^2 &= x^2 + y^2 = z\overline{z} \\ |z| &= \sqrt{x^2 + y^2} \end{aligned} \qquad \text{(B.11)}$$

(i) The *Law of Moduli* states that $|zw| = |z||w|$..

We can prove Property **(i)** using an algebraic identity.

*Prove Property **(i)**.* Let z and w be complex numbers $(z, w \in \mathrm{mathbbC})$. We are asked to prove

$$|zw| = |z||w|$$

But, it is actually easier to prove

$$|zw|^2 = |z|^2|w|^2$$

We start by simplifying the $|zw|^2$ equation above.

$$|zw|^2 = |z|^2|w|^2$$

Using the definition of the Modulus of a Complex Number in Equation (B.11), we can expand the modulus.

$$= (zw)(\overline{zw})$$

Using Property **(ii)** for multiplication allows us to do the next step.

$$= (zw)(\overline{zw})$$

Using Multiplicative Associativity and Multiplicative Commutativity, we can simplify this further.

$$\begin{aligned} &= (z\overline{z})(w\overline{w}) \\ &= |z|^2|w|^2 \end{aligned}$$

Note how we never needed to define z or w, so this is as general a result as possible. ■

B.4.1.1 Algebraic Effects of the Modulus' Property (i)

For this section, let $z = x_1 + iy_1$ and $w = x_2 + iy_2$. Now,

$$\begin{aligned} zw &= (x_1x_2 - y_1y_2) + i(x_1y_2 + x_2y_1) \\ |zw|^2 &= (x_1x_2 - y_1y_2)^2 + (x_1y_2 + x_2y_1)^2 \\ &= \left(x_1^2 + x_2^2\right)\left(x_2^2 + y_2^2\right) \\ &= |z|^2|w|^2 \end{aligned}$$

However, the Law of Moduli (Property **(i)**) does **not** hold for a hyper complex number system one that uses 2 or more imaginaries, i.e. $z = a + iy + jz$. But, the Law of Moduli (Property **(i)**) **does** hold for hyper complex number system that uses 3 imaginaries, $a = z + iy + jz + k\ell$.

B.4.1.2 Conceptual Effects of the Modulus' Property (i)

We are interested in seeing if $|zw| = (x_1^2 + y_1^2)(x_2^2 + y_2^2)$ can be extended to more complex terms (3 terms in the complex number).

However, Langrange proved that the equation below **always** holds. Note that the z below has no relation to the z above.

$$(x_1 + y_1 + z_1) \neq X^2 + Y^2 + Z^2$$

B.5 Circles and Complex Numbers

We need to define both a center and a radius, just like with regular purely real values. Equation (B.12) defines the relation required for a circle using Complex Numbers.

$$|z - a| = r \qquad \text{(B.12)}$$

Example B.1: Convert to Circle. Lecture 2, Example 1

Given the expression below, find the location of the center of the circle and the radius of the circle?

$$|5iz + 10| = 7$$

This is just a matter of simplification and moving terms around.

$$\begin{aligned} |5iz + 10| &= 7 \\ |5i(z + \frac{10}{5i})| &= 7 \\ |5i(z + \frac{2}{i})| &= 7 \\ |5i(z + \frac{2}{i}\frac{-i}{-i})| &= 7 \\ |5i(z - 2i)| &= 7 \end{aligned}$$

Now using the Law of Moduli (Property **(i)**) $|ab| = |a||b|$, we can simplify out the extra imaginary term.

$$\begin{aligned} |5i||z - 2i| &= 7 \\ 5|z - 2i| &= 7 \\ |z - 2i| &= \frac{7}{5} \end{aligned}$$

Thus, the circle formed by the equation $|5iz + 10| = 7$ is actually $|z - 2i| = \frac{7}{5}$, with a center at $a = 2i$ and a radius of $\frac{7}{5}$.

B.5.1 Annulus

Defn B.5.1 (Annulus)**.** An *annulus* is a region that is bounded by 2 concentric circles. This takes the form of Equation (B.13).

$$r_1 \leq |z - a| \leq r_2 \tag{B.13}$$

In Equation (B.13), each of the $\leq$ symbols could also be replaced with $<$. This leads to 3 different possibilities for the annulus:

1. If both inequality symbols are $\leq$, then it is a **Closed Annulus**.
2. If both inequality symbols are $<$, then it is an **Open Annulus**.
3. If **only one** inequality symbol $<$ and the other $\leq$, then it is not an **Open Annulus**.

The concept of an Annulus can be extended to angles and arguments of a Complex Number. A general example of this is shown below.

$$\theta_1 \leq \arg(z) \leq \theta_2$$

Angular Annuli follow all the same rules as regular annuli.

B.6 Polar Form

The polar form of a Complex Number is an alternative, but equally useful way to express a complex number. In polar form, we express the distance the complex number is from the origin and the angle it sits at from the real axis. This is seen in Equation (B.14).

$$z = r\big(\cos(\theta) + i\sin(\theta)\big) \tag{B.14}$$

Remark. Note that in the definition of polar form (Equation (B.14)), there is no allowance for the radius, r, to be negative. You must fix this by figuring out the angle change that is required for the radius to become positive.

Thus,

$$\begin{aligned} r &= |z| \\ \theta &= \arg(z) \end{aligned}$$

Example B.2: Find Polar Coordinates from Cartesian Coordinates. Lecture 2, Example 1

Find the complex number's $z = -\sqrt{3} + i$ polar coordinates?

We start by finding the radius of z (modulus of z).

$$\begin{aligned} r &= |z| \\ &= \sqrt{\operatorname{Re}\{z\}^2 + \operatorname{Im}\{z\}^2} \\ &= \sqrt{\left(-\sqrt{3}\right)^2 + 1^2} \\ &= \sqrt{3+1} \\ &= \sqrt{4} \\ &= 2 \end{aligned}$$

Thus, the point is 2 units away from the origin, the radius is 2 $r = 2$.
Now, we need to find the angle, the argument, of the Complex Number.

$$\begin{aligned} \cos(\theta) &= \frac{-\sqrt{3}}{2} \\ \theta &= \cos^{-1}\left(\frac{-\sqrt{3}}{2}\right) \\ &= \frac{5\pi}{6} \end{aligned}$$

Now that we have one angle for the point, we also need to consider the possibility that there have been an unknown amount of rotations around the entire plane, meaning there have been $2\pi k$, where $k = 0, 1, \ldots$.
We now have all the information required to reconstruct this point using polar coordinates:

$$\begin{aligned} r &= 2 \\ \theta &= \frac{5\pi}{6} \\ \arg(z) &= \frac{5\pi}{6} + 2\pi k \end{aligned}$$

B.6.1 Converting Between Cartesian and Polar Forms

Using Equation (B.14) and Equation (B.1), it is easy to see the relation between r, θ, x, and y.

Definition of a Complex Number in Cartesian form.

$$z = x + iy$$

Definition of a Complex Number in polar form.

$$\begin{aligned} z &= r\big(\cos(\theta) + i\sin(\theta)\big) \\ &= r\cos(\theta) + ir\sin(\theta) \end{aligned}$$

Thus,

$$\begin{aligned} x &= r\cos(\theta) \\ y &= r\sin(\theta) \end{aligned} \tag{B.15}$$

B.6.2 Benefits of Polar Form

Polar form is good for multiplication of Complex Numbers because of the way sin and cos multiply together. The Cartesian form is good for addition and subtraction. Take the examples below to show what I mean.

B.6.2.1 Multiplication For multiplication, the radii are multiplied together, and the angles are added.

$$\Big(r_1\big(\cos(\theta) + i\sin(\theta)\big)\Big)\Big(r_2\big(\cos(\phi) + i\sin(\phi)\big)\Big) = r_1 r_2\big(\cos(\theta+\phi) + i\sin(\theta+\phi)\big) \tag{B.16}$$

B.6.2.2 Division For division, the radii are divided by each other, and the angles are subtracted.

$$\frac{r_1\big(\cos(\theta) + i\sin(\theta)\big)}{r_2\big(\cos(\phi) + i\sin(\phi)\big)} = \frac{r_1}{r_2}\big(\cos(\theta-\phi) + i\sin(\theta-\phi)\big) \tag{B.17}$$

B.6.2.3 Exponentiation Because exponentiation is defined to be repeated multiplication, Paragraph B.6.2.1 applies. That this generalization is true was proven by de Moiver, and is called de Moiver's Law.

Defn B.6.1 (de Moiver's Law)**.** Given a complex number z, $z \in$ mathbbC and a rational number n, $n \in$ mathbbQ, the exponentiation of z^n is defined as Equation (B.18).

$$z^n = r^n\big(\cos(n\theta) + i\sin(n\theta)\big) \tag{B.18}$$

B.7 Roots of a Complex Number

de Moiver's Law also applies to finding **roots** of a Complex Number.

$$z^{\frac{1}{n}} = r^{\frac{1}{n}}\left(\cos\left(\frac{\arg z}{n}\right) + i\sin\left(\frac{\arg z}{n}\right)\right) \tag{B.19}$$

Remark. As the entire $\arg z$ term is being divided by n, the $2\pi k$ is **ALSO** divided by n.

Roots of a Complex Number satisfy Equation (B.20). To demonstrate that equation, $z = r\big(\cos(\theta) + i\sin(\theta)\big)$ and $w = \rho\big(\cos(\phi) + i\sin(\phi)\big)$.

$$w^n = z \tag{B.20}$$

A w that satisfies Equation (B.20) is an nth root of z.

Example B.3: Roots of a Complex Number. Lecture 2, Example 2

Find the cube roots of $z = -\sqrt{3} + i$?

From Example B.2, we know that the polar form of z is

$$z = 2\left(\cos\left(\frac{5\pi}{6} + 2\pi k\right) + i\sin\left(\frac{5\pi}{6} + 2\pi k\right)\right)$$

Because the question is asking for **cube** roots, that means there are 3 roots. Using Equation (B.19), we can find the general form of the roots.

$$\begin{aligned}
z &= 2\left(\cos\left(\frac{5\pi}{6} + 2\pi k\right) + i\sin\left(\frac{5\pi}{6} + 2\pi k\right)\right) \\
z^{\frac{1}{3}} &= \sqrt[3]{2}\left(\cos\left(\frac{1}{3}\left(\frac{5\pi}{6} + 2\pi k\right)\right) + i\sin\left(\frac{1}{3}\left(\frac{5\pi}{6} + 2\pi k\right)\right)\right) \\
&= \sqrt[3]{2}\left(\cos\left(\frac{\pi + 12\pi k}{18}\right) + i\sin\left(\frac{\pi + 12\pi k}{18}\right)\right)
\end{aligned}$$

Now that we have a general equation for **all** possible cube roots, we need to find all the unique ones. This is because after $k = n$ roots, the roots start to repeat themselves, because the $2\pi k$ part of the expression becomes effective, making the angle a full rotation. We simply enumerate $k \in \mathbb{Z}^+$, so $k = 0, 1, 2, \ldots$.

k = 0

$$\sqrt[3]{2}\left(\cos\left(\frac{\pi + 12\pi(0)}{18}\right) + i\sin\left(\frac{\pi + 12\pi(0)}{18}\right)\right) = \sqrt[3]{2}\left(\cos\left(\frac{\pi}{18}\right) + i\sin\left(\frac{\pi}{18}\right)\right)$$

k = 1

$$\sqrt[3]{2}\left(\cos\left(\frac{\pi + 12\pi(1)}{18}\right) + i\sin\left(\frac{\pi + 12\pi(1)}{18}\right)\right) = \sqrt[3]{2}\left(\cos\left(\frac{13\pi}{18}\right) + i\sin\left(\frac{13\pi}{18}\right)\right)$$

k = 2

$$\sqrt[3]{2}\left(\cos\left(\frac{\pi+12\pi(2)}{18}\right)+i\sin\left(\frac{\pi+12\pi(2)}{18}\right)\right)=\sqrt[3]{2}\left(\cos\left(\frac{25\pi}{18}\right)+i\sin\left(\frac{25\pi}{18}\right)\right)$$

k = 3

$$\begin{aligned}\sqrt[3]{2}\left(\cos\left(\frac{\pi+12\pi(3)}{18}\right)+i\sin\left(\frac{\pi+12\pi(3)}{18}\right)\right)&=\sqrt[3]{2}\left(\cos\left(\frac{\pi}{18}+\frac{36\pi}{18}\right)+i\sin\left(\frac{\pi}{18}+\frac{36\pi}{18}\right)\right)\\&=\sqrt[3]{2}\left(\cos\left(\frac{\pi}{18}+2\pi\right)+i\sin\left(\frac{\pi}{18}+2\pi\right)\right)\\&=\sqrt[3]{2}\left(\cos\left(\frac{\pi}{18}\right)+i\sin\left(\frac{\pi}{18}\right)\right)\end{aligned}$$

Thus, the 3 cube roots of z are:

$$\begin{aligned}z_1^{\frac{1}{3}}&=\sqrt[3]{2}\left(\cos\left(\frac{\pi}{18}\right)+i\sin\left(\frac{\pi}{18}\right)\right)\\z_2^{\frac{1}{3}}&=\sqrt[3]{2}\left(\cos\left(\frac{13\pi}{18}\right)+i\sin\left(\frac{13\pi}{18}\right)\right)\\z_3^{\frac{1}{3}}&=\sqrt[3]{2}\left(\cos\left(\frac{25\pi}{18}\right)+i\sin\left(\frac{25\pi}{18}\right)\right)\end{aligned}$$

B.8 Arguments

There are 2 types of arguments that we can talk about for a Complex Number.

1. The Argument
2. The Principal Argument

Defn B.8.1 (Argument)**.** The *argument* of a Complex Number refers to **all** possible angles that can satisfy the angle requirement of a Complex Number.

Example B.4: Argument of Complex Number. Lecture 3, Example 1

If $z=-1-i$, then what is its **Argument**?

You can plot this value on the Argand Plane and find the angle graphically/geometrically, or you can "cheat" and use $\tan^{-1}$ (so long as you correct for the proper quadrant). I will "cheat", as I cannot plot easily.

$$\begin{aligned}z&=-1-i\\\arg(z)=\tan(\theta)&=\frac{-i}{-1}\\&=\frac{\pi}{4}\end{aligned}$$

Remember to correct for the proper quadrant. We are in quadrant IV.

$$=\frac{5\pi}{4}$$

Now, we have to account for **all** possible angles that form this angle.

$$\arg(z)=\frac{5\pi}{4}+2\pi k$$

Thus, the argument of $z=-1-i$ is $\arg(z)=\frac{5\pi}{4}+2\pi k$.

Defn B.8.2 (Principal Argument)**.** The *principal argument* is the exact or reference angle of the Complex Number. By convention, the principal Argument of a complex number z is defined to be bounded like so: $-\pi<\operatorname{Arg}(z)\leq\pi$.

Example B.5: Principal Argument of Complex Number. Lecture 3, Example 1

If $z = -1 - i$, then what is its **Principal Argument**?

You can plot this value on the Argand Plane and find the angle graphically/geometrically, or you can "cheat" and use $\tan^{-1}$ (so long as you correct for the proper quadrant). I will "cheat", as I cannot plot easily.

$$\begin{aligned} z &= -1 - i \\ \arg(z) &= \tan(\theta) = \frac{-i}{-1} \\ &= \frac{\pi}{4} \end{aligned}$$

Remember to correct for the proper quadrant. We are in quadrant IV.

$$= \frac{5\pi}{4}$$

Thus, the Principal Argument of $z = -1 - i$ is $\operatorname{Arg}(z) = \frac{5\pi}{4}$.

B.9 Complex Exponentials

The definition of an exponential with a Complex Number as its exponent is defined in Equation (B.21).

$$e^z = e^{x+iy} = e^x\big(\cos(y) + i\sin(y)\big) \tag{B.21}$$

If instead of e as the base, we have some value a, then we have Equation (B.22).

$$\begin{aligned} a^z &= e^{z\ln(a)} \\ &= e^{\operatorname{Re}\{z\ln(a)\}}\Big(\cos\big(\operatorname{Im}\{z\ln(a)\}\big) + i\sin\big(\operatorname{Im}\{z\ln(a)\}\big)\Big) \end{aligned} \tag{B.22}$$

In the case of Equation (B.21), z can be presented in either Cartesian or polar form, they are equivalent.

Example B.6: Simplify Simple Complex Exponential. Lecture 3

Simplify the expression below, then find its Modulus, Argument, and its Principal Argument?

$$e^{-1+i\sqrt{3}}$$

If we look at the exponent on the exponential, we see

$$z = -1 + i\sqrt{3}$$

which means

$$\begin{aligned} x &= -1 \\ y &= \sqrt{3} \end{aligned}$$

With this information, we can simplify the expression **just** by observation, with no calculations required.

$$e^{-1+i\sqrt{3}} = e^{-1}\big(\cos(\sqrt{3}) + i\sin(\sqrt{3})\big)$$

Now, we can solve the other 3 parts of this example **by observation**.

$$\begin{aligned} |e^{-1+i\sqrt{3}}| &= |e^{-1}\big(\cos(\sqrt{3}) + i\sin(\sqrt{3})\big)| \\ &= e^{-1} \\ \arg\left(e^{-1+i\sqrt{3}}\right) &= \arg\left(e^{-1}\big(\cos(\sqrt{3}) + i\sin(\sqrt{3})\big)\right) \\ &= \sqrt{3} + 2\pi k \\ \operatorname{Arg}\left(e^{-1+i\sqrt{3}}\right) &= \operatorname{Arg}\left(e^{-1}\big(\cos(\sqrt{3}) + i\sin(\sqrt{3})\big)\right) \\ &= \sqrt{3} \end{aligned}$$

Example B.7: Simplify Complex Exponential Exponent. Lecture 3

Given $z = e^{-e^{-i}}$, what is this expression in polar form, what is its Modulus, its Argument, and its Principal Argument?

We start by simplifying the exponent of the base exponential, i.e. e^{-i}.

$$\begin{aligned} e^{-i} &= e^{0-i} \\ &= e^{0}\big(\cos(-1) + i\sin(-1)\big) \\ &= 1\big(\cos(-1) + i\sin(-1)\big) \end{aligned}$$

Now, with that exponent simplified, we can solve the main question.

$$\begin{aligned} e^{-e^{-i}} &= e^{-1\big(\cos(-1)+i\sin(-1)\big)} \\ &= e^{-1\big(\cos(1)-i\sin(1)\big)} \\ &= e^{-\cos(1)+i\sin(1)} \end{aligned}$$

If we refer back to Equation (B.21), then it becomes obvious what x and y are.

$$\begin{aligned} x &= -\cos(1) \\ y &= \sin(1) \\ e^{-e^{-i}} &= e^{-\cos(1)}\Big(\cos\big(\sin(1)\big) + i\sin\big(\sin(1)\big)\Big) \end{aligned}$$

Now that we have "simplified" this exponential, we can solve the other 3 questions by **observation**.

$$\begin{aligned} |e^{-e^{-i}}| &= |e^{-\cos(1)}\Big(\cos\big(\sin(1)\big) + i\sin\big(\sin(1)\big)\Big)| \\ &= e^{-\cos(1)} \\ \arg\left(e^{-e^{-i}}\right) &= \arg\left(e^{-\cos(1)}\Big(\cos\big(\sin(1)\big) + i\sin\big(\sin(1)\big)\Big)\right) \\ &= \sin(1) + 2\pi k \\ \operatorname{Arg}\left(e^{-e^{-i}}\right) &= \operatorname{Arg}\left(e^{-\cos(1)}\Big(\cos\big(\sin(1)\big) + i\sin\big(\sin(1)\big)\Big)\right) \\ &= \sin(1) \end{aligned}$$

Example B.8: Non-e Complex Exponential. Lecture 3

Find all values of $z = 1^{i}$?

Use Equation (B.22) to simplify this to a base of e, where we can use the usual Equation (B.21) to solve this.

$$\begin{aligned} a^{z} &= e^{z\ln(a)} \\ 1^{i} &= e^{i\ln(1)} \end{aligned}$$

Simplify the logarithm in the exponent first, ln(1).

$$\begin{aligned} \ln(1) &= \log_{e}|1| + i\arg(1) \\ &= \log_{e}(1) + i(0 + 2\pi k) \\ &= 0 + 2\pi ki \\ &= 2\pi ki \end{aligned}$$

Now, plug ln(1) back into the exponent, and solve the exponential.

$$\begin{aligned} e^{i(2\pi ki)} &= e^{2\pi ki^{2}} \\ &= e^{2\pi k(-1)} \\ z &= e^{-2\pi k} \end{aligned}$$

Thus, all values of $z = e^{-2\pi k}$ where $k = 0, 1, \ldots$.

B.9.1 Complex Conjugates of Exponentials

$$\overline{e^z} = e^{\overline{z}} \tag{B.23}$$

B.10 Complex Logarithms

There are some denotational changes that need to be made for this to work. The traditional real-number natural logarithm ln needs to be redefined to its defining form $\log_e$.

With that denotational change, we can now use ln for the Complex Logarithm.

Defn B.10.1 (Complex Logarithm)**.** The *complex logarithm* is defined in Equation (B.24). The only requirement for this equation to hold true is that $w \neq 0$.

$$\begin{aligned} e^z &= w \\ z &= \ln(w) \\ &= \log_e|w| + i\arg(w) \end{aligned} \tag{B.24}$$

Remark B.10.1.1. The Complex Logarithm is different than it's purely-real cousin because we allow negative numbers to be input. This means it is more general, but we must lose the precision of the purely-real logarithm. This means that each nonzero number has infinitely many logarithms.

Example B.9: All Complex Logarithms of Simple Expression. Lecture 3

What are **all** Complex Logarithms of $z = -1$?

We can apply the definition of a Complex Logarithm (Equation (B.24)) directly.

$$\begin{aligned} \ln(z) &= \log_e|z| + i\arg(z) \\ &= \log_e|-1| + i\arg(-1) \\ &= \log_e(1) + i(\pi + 2\pi k) \\ &= 0 + i(\pi + 2\pi k) \\ &= i(\pi + 2\pi k) \end{aligned}$$

Thus, all logarithms of $z = -1$ are defined by the expression $i(\pi + 2\pi k)$, $k = 0, 1, \ldots$.

Remark. You can see the loss of specificity in the Complex Logarithm because the variable k is still present in the final answer.

Example B.10: All Complex Logarithms of Complex Logarithm. Lecture 3

What are **all** the Complex Logarithms of $z = \ln(1)$?

We start by simplifying z, before finding $\ln(z)$. We can make use of Equation (B.24), to simplify this value.

$$\begin{aligned} \ln(w) &= \log_e|w| + i\arg(w) \\ \ln(1) &= \log_e|1| + i\arg(1) \\ &= \log_e 1 + i(0 + 2\pi k) \\ &= 0 + 2\pi ki \\ &= 2\pi ki \end{aligned}$$

Now that we have simplified z, we can solve for $\ln(z)$.

$$\begin{aligned} \ln(z) &= \ln(2\pi ki) \\ &= \log_e|2\pi ki| + i\arg(2\pi ki) \\ &= \log_e(2\pi|k|) + \left(i \begin{cases} \frac{\pi}{2} + 2\pi m & k > 0 \\ \frac{-\pi}{2} + 2\pi m & k < 0 \end{cases}\right) \end{aligned}$$

The $|k|$ is the **absolute value** of k, because k is an integer.

Thus, our solution of $\ln\big(\ln(1)\big) = \log_e(2\pi|k|) + \left(i \begin{cases} \frac{\pi}{2} + 2\pi m & k > 0 \\ \frac{-\pi}{2} + 2\pi m & k < 0 \end{cases}\right)$.

B.10.1 Complex Conjugates of Logarithms

$$\overline{\log(z)} = \log(\overline{z}) \tag{B.25}$$

B.11 Complex Trigonometry

For the equations below, $z \in$ mathbbC. These equations are based on Euler's relationship, Appendix C.2

$$\cos(z) = \frac{e^{iz} + e^{-iz}}{2} \tag{B.26}$$

$$\sin(z) = \frac{e^{iz} - e^{-iz}}{2i} \tag{B.27}$$

Example B.11: Simplify Complex Sinusoid. Lecture 3

Solve for z in the equation $\cos(z) = 5$?

We start by using the defintion of complex cosine Equation (B.26).

$$\begin{aligned} \cos(z) &= 5 \\ \frac{e^{iz} + e^{-iz}}{2} &= 5 \\ e^{iz} + e^{-iz} &= 10 \\ e^{iz}\left(e^{iz} + e^{-iz}\right) &= e^{iz}(10) \\ e^{iz^2} + 1 &= 10e^{iz} \\ e^{iz^2} - 10e^{iz} + 1 = 0 \end{aligned}$$

Solve this quadratic equation by using the Quadratic Equation.

$$\begin{aligned} e^{iz} &= \frac{-(-10) \pm \sqrt{(-10)^2 - 4(1)(1)}}{2(1)} \\ &= \frac{10 \pm \sqrt{100 - 4}}{2} \\ &= \frac{10 \pm \sqrt{96}}{2} \\ &= \frac{10 \pm 4\sqrt{6}}{2} \\ &= 5 \pm 2\sqrt{6} \end{aligned}$$

Use the definition of complex logarithms to simplify the exponential.

$$\begin{aligned} iz &= \ln(5 \pm 2\sqrt{6}) \\ &= \log_e|5 \pm 2\sqrt{6}| + i\arg(5 \pm 2\sqrt{6}) \\ &= \log_e|5 \pm 2\sqrt{6}| + i(0 + 2\pi k) \\ &= \log_e|5 \pm 2\sqrt{6}| + 2\pi k i \\ z &= \frac{1}{i}\left(\log_e|5 \pm 2\sqrt{6}| + 2\pi k i\right) \\ &= \frac{-i}{-i}\frac{1}{i}\left(\log_e|5 \pm 2\sqrt{6}|\right) + 2\pi k \\ &= 2\pi k - i\log_e|5 \pm 2\sqrt{6}| \end{aligned}$$

Thus, $z = 2\pi k - i\log_e|5 \pm 2\sqrt{6}|$.

B.11.1 Complex Angle Sum and Difference Identities

Because the definitions of sine and cosine are unsatisfactory in their Euler definitions, we can use angle sum and difference formulas and their Euler definitions to yield a set of Cartesian equations.

$$\cos(x+iy) = \big(\cos(x)\cosh(y)\big) - i\big(\sin(x)\sinh(y)\big) \tag{B.28}$$

$$\sin(x+iy) = \big(\sin(x)\cosh(y)\big) + i\big(\cos(x)\sinh(y)\big) \tag{B.29}$$

Example B.12: Simplify Trigonometric Exponential. Lecture 3

Simpify $z = e^{\cos(2+3i)}$, and find z's Modulus, Argument, and Principal Argument?

We start by simplifying the cos using Equation (B.28).

$$\begin{aligned} \cos(x+iy) &= \big(\cos(x)\cosh(y)\big) - i\big(\sin(x)\sinh(y)\big) \\ \cos(2+3i) &= \big(\cos(2)\cosh(3)\big) - i\big(\sin(2)\sinh(3)\big) \end{aligned}$$

Now that we have put the cos into a Cartesian form, one that is usable with Equation (B.21), we can solve this.

$$\begin{aligned} e^z = e^{x+iy} &= e^x\big(\cos(y) + i\sin(y)\big) \\ x &= \cos(2)\cosh(3) \\ y &= -\sin(2)\sinh(3) \\ e^{\cos(2)\cosh(3) - i\sin(2)\sinh(3)} &= e^{\cos(2)\cosh(3)}\Big(\cos\big(-\sin(2)\sinh(3)\big) + i\sin\big(-\sin(2)\sinh(3)\big)\Big) \end{aligned}$$

Now that we have simplified z, we can solve for the modulus, argument, and principal argument **by observation**.

$$\begin{aligned} |z| &= |e^{\cos(2)\cosh(3)}\Big(\cos\big(-\sin(2)\sinh(3)\big) + i\sin\big(-\sin(2)\sinh(3)\big)\Big)| \\ &= e^{\cos(2)\cosh(3)} \\ \arg(z) &= \arg(e^{\cos(2)\cosh(3)}\Big(\cos\big(-\sin(2)\sinh(3)\big) + i\sin\big(-\sin(2)\sinh(3)\big)\Big)) \\ &= -\sin(2)\sinh(3) + 2\pi k \\ \operatorname{Arg}(z) &= \operatorname{Arg}(e^{\cos(2)\cosh(3)}\Big(\cos\big(-\sin(2)\sinh(3)\big) + i\sin\big(-\sin(2)\sinh(3)\big)\Big)) \\ &= -\sin(2)\sinh(3) \end{aligned}$$

B.11.2 Complex Conjugates of Sinusoids

Since sinusoids can be represented by complex exponentials, as shown in Appendix C.2, we could calculate their complex conjugate.

$$\begin{aligned} \overline{\cos(x)} &= \cos(x) \\ &= \frac{1}{2}\left(e^{ix} + e^{-ix}\right) \end{aligned} \tag{B.30}$$

$$\begin{aligned} \overline{\sin(x)} &= \sin(x) \\ &= \frac{1}{2i}\left(e^{ix} - e^{-ix}\right) \end{aligned} \tag{B.31}$$

C Trigonometry

C.1 Trigonometric Formulas

$$\sin(\alpha) \pm \sin(\beta) = 2\sin\left(\frac{\alpha \pm \beta}{2}\right)\cos\left(\frac{\alpha \mp \beta}{2}\right) \tag{C.1}$$

$$\cos(\theta)\sin(\theta) = \frac{1}{2}\sin(2\theta) \tag{C.2}$$

C.2 Euler Equivalents of Trigonometric Functions

$$e^{\pm j\alpha} = \cos(\alpha) \pm j\sin(\alpha) \tag{C.3}$$

$$\cos(x) = \frac{e^{jx} + e^{-jx}}{2} \tag{C.4}$$

$$\sin(x) = \frac{e^{jx} - e^{-jx}}{2j} \tag{C.5}$$

$$\sinh(x) = \frac{e^{x} - e^{-x}}{2} \tag{C.6}$$

$$\cosh(x) = \frac{e^{x} + e^{-x}}{2} \tag{C.7}$$

C.3 Angle Sum and Difference Identities

$$\sin(\alpha \pm \beta) = \sin(\alpha)\cos(\beta) \pm \cos(\alpha)\sin(\beta) \tag{C.8}$$

$$\cos(\alpha \pm \beta) = \cos(\alpha)\cos(\beta) \mp \sin(\alpha)\sin(\beta) \tag{C.9}$$

C.4 Double-Angle Formulae

$$\sin(2\alpha) = 2\sin(\alpha)\cos(\alpha) \tag{C.10}$$

$$\cos(2\alpha) = \cos^2(\alpha) - \sin^2(\alpha) \tag{C.11}$$

C.5 Half-Angle Formulae

$$\sin\left(\frac{\alpha}{2}\right) = \sqrt{\frac{1-\cos(\alpha)}{2}} \tag{C.12}$$

$$\cos\left(\frac{\alpha}{2}\right) = \sqrt{\frac{1+\cos(\alpha)}{2}} \tag{C.13}$$

C.6 Exponent Reduction Formulae

$$\sin^2(\alpha) = \big(\sin(\alpha)\big) = \frac{1-\cos(2\alpha)}{2} \tag{C.14}$$

$$\cos^2(\alpha) = \big(\cos(\alpha)\big) = \frac{1+\cos(2\alpha)}{2} \tag{C.15}$$

C.7 Product-to-Sum Identities

$$2\cos(\alpha)\cos(\beta) = \cos(\alpha-\beta) + \cos(\alpha+\beta) \tag{C.16}$$

$$2\sin(\alpha)\sin(\beta) = \cos(\alpha-\beta) - \cos(\alpha+\beta) \tag{C.17}$$

$$2\sin(\alpha)\cos(\beta) = \sin(\alpha+\beta) + \sin(\alpha-\beta) \tag{C.18}$$

$$2\cos(\alpha)\sin(\beta) = \sin(\alpha+\beta) - \sin(\alpha-\beta) \tag{C.19}$$

C.8 Sum-to-Product Identities

$$\sin(\alpha) \pm \sin(\beta) = 2\sin\left(\frac{\alpha \pm \beta}{2}\right)\cos\left(\frac{\alpha \mp \beta}{2}\right) \tag{C.20}$$

$$\cos(\alpha) + \cos(\beta) = 2\cos\left(\frac{\alpha + \beta}{2}\right)\cos\left(\frac{\alpha - \beta}{2}\right) \tag{C.21}$$

$$\cos(\alpha) - \cos(\beta) = -2\sin\left(\frac{\alpha + \beta}{2}\right)\sin\left(\frac{\alpha - \beta}{2}\right) \tag{C.22}$$

C.9 Pythagorean Theorem for Trig

$$\cos^2(\alpha) + \sin^2(\alpha) = 1^2 \tag{C.23}$$

$$\cosh^2(\alpha) - \sinh^2(\alpha) = 1^2 \tag{C.24}$$

C.10 Rectangular to Polar

$$a + jb = \sqrt{a^2 + b^2}e^{j\theta} = re^{j\theta} \tag{C.25}$$

$$\theta = \begin{cases} \arctan\left(\frac{b}{a}\right) & a > 0 \\ \pi - \arctan\left(\frac{b}{a}\right) & a < 0 \end{cases} \tag{C.26}$$

C.11 Polar to Rectangular

$$re^{j\theta} = r\cos(\theta) + jr\sin(\theta) \tag{C.27}$$

D Calculus

D.1 L'Hopital's Rule

L'Hopital's Rule can be used to simplify and solve expressions regarding limits that yield irreconcialable results.

Lemma D.0.1 (L'Hopital's Rule)**.** *If the equation*

$$\lim_{x \to a} \frac{f(x)}{g(x)} = \begin{cases} \frac{0}{0} \\ \frac{\infty}{\infty} \end{cases}$$

then Equation (D.1) *holds.*

$$\lim_{x \to a} \frac{f(x)}{g(x)} = \lim_{x \to a} \frac{f'(x)}{g'(x)} \tag{D.1}$$

D.2 Fundamental Theorems of Calculus

Defn D.2.1 (First Fundamental Theorem of Calculus)**.** The *first fundamental theorem of calculus* states that, if f is continuous on the closed interval $[a, b]$ and F is the indefinite integral of f on $[a, b]$, then

$$\int_a^b f\left(x\right) dx = F\left(b\right) - F\left(a\right) \tag{D.2}$$

Defn D.2.2 (Second Fundamental Theorem of Calculus)**.** The *second fundamental theorem of calculus* holds for f a continuous function on an open interval I and a any point in I, and states that if F is defined by

$$F\left(x\right) = \int_a^x f\left(t\right) dt,$$

then

$$\begin{aligned} \frac{d}{dx} \int_a^x f\left(t\right) dt &= f\left(x\right) \\ F'\left(x\right) &= f\left(x\right) \end{aligned} \tag{D.3}$$

Defn D.2.3 (argmax)**.** The arguments to the *argmax* function are to be maximized by using their derivatives. You must take the derivative of the function, find critical points, then determine if that critical point is a global maxima. This is denoted as

$$\underset{x}{\operatorname{argmax}}$$

D.3 Rules of Calculus

D.3.1 Chain Rule

Defn D.3.1 (Chain Rule)**.** The *chain rule* is a way to differentiate a function that has 2 functions multiplied together.

If

$$f(x) = g(x) \cdot h(x)$$

then,

$$\begin{aligned} f'(x) &= g'(x) \cdot h(x) + g(x) \cdot h'(x) \\ \frac{df(x)}{dx} &= \frac{dg(x)}{dx} \cdot g(x) + g(x) \cdot \frac{dh(x)}{dx} \end{aligned} \tag{D.4}$$

D.4 Useful Integrals

$$\int \cos(x)\; dx = \sin(x) \tag{D.5}$$

$$\int \sin(x)\; dx = -\cos(x) \tag{D.6}$$

$$\int x \cos(x)\; dx = \cos(x) + x \sin(x) \tag{D.7}$$

Equation (D.7) simplified with Integration by Parts.

$$\int x \sin(x)\, dx = \sin(x) - x\cos(x) \tag{D.8}$$

Equation (D.8) simplified with Integration by Parts.

$$\int x^2 \cos(x)\, dx = 2x\cos(x) + (x^2 - 2)\sin(x) \tag{D.9}$$

Equation (D.9) simplified by using Integration by Parts twice.

$$\int x^2 \sin(x)\, dx = 2x\sin(x) - (x^2 - 2)\cos(x) \tag{D.10}$$

Equation (D.10) simplified by using Integration by Parts twice.

$$\int e^{\alpha x}\cos(\beta x)\, dx = \frac{e^{\alpha x}\big(\alpha\cos(\beta x) + \beta\sin(\beta x)\big)}{\alpha^2 + \beta^2} + C \tag{D.11}$$

$$\int e^{\alpha x}\sin(\beta x)\, dx = \frac{e^{\alpha x}\big(\alpha\sin(\beta x) - \beta\cos(\beta x)\big)}{\alpha^2 + \beta^2} + C \tag{D.12}$$

$$\int e^{\alpha x}\, dx = \frac{e^{\alpha x}}{\alpha} \tag{D.13}$$

$$\int x e^{\alpha x}\, dx = e^{\alpha x}\left(\frac{x}{\alpha} - \frac{1}{\alpha^2}\right) \tag{D.14}$$

Equation (D.14) simplified with Integration by Parts.

$$\int \frac{dx}{\alpha + \beta x} = \int \frac{1}{\alpha + \beta x}\, dx = \frac{1}{\beta}\ln(\alpha + \beta x) \tag{D.15}$$

$$\int \frac{dx}{\alpha^2 + \beta^2 x^2} = \int \frac{1}{\alpha^2 + \beta^2 x^2}\, dx = \frac{1}{\alpha\beta}\arctan\left(\frac{\beta x}{\alpha}\right) \tag{D.16}$$

$$\int \alpha^x\, dx = \frac{\alpha^x}{\ln(\alpha)} \tag{D.17}$$

$$\frac{d}{dx}\alpha^x = \frac{d\alpha^x}{dx} = \alpha^x\ln(x) \tag{D.18}$$

D.5 Leibniz's Rule

Lemma D.0.2 (Leibniz's Rule). *Given*

$$g(t) = \int_{a(t)}^{b(t)} f(x,t)\, dx$$

with $a(t)$ and $b(t)$ differentiable in t and $\frac{\partial f(x,t)}{\partial t}$ continuous in both t and x, then

$$\frac{d}{dt}g(t) = \frac{dg(t)}{dt} = \int_{a(t)}^{b(t)} \frac{\partial f(x,t)}{\partial t}\, dx + f\big[b(t), t\big]\,\frac{db(t)}{dt} - f\big[a(t), t\big]\,\frac{da(t)}{dt} \tag{D.19}$$

E Laplace Transform

E.1 Laplace Transform

Defn E.1.1 (Laplace Transform)**.** The *Laplace transformation* operation is denoted as $\mathcal{L}\{x(t)\}$ and is defined as

$$X(s) = \int\limits_{-\infty}^{\infty} x(t)e^{-st}dt \tag{E.1}$$

E.2 Inverse Laplace Transform

Defn E.2.1 (Inverse Laplace Transform)**.** The *inverse Laplace transformation* operation is denoted as $\mathcal{L}^{-1}\{X(s)\}$ and is defined as

$$x(t) = \frac{1}{2j\pi} \int_{\sigma-\infty}^{\sigma+\infty} X(s)e^{st}\,ds \tag{E.2}$$

E.3 Properties of the Laplace Transform

E.3.1 Linearity

The Laplace Transform is a linear operation, meaning it obeys the laws of linearity. This means Equation (E.3) must hold.

$$x(t) = \alpha_1 x_1(t) + \alpha_2 x_2(t) \tag{E.3a}$$

$$X(s) = \alpha_1 X_1(s) + \alpha_2 X_2(s) \tag{E.3b}$$

E.3.2 Time Scaling

Scaling in the time domain (expanding or contracting) yields a slightly different transform. However, this only makes sense for $\alpha > 0$ in this case. This is seen in Equation (E.4).

$$\mathcal{L}\big\{x(\alpha t)\big\} = \frac{1}{\alpha}X\left(\frac{s}{\alpha}\right) \tag{E.4}$$

E.3.3 Time Shift

Shifting in the time domain means to change the point at which we consider $t = 0$. Equation (E.5) below holds for shifting both forward in time and backward.

$$\mathcal{L}\big\{x(t-a)\big\} = X(s)e^{-as} \tag{E.5}$$

E.3.4 Frequency Shift

Shifting in the frequency domain means to change the complex exponential in the time domain.

$$\mathcal{L}^{-1}\big\{X(s-a)\big\} = x(t)e^{at} \tag{E.6}$$

E.3.5 Integration in Time

Integrating in time is equivalent to scaling in the frequency domain.

$$\mathcal{L}\left\{\int_0^t x(\lambda)\,d\lambda\right\} = \frac{1}{s}X(s) \tag{E.7}$$

E.3.6 Frequency Multiplication

Multiplication of two signals in the frequency domain is equivalent to a convolution of the signals in the time domain.

$$\mathcal{L}\big\{x(t) * v(t)\big\} = X(s)V(s) \tag{E.8}$$

E.3.7 Relation to Fourier Transform

The Fourier transform looks and behaves very similarly to the Laplace transform. In fact, if $X(\omega)$ exists, then Equation (E.9) holds.

$$X(s) = X(\omega)|_{\omega=\frac{s}{j}} \tag{E.9}$$

E.4 Theorems

There are 2 theorems that are most useful here:

1. Intial Value Theorem
2. Final Value Theorem

Theorem E.1 (Intial Value Theorem)**.** *The Initial Value Theorem states that when the signal is treated at its starting time, i.e. $t = 0^+$, it is the same as taking the limit of the signal in the frequency domain.*

$$x(0^+) = \lim_{s\to\infty} sX(s)$$

Theorem E.2 (Final Value Theorem)**.** *The Final Value Theorem states that when taking a signal in time to infinity, it is equivalent to taking the signal in frequency to zero.*

$$\lim_{t\to\infty} x(t) = \lim_{s\to 0} sX(s)$$

E.5 Laplace Transform Pairs

Time Domain	Frequency Domain
$x(t)$	$X(s)$
$\delta(t)$	1
$\delta(t - T_0)$	e^{-sT_0}
$\mathcal{U}(t)$	$\frac{1}{s}$
$t^n\,\mathcal{U}(t)$	$\frac{n!}{s^{n+1}}$
$\mathcal{U}(t - T_0)$	$\frac{e^{-sT_0}}{s}$
$e^{at}\,\mathcal{U}(t)$	$\frac{1}{s-a}$
$t^n e^{at}\,\mathcal{U}(t)$	$\frac{n!}{(s-a)^{n+1}}$
$\cos(bt)\,\mathcal{U}(t)$	$\frac{s}{s^2+b^2}$
$\sin(bt)\,\mathcal{U}(t)$	$\frac{b}{s^2+b^2}$
$e^{-at}\cos(bt)\,\mathcal{U}(t)$	$\frac{s+a}{(s+a)^2+b^2}$
$e^{-at}\sin(bt)\,\mathcal{U}(t)$	$\frac{b}{(s+a)^2+b^2}$
$re^{-at}\cos(bt+\theta)\,\mathcal{U}(t)$	$\begin{cases} a: & \frac{sr\cos(\theta)+ar\cos(\theta)-br\sin(\theta)}{s^2+2as+(a^2+b^2)} \\ b: & \frac{1}{2}\left(\frac{re^{j\theta}}{s+a-jb} + \frac{re^{-j\theta}}{s+a+jb}\right) \\ c: & \frac{As+B}{s^2+2as+c} \begin{cases} r & = \sqrt{\frac{A^2c+B^2-2ABa}{c-a^2}} \\ \theta & = \arctan\left(\frac{Aa-B}{A\sqrt{c-a^2}}\right) \end{cases} \end{cases}$
$e^{-at}\left(A\cos(\sqrt{c-a^2}t) + \frac{B-Aa}{\sqrt{c-a^2}}\sin(\sqrt{c-a^2}t)\right)\mathcal{U}(t)$	$\frac{As+B}{s^2+2as+c}$

E.6 Higher-Order Transforms

Time Domain	Frequency Domain
$x(t)$	$X(s)$
$x(t)\sin(\omega_0 t)$	$\frac{j}{2}\left(X(s+j\omega_0) - X(s-j\omega_0)\right)$
$x(t)\cos(\omega_0 t)$	$\frac{1}{2}\left(X(s+j\omega_0) + X(s-j\omega_0)\right)$
$t^n x(t)$	$(-1)^n \frac{d^n}{ds^n}X(s)\; n \in \mathbb{N}$
$\frac{d^n}{dt^n}x(t)$	$s^n X(s) - \sum_{0}^{n-1} s^{n-1-i}\frac{d^i}{dt^i}x(t)\rvert_{t=0^-}\; n \in \mathbb{N}$

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