Queensland University of Technology

CAB403

Systems Programming

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Chapter 1

Introduction to Operating Systems

1.1 Operating System Structures

1.1.1 Operating System Services

- Operating systems provide an environment for execution of programs and services to programs and users
- Operating System services provides functions that are helpful to the user
  - User Interface - Almost all opeating systems have a user interface (UI)
    - Graphical (GUI)
    - Command Line (CLI)
    - Batch
  - Program Execution - The system must be able to load a program into memory and run that program, end execution, either normally or abnormally (indicating error)
  - I/O operations - A running program may require I/O, which involves either a file or I/O device

Chapter 2

Operating System Structures

Chapter 3

Processes

Chapter 4

Threads

A thread is a fundamental unit of CPU utilization, which forms the basis of multithreaded computer systems. Many modern applications are multithreaded, with threads running within an application. An application can divide tasks to seperate threads such as

- Updating the display
- Fetching data
- Spell checking
- Answering network requests

Thread creation, as opposed to process creation is lightweight, can simplify code, and increase efficiency. For this reason, kernels are often multithreaded.

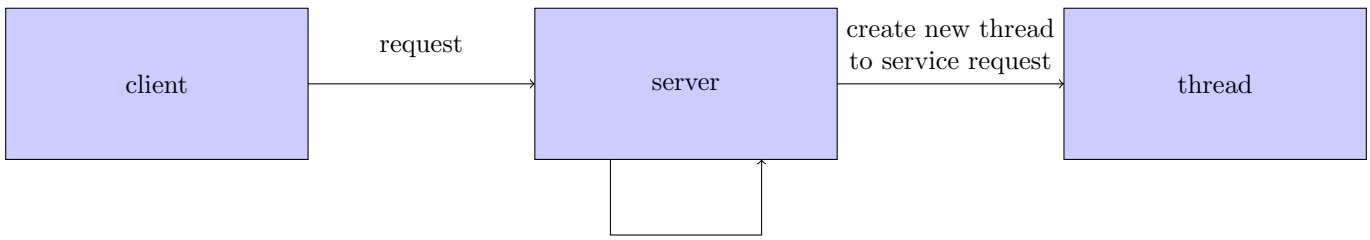


Figure 4.1: Multithreaded Server Architecture

Multithreading has the following benefits

- **Responsiveness**

  May allow continued execution if part of a process is blocked, important with user interfaces.

- **Resource Sharing**

  Threads share resources of process, easier to manage than shared memory or message parsing.

- **Economy**

  Cheaper than process creation, thread switching has lower overhead than context switching.

- **Scalability**

  Processes can take advantage of a multiprocessor architecture

4.1 Multicore Programming

In the early history of computer design, in order to combat the need for increased computing performance, single-CPU systems evoled into mult-CPU systems. Later, this evolved into including multiple compute cores on a single processing chip, where each core appears as a seperate CPU to the operating systems. These systems are defined as **multicore**.

4.1.1 Programming Challenges

The trend towards multicore systems continually places pressure on system designers and programmers to make better use of multiple compute cores. Designers of operating systems must write scheduling algorithms that use multiple processing cores to allow parallel execution

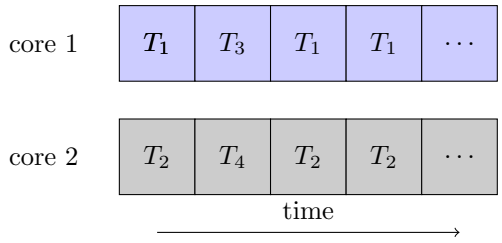


Figure 4.2: Parallel Execution on a Multicore System

In general, five areas present challenges in programming for multicore systems

- Identifying tasks

  This involves examining applications to find areas that can be divided into seperate, concurrent tasks. Ideally, tasks are independent of one another and thus can run in parallel on individual cores

- Balance

  While Identifying tasks that run in parallel, programmers msut also ensure that 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. Using seperate execution cores for that task might not be worth the cost

- Data Splitting

  Data accessed and manipulated by tasks must be divded to run on seperate cores, similar to how applications are divided to seperate tasks

- Data Dependency

  The data accessed by he tasks must be examined for dependencies between the two or more tasks. When data is dependent between cores, programmers must ensure that the execution of the tasks is synchronized to accomodate the dependency.

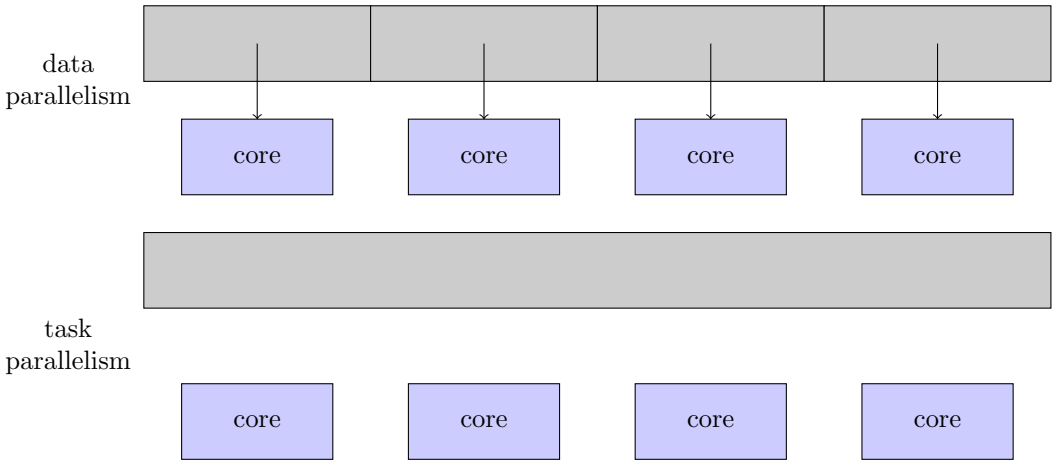


Figure 4.3: Data and Task Parallism

- Testing and Debugging

  When a program is running in parallel n multiple cores, many different execution paths are possible. Testing and debugging such concurrent programs is inherently more difficult than testing and debugging single threaded applications

4.1.2 Parallelism

Types of parallelism

- Data Parallelism

  Focuses on distributing subsets of the same data across multiple compute cores, performing the same operation on each core.

  Example: summing the contents of an array size N, on a dual core system, thread A sums the elements [0] ... $[N/2-1]$, thread B sums the elements $[N/2]$ ... $[N-1]$. These threads will run in parallel on seperate cores.

- Task Parallelism

  Distributes tasks across multiple cores. Each thread peforms a unique operation. Different threads may operate on the same or different data.

  Example: Dual core system, applying two different arithmetic and/or other operation on the same block of data on seperate threads. These threads will will run parallel on seperate cores.

Data and Task parallelism may be done together, in a hybrid solution.

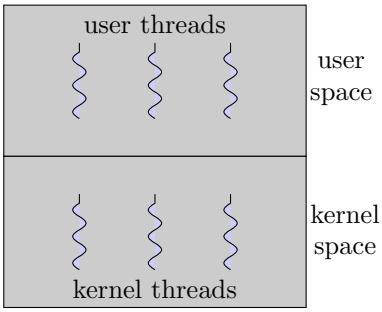


Figure 4.4: Use and Kernel Data Spaces

4.2 Multithreading Models

4.2.1 Many-To-One Model

Many user-level threads are mapped to a single kernel thread.
One thread block causes all to block.
Multiple threads cannot run in parallel on a multicore system because the kernel can only handle a single thread.
Rarely used.
Examples include

- Solaris Green threads
- GNU Portable threads

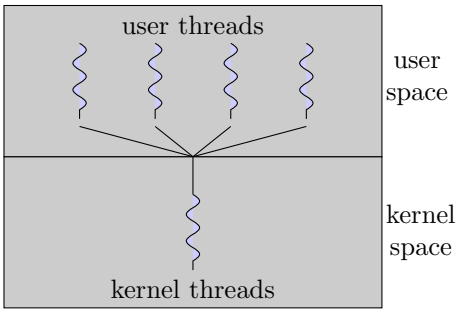


Figure 4.5: Many-to-one model

4.2.2 One-To-One Model

Each user-level thread maps to a kernel thread.
Creating a user level thread creates a kernel thread.
More concurrency than many-to-one.
Number of threads per process sometimes restricted due to overhead.
Examples include.

- Windows
- Linux
- Solaris (9 and later)

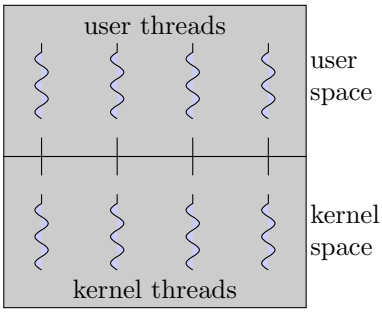


Figure 4.6: One-to-one model

4.2.3 Many-to-many model

Allows many user level threads to be mapped to many kernel threads.
Allows the operating system to create a sufficient number of kernel threads.
Examples include

- Solaris (pre version 9)
- Windows (*ThreadFiber* package)

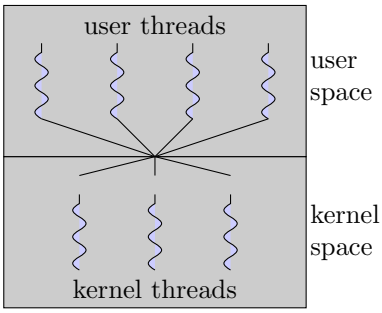


Figure 4.7: Many-to-many model

4.2.4 Two-level model

Similar to Many-to-many, except allows a user thread to be **bound** to a kernel thread Examples include

- IRIX
- HP-UX
- Tru64 UNIX
- Solaris (8 and earlier)

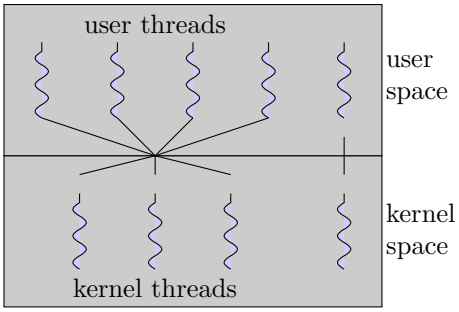


Figure 4.8: Two-level model

4.3 Thread Libraries

4.3.1 Pthreads

Refers to the POSIX standard (IEEE 1003.1c) defining an API for thread creation and synchronisation. This is a specification not an implementation

```c
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

long double sum;           /* this data is shared by the thread(s) */
void *runner(void *param); /* threads call this function */

int main(int argc, char **argv)
{
    pthread_t thread_id;        /* thread identifier */
    pthread_attr_t thread_attr; /* thread attributes */

    if (argc != 2)
    {
        fprintf(stderr, "usage: a.out <integer value>\n");
        return -1;
    }
    if (atoi(argv[1]) < 0)
    {
        fprintf(stderr, "%d must be >= 0\n", atoi(argv[1]));
        return -1;
    }
    /* get default attributes */
    pthread_attr_init(&thread_attr);
    /* create the thread */
    pthread_create(&thread_id, &thread_attr, runner, argv[1]);
    /* wait for the thread to exit */
    pthread_join(thread_id, NULL);
    printf("sum = %Lf\n", sum);
}

/* thread executes this function */
void *runner(void *param)
{
    int i, upper = atoi(param);
    sum = 0;
    for (i = 1; i <= upper; i++)
    {
        sum += i;
    }
    pthread_exit(0);
}
```

Figure 4.9: Multithreading using the pthreads API

Although Windows does not natively support pthreads, some third-party implementations are available

```c
#define NUM_THREADS 10
/* an array of threads to be joined upon */
pthread_t workers[NUM_THREADS];

for (int i = 0; i < NUM_THREADS; i++)
{
    pthread_join(workers[i], NULL);
}
```

Figure 4.10: Joining 10 threads using the pthreads API

4.3.2 Windows Threads

Similar to the technique used in pthreads. Uses a different library

```c
#include <windows.h>
#include <stdio.h>

DWORD Sum; /* data is shared by the threads */
/* The thread will execute this function */
DWORD WINAPI Summation(LPVOID Param)
{
    DWORD Upper = *(DWORD*)Param;
    for (DWORD i = 1; i <= Upper; i++)
    {
        Sum += i;
    }
    return 0;
}

int main(int argc, char **argv)
{
    DWORD ThreadID;
    HANDLE ThreadHandle;
    int Param;

    Param = atoi(argv[1]);
    /* create the thread */
    ThreadHandle = CreateThread(
        NULL, /* default security attributes */
        0, /* default stack size */
        Summation, /* thread function */
        &Param, /* parameter to thread function */
        0, /* default creation flags */
        &ThreadID /* returns thread identifier */
    );

    /* close the thread handle */
    CloseHandle(ThreadHandle);

    printf("sum = %d\n", Sum);
}
```

Figure 4.11: Multithreading using the Windows API

4.4 Implicit Threading

The growing popularity of multicore processing means that applications now require hundreds, or thousands of threads. When designing such programs, correctness grows more and more difficult. Creating and management of threads done by compilers and run-time libraries are favoured in this case.

4.4.1 Thread Pools

Creates a number of threads in a pool where they await work Advantages

- Usually faster to service a request with an existing thread than create a new thread
- Alows the number of threads in an application(s) to be bound to the size of the pool
- Seperating tasks to be performed from mechanics of creating task allows different stratgeies for running task

    Tasks could be scheduled to be run periodically

```
DWORD WINAPI PoolFunction(PVOID Param)
{
    /*
    * this function runs as a seperate thread
    */
}
```

Figure 4.12: Thread pooling in the Windows API

OpenMP

Set of compiler directives and an API for C, C++, FORTRAN.
Provides support for parallel programming and shared-memory environments.
Identifies parallel regions - blocks of code that can run in parallel.

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

int main(int argc, char **argv)
{
    int thread_id;

    #pragma omp parallel
    {
        printf("Hello from process %d\n", omp_get_thread_num());
    }
    return 0;
}
```

Figure 4.13: OpenMP

4.4.2 Grand Central Dispatch

- Apple technology for Mac OS X and iOS operating systems
- Extensions to C, C++, API and run-time library
- Allows identification of parallel sections
- Manages most details of threading
- Blocks is in "^{}" - `^{ printf("I am a block"); }`
- Blocks are placed in dispatch queue and then assigned to avaiable threads in thread pool when removed
- Two types of dispatch queues
  - **Serial** - blocks are removed FIFO, queue is per process, called **Main Queue**

    Programmers create additional serial queues within program
  - **Concurrent** - removed in FIFO, but many be removed at a time

    Three system wide queues with priorities low, default, high

```
dispatch_queue_t queue = dispatch_get_global_queue(DISPATCH_QUEUE_PRIORITY_DEFAULT, 0);
dispatch_async(queue, ^{ printf("I am a block."); });
```

4.5 Threading Issues

- Semantics of **fork()** and **exec()** system calls.
- Signal handling (synchronous and asynchronous)
- Thread cancellation of target thread (asynchronous or deferred)

- Thread local storage
- Scheduler activations

4.5.1 Semantics of fork() and exec()

- Does fork() duplicate only the calling thread or all threads?

  Some UNIXes have two versions of fork

- exec() usually works as normal (replaces running process including all threads)

4.5.2 Signal Handling

- Signals are used in UNIX systems to notify a process that a particular event has occurred
- A signal handler is used to process signals
  - Signal is generated by an event
  - Signal is delivered to a process
  - Signal is handled by one of two signal handlers

    default

    user-defined
- Every signal has a default handler that kernel runs when handling a signal
  - User-defined signal handler can override default
  - For single-threaded, signal delivered to process
- Where is the signal delivered in multi-threaded?
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in process

4.5.3 Thread Cancellation

- Terminating a thread before it has finished
- Thread to be canceled is target thread
- Two general approaches
  - **Asynchronous cancellation** terminates the target thread immediately
  - **Deferred cancellation** allows the target thread to periodically check if it should be cancelled

```
pthread_t thread_id;
/* create the thread */
pthread_create(&thread_id, 0, worker, NULL);
...
/* cancel the thread */
pthread_cancel(thread_id);
```

Figure 4.14: pthread code to create and cancel a thread

- Invoking thread cancellation requests cancellation, but actual cancellation depends on the thread state

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

Figure 4.15: Thread States

- If a thread has cancellation disabled, cancellation remains pending till enabled
- Default type is deferred

  Cancellation only occurs when thread reaches cancellation point
  - i.e., `pthread_testcancel();`
  - Then cleanup handler is invoked
- On Linux, thread cancellation is handled through signals

4.5.4 Thread-Local Storage

- Thread-local-storage (TLS) allows each thread to have its own copy of data
- Useful when you don't have control over thread creation (i.e., using a thread pool)
- Different from local variables
  - Local variables visible only during single function invocation
  - TLS visible across function invocations
- Similar to static data
  - TLS is unique to each thread

4.5.5 Scheduler Activations

- Both Many to Many and Two-Level require communication to maintain the appropriate number of kernel threads allocated to the application
- Typically use an intermediate data structure between user and kernel threads (lightweight process (LWP))
  - Appears to be a virtual processor on which process can schedule user thread to run
  - Each LWP is attached to a kernel thread
  - How many LWPs to create?
- Scheduler activations provide upcalls - a communication mechanism from the kernel to the upcall handler in the thread library
- This communication allows an application to maintain the correct number of kernel threads

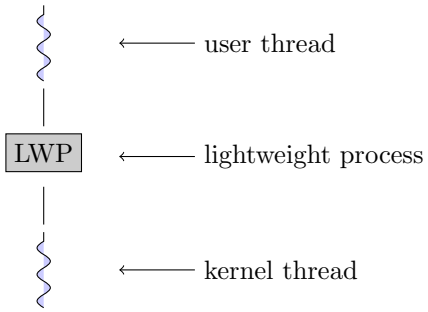


Figure 4.16: Lightweight Process (LWP)

Chapter 5

Synchronisation

Processes can either execute concurrently or in parallel. These processes may be interrupted at any time, partially completing execution. Concurrent access to any shared memory may result in data inconsistency if not properly controlled.
Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.

Example:

Suppose we wanted to provide a solution to the consumer-product problem that fills **all** the buffers. We can do so by having an integer `counter` that keeps track of the number of full buffers. Initially, `counter` is set to 0. It is incremented by the producer after producing a new buffer, and decremented by the consumer after it consumes a buffer.

```
while (true) {
    /* produce an item in next produced */
    while (counter == BUFFER_SIZE);
        /* do nothing */
    buffer[in] = next_produced;
    in = (in + 1) % BUFFER_SIZE;
    counter++;
}
```

```
while (true) {
    while (counter == 0);
        /* do nothing */
    next_consumed = buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    counter--;
    /* consume the item in next_consum
}
```

Figure 5.1: Producer and Consumer

5.1 Race Conditions

While the producer and consumer routines shown are correct seperately, they may not function correctly when executed concurrently. For example: Suppose that the value of the variable `count` is currently 5 and the producer and consumer processes concurrently execute the statements "`count++`" and "`count--`". This will lead to the variable being 4, 5 or 6. With the only correct value being `count == 5`, which is executed if the producer and consumer execute seperately. We can show the value maybe incorrect by using the following implementation

$$\begin{aligned} register_1 &= count \\ register_1 &= register_1 + 1 \\ count &= register_1 \end{aligned}$$

where $register_1$ is one of the local CPU registers.
Similarly, the statement `count - 1` is implemented as follows

$$\begin{aligned} register_2 &= count \\ register_2 &= register_2 - 1; \\ count &= register_2 \end{aligned}$$

where again, $register_2$ is a local CPU register.
Even though $register_1$ and $register_2$ are local CPU registers, the value of this register will be saved and stored by the interrupt handler

The concurrent execution `count++` and `count -- 1` is equivalent to the sequential execution where lower evel statements previously are interleaved in an arbitrary order, with the order of the high-level statement is preserved.

$$T_0 \quad producer \quad \text{execute} \quad register_1 = count \quad \{register_1 = 5\}$$

Chapter 6

Safety Critical Systems

Safety is the freedom from conditions that cause death, injury, illness, damage to or loss of equipment or property, or environmental harm
Software is inherently not safe or unsafe, however can contribute to unsafe conditions in a safety critical system. Such software is **Safety Critical**
IEEE definition: "Software whose use in a system can result in unacceptable risk. Safety-critical software incliudes softwre whose operation or failure to operate can lead to a hazardous state. Software intended to reover from hazardous states, and software intended to mitigate the severity of an incident"

6.1 MISRA C

- Motor Industry Software Reliability Association

6.2 NASA Power of 10

- Avoid complex flow constructs (goto, recursion, jumps)
- All loops must have fixed bounds (prevents runaway code)
- Avoid heap memory allocation (no malloc, define everything in main)
- Restrict functions to a single page (max 50 lines)
- Use a minimum of two runtime assertions per function
- Restrict the scope of data to the smallest possible
- Check the return value of all non-void functions, or cast to void to indicate the return is useless
- Use the preprocessor sparingly. (DO NOT USE stdio.h, local.h, abort/exit/system from stdlib.h, time handling from time.h)
- Limit pointer use to a single dereference and DO NOT USE FUNCTION POINTERS
- Compile with all warnings active (Wall, Wextra, etc.) all warnings should then be addressed before release

Chapter 7

Distributed Systems

A distributed system is a collection of processors that do not share memory or a clock. Instead, each node has its own local memory. The nodes communicate over various networks, such as high-speed busses.
Applications of distributed systems vary widely, from providing transparent file access inside an organization, to large-scale cloud storage services, to business analysis of trends on large datasets, to parallel processing of scientific data. With the most ubiqiutous form of a distributed system being the Internet.

7.1 Basic Concepts

A distributed system is a collection of loosely coupled nodes interconnected by a communication network. From the point of view of a specific node in a distributed system, the rest of the nodes and their respective resources are remote, whereas its own resources are local.
Processors are variously called **nodes, computers, machines, hosts**

- **Site** is the location of the processor
- Generally a **server** has a resource a **client** node at a different site wants to use

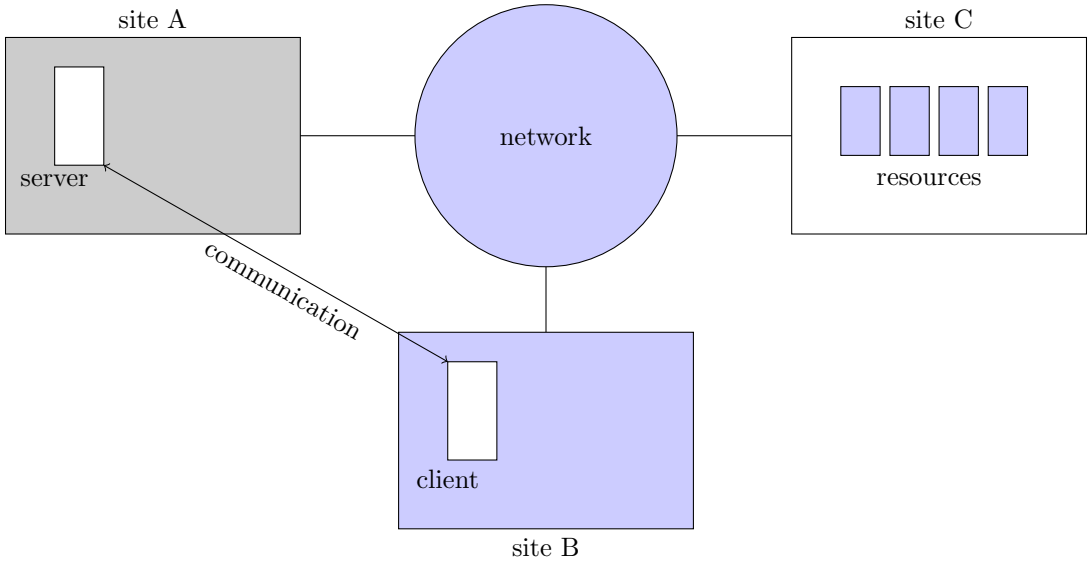


Figure 7.1: A client-server distributed system

7.2 Advantages of Distributed Systems

- **Resource Sharing**
  - Sharing and printing files at remote sites

  - Processing information in a distributed database
  - Using remote specialized hardware devices
- **Computation speedup**
  - **Load sharing**
  - **Job migration**
- **Reliability**

  Detect and recover from site failure, function transfer, reintegrate failed site.
- **Communication**

  Message passing
  All higher-level functions of a standalone system can be expanded to encompass a distributed system

Computers can be downsized, more flexibility, better user interfaces and easier maintenance by moving from a large system to a cluster of smaller systems performing distributed computing

7.3 Network-Operating Systems

7.4 Distributed Operating Systems

Chapter 8

CPU Scheduling

CPU scheduling is the basis of multiprogrammed operating systems. By switching the CPU among processes, the operating system can make the computer more productive.

8.1 Basic Concepts

A single core system can only run a single process at a time. Others must wait till the CPU's core is free and can be rescheduled. Multiprogramming is the idea of having a process running at all times to maximise CPU utilization.
A process is executed until it must wait, typically for the completion of an I/O request. A simple computer system just idles during this period, waiting compute time, no work is accomplished. With multiprogramming, we try to use this time productively. By keeping several processes in memory, when one process has to wait, the operating takes the CPU away from the process and gives it to another process. On a multicore system this is extended to all processing cores on the system.
Such scheduling is fundamental to an operating system's functionality. Almost all computer resources are scheduled before use. The CPU, being one of the primary resources of a computer needs special attention during its scheduling

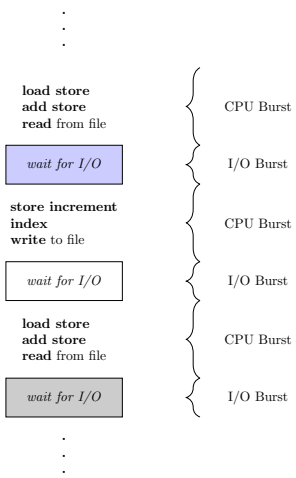


Figure 8.1: Alternating Sequence of CPU and I/O Bursts

8.2 CPU Scheduler

Whenever the CPU idles, the operating system must select a process in the ready queue to be executed.
This is selected by the CPU Scheduler. Which selects a process from the processes in memory that are ready to execute, and allocates the CPU to it.
The short-term scheduler seelcts from processes in the ready queue and allocates the CPU to one of them.
CPU scheduling happens when

- Switching from running to waiting
- Switching from running to ready

- Switching from waiting to ready
- Terminating

8.2.1 Preemptive and Non-Preemptive Scheduling

CPU-scheduling decisions may take place under the following four circumstances

1. Process switching from running state to the waiting state (I/O request, wait invocation for Terminating a child process)
2. Process switching from running to ready state (interrupt)
3. Process switching from waiting to ready (I/O completion, release of a semaphore)
4. Process terminating

For circumstances 1 and 4, there is no choice in scheduling, a new process (if exists) must be selected for execution. For circumstances 2 and 3, a choice exists.
Circumstance 1, and 4 are called non preemptive or cooperative. Otherwise it is preemptive.
Non-preemptive scheduling keeps the CPU once the process is allocated till termination or switching to the wait state.

Preemptive Scheduling

Virtually all modern operating systems use preemptive scheduling.
However, Preemptive scheduling can result in race conditions when data is shared between processes (first process is updating data while the second process tries to read it, which is in an inconsistent state).
Kernel design must be modified to accomodate a preemptive scheduler as race conditions in updating or modifying important kernel data (IO queues, process table, etc.) while they are being read can cause the system to crash.
Therefore, a preemptive kernel requires mechanisms such as mutex locks to prevent race conditions when accessing shared kernel data structues.
Most modern operating systems are full prememptive when running in kernel mode.

Non Preemptive Scheduling

Non preemptive scheduling is simpler than preemptive scheduling as there is no need for any special hardware or kernel mode privileges.
However, non preemptive scheduling is not suitable for modern operating systems as it does not allow the kernel to respond to interrupts while running in kernel mode.
Non preemptive scheduling is used in embedded systems where the kernel is the only process running on the system.
Non preemptive scheduling is also used in real time systems where the kernel is the only process running on the system.

8.3 Dispatcher

Is the module that gives control of the CPU's core to the process selected by the scheduler. Involves

- Context switching
- Switching to user model
- Jumping to the proper location in the user program to resume that program

Speed is crucial with the dispatcher as it is invoked during every context switch.
Dispatch latency is the time taken for the dispatcher to stop one process and starty another running.

8.4 Scheduling

Optimisation objectives

- Max CPU utilization
- Max throughput
- Min turnaround time
- Min waiting time

- Min response time

8.4.1 First-Come, First-Served (FCFS) Scheduling

The process that requests the CPU first is allocated the CPU first.
Managed using a FIFO queue.
Given the following process table

Process	Burst Time	Arrival Time
P1	24	0
P2	3	1
P3	3	2

(a) Process Table

(b) FIFO Gantt Chart

Waiting time for P_1 is 0, P_2 is 24, P_3 is 27. Average waiting time is 17.

Figure 8.2: Process Table and FIFO Gantt Chart with waiting times

Process	Burst Time	Arrival Time
P1	24	3
P2	3	1
P3	3	2

(a) Process Table

(b) FIFO Gantt Chart

Waiting time for P_1 is 6, P_2 is 0, P_3 is 3. Average waiting time is 3.

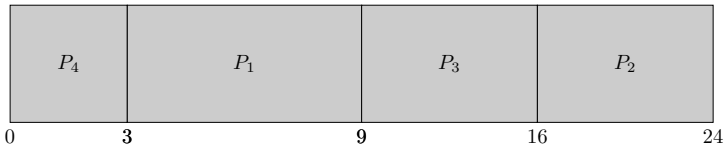
Figure 8.3: Process Table and FIFO Gantt Chart with waiting times

8.4.2 Shortest-Job-First (SJF) Scheduling

By associating each process with the length of its next CPU burst, we can schedule the process with the shortest time.
SJF is optimal, giving the minimum average waiting time for a given set of processes.
However, knowing the length of the next CPU burst is difficult to predict the length of the next CPU burst.

Process	Burst Time
P1	6
P2	8
P3	7
P4	3

(a) Process Table



(b) SJF Gantt Chart

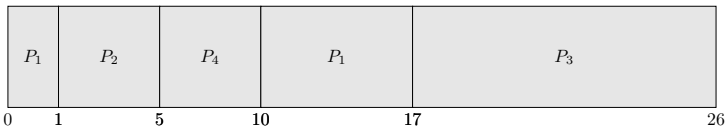
Average waiting time is 7

Figure 8.4: Process Table and SJF Gantt Chart with waiting times

SJF can be either preemptive or non preemptive.
Preemptive SJF is also called Shortest Remaining Time First

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
P4	3	5

(a) Process Table with Arrival Time



(b) SRTF Gantt Chart

Average waiting time is 6.5

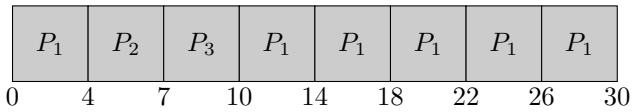
Figure 8.5: Process Table and SRTF Gantt Chart with waiting times

8.4.3 Round Robin Scheduling

Each process is given a small unit of CPU time (time quantum or time slice q) that is 10-100 millisecond. After that time, the process is preempted and added to the end of the ready queue.
If there are n processes in the ready queue and the time quantum is q, then each process gets 1/n of the CPU time in chunks of at most q time units at once. No process waits more than (n-1)q time units.
Timer interrupts every quantum to schedule the next process.

Process	Burst Time
P1	24
P2	3
P3	3

(a) Process Table



(b) Round Robin Gantt Chart

Figure 8.6: Round Robin Gantt Chart with time quantum 4

Typically, round robin has a higher average turnaround than SJF but has better reponse.

Chapter 9

Deadlocks

9.1 System Model

A system consists of finite resources distributed among a number of competing threads. These resources must be partitioned into several types or classes, each consisting of identical instances.
Under normal operation, a thread may utilize a resource in the following sequence

1. **Request** - The thread requests the resource. If the request cannot be granted immediately (for example, if a mutex lock is held by another thread) the requesting thread must wait till it can acquire the resource.
2. **Use** - The thread can operate on the resource (for example, if the resource is a mutex lock, it can access its critical section)
3. **Release** - The thread releases the resource (for example, if the resource is a mutex lock, it releases the lock, allowing another thread to acquire it)

9.2 Deadlock Characterization

Deadlocks can arise if four conditions hold simultaneously

- **Mutual exclusion** - At least one resource must be held in a nonsharable mode; that is, only one thread ata time can use the resource. If another thread requests that resource, the requesting thread must be delayed until the resource is released.
- **Hold and Wait** - A thread must be holding at least one resource and waiting to acquire additional resources that are currently being hld by other threads
- **No Preemption** - Resources cannot be preempted; resources can only be released voluntarily by the thread holding it, after that the thread has completed its task.
- **Circular Wait** - A set of waiting threads must exist such that T_0 is waiting for a resource held by T_1, T_1 is waiting for a resource held by T_2, ... T_{n-1} is waiting for a resource held by T_n, and T_n is waiting for a resource held by T_0.

Note that circular wait implies hold and wait

9.3 Resource-Allocation Graph

A set of vertices V and a set of edges E.

- V is partitioned into two types

  P - Set consisting of all the threads in the system

  R - Set consisting of all resource types in the system

- **Request edge**

  Directed edge $T_i \rightarrow R_j$

- **Assignment edge**

  Directed edge $R_j \rightarrow T_i$

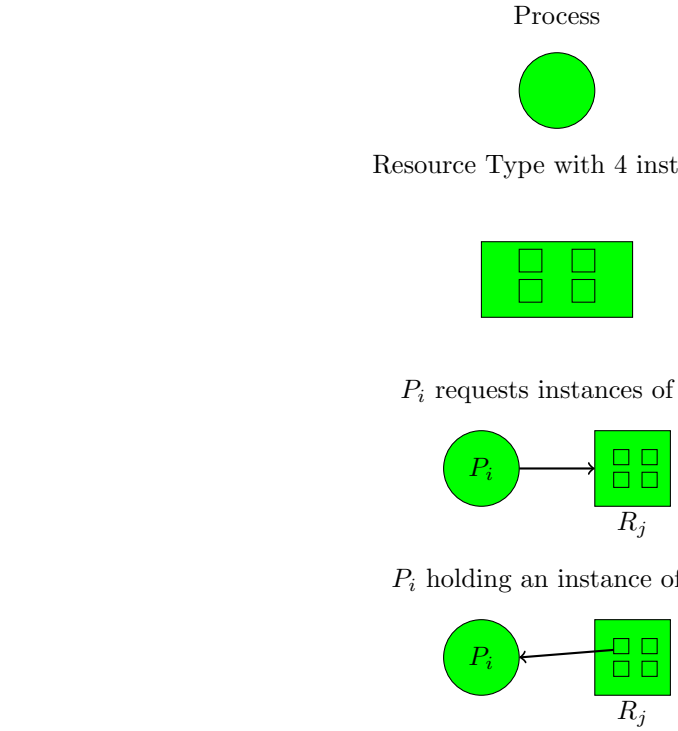
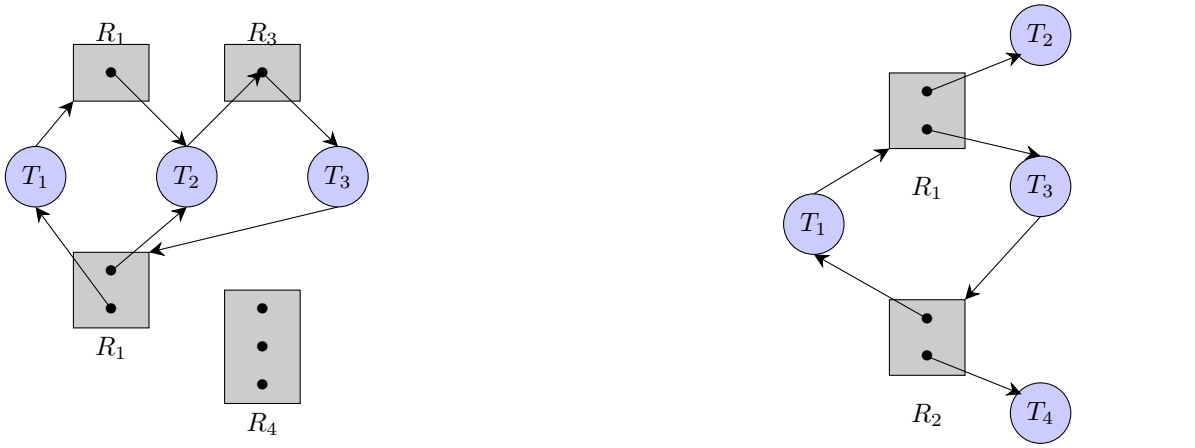


Figure 9.1: Resource Allocation Graph



(a) Resource Allocation Graph with Deadlock

(b) Resource Allocation Graph without Deadlock

Figure 9.2: Resource Allocation Graphs

9.3.1 Basic Facts

- If a graph has no cycles there is no deadlock
- If a graph has a cycle

  If only one instance per resource type, then there's a deadlock

  If several instances per resource type, then deadlock may or may not exist

9.4 Methods for Handling Deadlocks

Ensure the system will never enter a deadlock state, or make sure that once a deadlock occurs, it will be recovered from the state. OR ignore the problem and pretend that deadlocks never occur in the system (UNIX, Linux, Windows).

9.5 Deadlock Prevention

Restrain the way requests can be made

- **Mutual Exclusion** - Not required for sharable resources, must hold for nonsharable resources
- **Hold and Wait** - Must guarantee that whenever a thread requests a resource, it does not hold any other resources
  - Require that each thread request all its resources at one time
  - Require that once a thread holds a resource, it cannot request additional resources
  - Require that once a thread requests a resource, it cannot request additional resources till the requested resource has been allocated to it
- **No preemption**
  - If a process that is holding some resources requests another resource that cannot immediately allocated to it, then all resources held must be released.
  - Preempted resources are added to the list of resources for which the process is waiting
  - Process will be restarted only when it can regain old resources, as as the ones requested
- **Circular Wait**
  - Impose a total ordering of all resource types, and require that each thread requests resources in an increasing order of enumeration

9.6 Deadlock Avoidance

Requires that the system has some additional **a priori** information available.

- Simplest and most useful model requires that each process declare the **maximum number** of resources of each type it may need
- The deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that there can never be a circular-wait condition
- Resource-allocation state is defined by the number of available and allocated resources, and the maximum demands of the processes/threads.

9.6.1 Basic Facts

- If a system is in safe state, no deadlocks
- If a system is in unsafe state, possibility of deadlock
- Avoidance, ensure that a system will never enter an unsafe state

9.7 Safe State

When a process requests and available resource, the system must decide if immediate allocation leaves the system in a safe state. The system is in a **safe state** if there exists a sequence of **ALL** the processes in the system such that for each P_i, the resources that P_i can still request can be satisfied by currently available resources + resources held by all the P_j, with $j < i$. i.e.,

- If P_i requests a resource, it may have to wait till all the P_j with $j < i$ have finished
- When P_j is finished, P_i can obtain its needed resources, execute, return allocated resources, and terminate
- When P_i terminates, P_{i+1} can obtain its needed resources, and so on

9.8 Deadlock Avoidance Algorithms

9.8.1 Resource Allocation Graph Scheme

- Claim edge $P_i \rightarrow R_j$ indicated that processes P_i may request resource R_j.

- Claim edge converts to request edge when a process/thread requests a resource.
- Request edge converted to an assignment edge when the resource is allocated to the process/thread.
- When a resource is released by a process, assignment edge reconverts to a claim edge.
- Resources must be claimed *a priori* in the system.

(a) Safe State (b) Unsafe State

Figure 9.3: Resource Allocation Graphs

The request can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph.

9.9 Banker's Algorithm

Used for multiple instances of resources, where each process must a priori claim the maximum number of resources. When a process requests a resource it may have to wait. When a process gets all of its resources, it must return them in a finite amount of time.

9.9.1 Data Structures

With n processes and m resource types, the following data structures are used

- **Available** - Vector of length m. If *available[j]* = k, there are k instances of resource type R_j available.
- **Max** - $n \times m$ matrix. If *Max[i,j]* = k, then process P_i may request at most k instances of resource type R_j.
- **Allocation** - $n \times m$ matrix. If *Allocation[i,j]* = k, then process P_i is currently allocated k instances of R_j.
- **Need** - $n \times m$ matrix. If *Need[i,j]* = k, then process P_i may need k more instances of R_j to complete its task.

$$Need[i,j] = Max[i,j] - Allocation[i,j]$$

9.9.2 Safety Algorithm

1. Letting **Work** and **Finish** be vectors of length m and n respectively.
2. Initialising **Work** = **Available** and **Finish[i]** = false for $i = 0, 1, ..., n-1$
3. Find an **i** such that **Finish[i] = false** and **Need**$\leq$**Work**

   If no such **i** exists, go to step 4
4. **Work = Work + Allocation[i]**, **Finish[i] = true**

   Go to step 2
5. If **Finish[i] = true** for all **i**, the system is in a safe state.

9.9.3 Resource-Request Algorithm for Process P_i

Request[i] = request vector for process P_i. If **Request[i,j] = k**, then process P_i wants k instances of resource type R_j.

1. if **Request[i]** $\leq$ **Need[i]**, go to step 2. Otherwise, raise error condition since process has exceeded its maxmimum claim.
2. if **Request[i]** $\leq$ **Available**, go to step 3. Otherwise, P_i must wait as resources are unavailable.

3. Pretend to allocate the requested resources to P_i by modifying the state as follows

$$\textbf{Available = Available - Request}$$
$$\textbf{Allocation[i] = Allocation[i] - Request[i]}$$
$$\textbf{Need[i] = Need[i] - Request[i]}$$

- If safe state, then resources will be allocated to P_i
- If unsafe state, P_i must wait, and the old resource-allocation state will be stored

9.9.4 Example

Given 4 processes $[P_0, P_1, P_2, P_3, P_4]$ and 3 resource types [A (10 instances), B (5 instances), C (7 instances)].
At time t_0, the following snapshot of the system has been taken

	Allocation	Max	Available
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	3 3 2
P_1	2 0 0	3 2 2	
P_2	3 0 2	9 0 2	
P_3	2 1 1	2 2 2	
P_4	0 0 2	4 3 3	

The content of matrix **Need** is calculated as follows

	Allocation	Max	Need
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	7 4 3
P_1	2 0 0	3 2 2	1 2 2
P_2	3 0 2	9 0 2	6 0 0
P_3	2 1 1	2 2 2	0 1 1
P_4	0 0 2	4 3 3	4 3 1

This system is in a safe state since the sequence $< P_1, P_3, P_4, P_0, P_2 >$ satisfies the safety algorithm.

Chapter 10

Virtual Machines

10.1 Benefits and Features

- Templating - create an OS + application VM, provide it to customers, use it to create multiple instances

  Docker containers, AWS AMIs, etc.

- Live Migration - Move a running VM from host to another

  No interruption of user access

- All these features together $\Longrightarrow$ cloud computing

  Using APIs, programs tell cloud infrastructure (servers, networking, storage) to create new guests, VMs, virtual desktops

10.2 Types of Virtual Machines

Many variations as well as hardware details, assiming VMMs take advantage of hardware features, they can simplify implementation and improve performance All Virtual Machines have a lifecycle

- Created by the VMM
- Resources assigned to it (cores, amount of memory, networking details, storage details)
- In type 0 hypervisor, resources are usually dedicated
- Other types dedicate or share resource (or mix)
- When no longer needed, VMs can be deleted, freeing resources

Steps are simpler and faster than a physical machine install

- Can lead to VM sprawl with lots of VMs, history and state are difficult to track

10.3 Types of VMs

10.3.1 Type 0 Hypervisor

Is an older idea under many names by hardware manufacturers

- Partitions, Domains

Hardware features must be implemented in firemware, the VMM is in firmware. Smaller feature set than other types

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Chapter 11

Practicals

11.1 Introduction to Operating Systems

11.2 Operating System Structures

11.3 Processes

11.4 Threads

11.4.1 Thread Creation

Exercise: Modify sampleThread.c. Create a third thread and this time sum up the first 20 numbers 1,2,...20. Practice passing a struct to the thread:

```
typedef struct num_thdata {
    int thread_no;
    int sum_to;
} thsum;
```

```
#include <unistd.h>     /* Symbolic Constants */
#include <sys/types.h> /* Primitive System Data Types */
#include <errno.h>      /* Errors */
#include <stdio.h>      /* Input/Output */
#include <stdlib.h>     /* General Utilities */
#include <pthread.h>    /* POSIX Threads */
#include <string.h>     /* String handling */

#define MESSAGE_REPEAT 2

/* struct to hold data to be passed to a thread
   this shows how multiple data items can be passed to a thread */
typedef struct str_thdata {
    int thread_no;
    char message[100];
} thdata;

typedef struct num_thdata {
    int thread_no;
    int sum_to;
} thsum;
/* declare sum as global */
int sum;
/* prototype for thread routine */
void *print_message_function(void *ptr);
void *sum_to_function(void *ptr);
```

```c
int main(int argc, char *argv[]) {
    pthread_t thread1, thread2, thread3; /* thread variables */
    thdata data1, data2;        /* structs to be passed to threads */
    thsum data3;
    /* initialize data to pass to thread 1 */
    data1.thread_no = 1;
    strcpy(data1.message, "Hello! Welcome to Practical 5 - Week 5 already!!!");

    /* initialize data to pass to thread 2 */
    data2.thread_no = 2;
    strcpy(data2.message, "Hi! Week 5 - Time flies by when programming in C");

    /* initialize data to pass to thread 3 */
    data3.thread_no = 3;
    data3.sum_to = 20;
    /* create threads 1, 2, and 3
    *  function must take a parameter of void *(the second void *)
    *  return a value of void * (first void)
    */
    pthread_create(&thread3, NULL, sum_to_function, &data3);
    pthread_create(&thread1, NULL, print_message_function, &data1);
    pthread_create(&thread2, NULL, print_message_function, &data2);
    /* Main block now waits for both threads to terminate, before it exits
       If main block exits, both threads exit, even if the threads have not
       finished their work */
    pthread_join(thread3, NULL);
    pthread_join(thread1, NULL);
    pthread_join(thread2, NULL);

    /* exit */
    return EXIT_SUCCESS;
} /* main() */

/**
 * print_message_function is used as the start routine for the threads used
 * it accepts a void pointer
**/
void *print_message_function(void *ptr) {
    thdata *data;
    data = ptr; /* type cast to a pointer to thdata */

    /* do the work */
    for (int x = 0; x < MESSAGE_REPEAT; x++)  {
        printf("\n\nThread %d has the following message -->  %s \n", data->thread_no, data->message);
    }
    return NULL;
}

void *sum_to_function(void *ptr)
{
    thsum data = *((thsum*)ptr); // cast void to thsum
    for (int i = 0; i <= data.sum_to; i++)
    {
        sum += i;
    }
    printf("Thread number %d reports that the sum of the first %d numbers is = %d\n", data.thread_no, data.sum_t
    return NULL;
}
```

11.4.2 Producer and Consumer Threads

11.4.3 Searching Hash Table Values

11.4.4 OpenMP

11.5 Synchronisation

11.6 Safety Critical Systems

11.7 Distributed Systems

11.8 CPU Scheduling

11.9 Deadlocks