Processes

- Basic concept to build the OS, from old IBM mainframe OS to the most modern Windows
- Used to express the requirements to be met by an OS
  - Interleave the execution of multiple processes, to maximize CPU utilization while providing good response time
  - Allocate resources to processes using a policy while avoiding deadlocks
  - Support interprocess communications and user creation of processes to help structuring applications
- Background
  - Computer platform
    * Collection of hardware resources – CPU, memory, I/O modules, timers, storage devices
  - Computer applications
    * Developed to perform some task
    * Input, processing, output
  - Efficient to write applications for a given CPU
    * Common routines to access computer resources across platforms
    * CPU provides only limited support for multiprogramming; software manages sharing of CPU and other resources by multiple applications concurrently
    * Data and resources for multiple concurrent applications must be protected from other applications
- Process
  - Abstraction of a running program
  - Unit of work in the system
  - Split into two abstractions in modern OS
    * Resource ownership (traditional process view)
    * Stream of instruction execution (thread)
  - Pseudoparallelism, or interleaved instructions
  - A process is *traced* by listing the sequence of instructions that execute for that process
- Modeling sequential process/task
  - Program *during* execution
  - Program code
  - Current activity
  - Process stack
    * Function parameters
    * Return addresses
    * Temporary variables
  - Data section
    * Global variables
- Concurrent Processes
  - Multiprogramming
  - Interleaving of traces of different processes characterizes the behavior of the CPU
  - Physical resource sharing
    * Required due to limited hardware resources

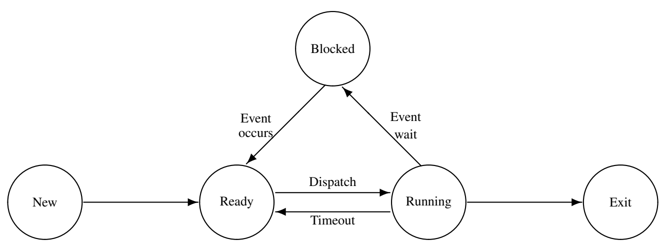
- Logical resource sharing
  - Concurrent access to the same resource like files
- Computation speedup
  - Break each task into subtasks
  - Execute each subtask on separate processing element
- Modularity
  - Division of system functions into separate modules
- Convenience
  - Perform a number of tasks in parallel
- Real-time requirements for I/O

• Process Hierarchies

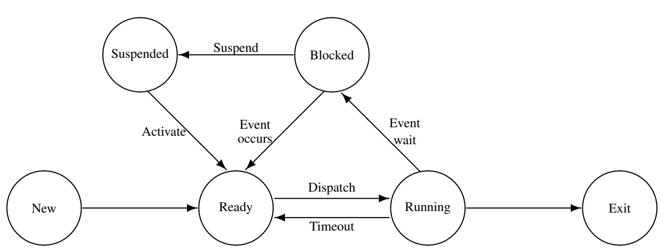
- Parent-child relationship
- `fork(2)` call in Unix
- In older non-multitasking systems such as MS-DOS, parent suspends itself and lets the child execute

• Process states

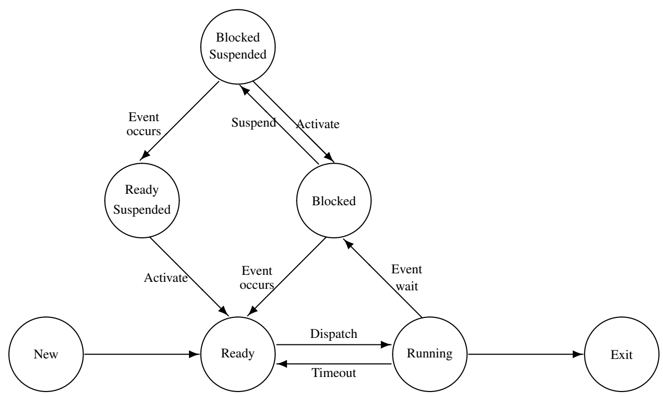
- A two-state process model
  - Simplest possible model
  - A process is either `executing` (running state) or it is `idle` (not-running state)
  - For a new process, the OS creates a new process control block and brings that process into memory in a not-running state
- A five-state model
  - `Running`
  - `Ready` – Not running, waiting for the CPU
  - `Blocked` – Wait on an event (other than CPU)
  - Two other states complete the five-state model – `New` and `Exit`
    - A process being created can be said to be in state `New`; it will be in state `Ready` after it has been created
    - A process being terminated can be said to be in state `Exit`



- Above model suffices for most of the discussion on process management in operating systems; however, it is limited in the sense that the system screeches to a halt (even in the model) if all the processes are resident in memory and they all are waiting for some event to happen
- Create a new state Suspend to keep track of blocked processes that have been temporarily kicked out of memory to make room for new processes to come in
- The state transition diagram in the revised model is



- Which process to grant the CPU when the current process is swapped out?
  * Preference for a previously suspended process over a new process to avoid increasing the total load on the system
  * Suspended processes are actually blocked at the time of suspension and making them ready will just change their state back to blocked
  * Decide whether the process is blocked on an event (suspended or not) or whether the process has been swapped out (suspended or not)
- The new state transition diagram is



- Process sleep state
  * A process can put itself to sleep while waiting for an event
    · Instead of constantly polling for input from keyboard, a shell puts itself to sleep
  * Process sleeps on a particular wait channel (`WCHAN`)
  * When the event associated with `WCHAN` occurs, every process waiting on that `WCHAN` is woken up
  * The awakened processes check to see if the signal was meant for them
    · Consider a set of processes waiting for data from the disk
    · Once data becomes available, processes check whether the data is ready for them
  * If the signal is not for the processes, they put themselves to sleep on the same `WCHAN`

Process control

- Modes of execution
  - OS execution vs user process execution
  - OS may prevent execution of some instructions in user mode and allow them to be executed only in privileged mode (also called kernel mode, system mode, or control mode)
    * Read/write a control register, such as PSW
    * Primitive I/O and memory management
  - The two modes protect the OS data structures from interference by user code
  - Kernel mode provides full control of the system that may not be needed for user programs
  - The kernel mode can be entered by setting a bit in the PSW
  - The system can enter privileged mode as a result of a request from user code and returns to user mode after completing the request
- Implementation of processes
  - Process table
    * One entry for each process

    * program counter
    * stack pointer
    * memory allocation
    * open files
    * accounting and scheduling information
  - *Interrupt vector*
    * Contains address of *interrupt service procedure*
      · saves all registers in the process table entry
      · services the interrupt

- Process creation
  - Assign a unique process identifier to the new process; add this process to the system process table that contains one entry for each process
  - Allocate space for all elements of process image – space for code, data, and user stack; values can be set by default or based on parameters entered at job creation time
  - Allocation of resources (CPU time, memory, files) – use either of the following policies
    * New process obtains resources directly from the OS
    * New process constrained to share resources from a subset of the parent process
  - Build the data structures that are needed to manage the process, especially process control block
  - When is a process created? – job submission, login, application such as printing
  - Initialization data (input)
  - Process execution
    * Parent continues to execute concurrently with its children
    * Parent waits until all its children have terminated
- Process switching
  - Interrupt a running process and assign control to a different process
  - Difference between process switching and mode switching
  - When to switch processes
    * Any time when the OS has control of the system
    * OS can acquire control by
      · Interrupt – asynchronous external event; not dependent on instructions; clock interrupt
      · Trap – Exception handling; associated with current instruction execution
      · Supervisor call – Explicit call to OS
- Processes in Unix
  - Identified by a unique integer – *process identifier*
  - Created by the `fork(2)` system call
    * Copy the three segments (instructions, user-data, and system-data) without initialization from a program
    * New process is the copy of the address space of the original process to allow easy communication of the parent process with its child
    * Both processes continue execution at the instruction after the `fork`
    * Return code for the `fork` is
      · zero for the child process
      · process id of the child for the parent process
    * Implementation of `fork(2)` in Unix

- Both parent's data and code need to be duplicated in the copies assigned to child
- Not very efficient to make copies since most of the time, `fork(2)` may be followed by an `exec` call
- Hardware paging allows kernels to use Copy-On-Write approach to defer page duplication until the last possible moment, that is, when parent or child need to write into the page

– Use `exec(2)` system call after `fork` to replace the child process's memory space with a new program (binary file)
  * Overlay the image of a program onto the running process
  * Reinitialize a process from a designated program
  * Program changes while the process remains
– `exit(2)` system call
  * Finish executing a process
  * Kernel releases resources owned by the process
  * Sends a `SIGCHLD` signal to parent
– `wait(2)` system call
  * Wait for child process to stop or terminate
  * Synchronize process execution with the `exit` of a previously `fork`ed process
– `signal(3)` library function
  * Control process response to extraordinary events
  * The complete family of `signal` functions (see man page; section 7) provides for simplified signal management for application processes
– Daemons or kernel threads
  * Privileged processes in Unix
  * Run in kernel mode in kernel address space
  * Background processes to do useful work on behalf of the user
    - Just sit in the machine, doing one or the other thing
  * Differ from normal processes in the sense that daemons do not have a `stdin` or `stdout`, and sleep most of the time
    - Communication with humans achieved via logs
  * Created during system startup and remain alive until the system is shut down
  * Common daemons are
    - `update` to synchronize the file system with its image in kernel memory
    - `cron` for general purpose task scheduling
    - `lpd` or `lpsched` as a line printer daemon to pick up files scheduled for printing and distributing them to the printers
    - `init` – the boss of it all
    - `swapper` to handle kernel requests to swap pages of memory to/from disk
– Zombies
  * Processes waiting to send a message to parent so that they can die
  * `init` routinely issues `wait(2)` system call whose side effect is to get rid of all orphaned zombies
– Wait queues
  * Represent sleeping processes to be woken up by kernel when a condition becomes true
  * Used for interrupt handling, process synchronization, and timing
  * Disk operation to terminate, a system resource to be released, or a fixed interval of time to elapse
  * A process waiting for a specific event is put into the corresponding wait queue
  * Modified by interrupt handlers and major kernel functions
    - Must be protected from concurrent access

            · Synchronization achieved by a spin lock in the wait queue head

- MS-DOS Processes
  - Created by a system call to load a specified binary file into memory and execute it
  - Parent is suspended and waits for child to finish execution
- Process termination
  - Normal termination
    * Process terminates when it executes its last statement
    * Upon termination, the OS deletes the process
    * Process may return data (output) to its parent
  - Abnormal termination
    * Process terminates by executing the library function `abort`(3C)
    * All the file streams are closed and other housekeeping performed as defined in the signal handler
  - Termination by another process
    * Termination by the system call `kill`(2) with the signal `SIGKILL`
    * Usually terminated only by the parent of the process because
      · child may exceed the usage of its allocated resources
      · task assigned to the child is no longer required
  - Cascading termination
    * Upon termination of parent process
    * Initiated by the OS
- Process removal
  - A process can query the kernel to get the execution state of its children
  - A process can create a child process to perform a specific task and `wait` to check whether the child has terminated
  - The termination code of child tells the parent process whether the task is completed successfully
  - Because of these design choices, Unix kernel is not allowed to discard data in a PCB right after the process terminates; it has to wait till the parent issues a `wait` that refers to the terminated process
  - `EXIT_ZOMBIE` state: process is technically dead but its descriptor must be saved until the parent has received notification
  - If the parent is dead, the orphan becomes a child of `init` who destroys zombies by issuing a `wait`

Process states in Linux

- Described by six flags and are mutually exclusive
- `TASK_RUNNING`
- `TASK_INTERRUPTIBLE`
  - Process is suspended, waiting for a condition such as hardware interrupt, a system resource, or delivery of a signal
  - Changes to `TASK_RUNNING` when that happens
- `TASK_UNINTERRUPTIBLE`
  - Delivering a signal to sleeping process leaves it state unchanged
  - Process opens a device file and corresponding device driver starts to probe for corresponding hardware device

        * Device driver cannot be interrupted until the probing is complete, or hardware device can be left in an unpredictable state

- `TASK_STOPPED`
  - Process execution stopped
  - Result of receiving a `SIGSTOP`, `SIGTSTP`, `SIGTTIN`, or `SIGTTOU` signal
- `TASK_TRACED`
  - Process stopped by a debugger
- `EXIT_ZOMBIE`
  - Process finished execution but parent has not yet issued a wait system call
- `EXIT_DEAD`
  - Process being removed after the parent has just issued a wait system call
  - Changing state from `EXIT_ZOMBIE` to `EXIT_DEAD` avoids race conditions due to other threads of execution that execute `wait()`-like calls on the same process

Principles of concurrency

- Management of processes and threads is the central theme in OS design

  Multiprogramming: Management of multiple processes within a uniprocessor system

  Multitasking: Management of multiple processes by interleaving their execution on a uniprocessor system, possibly by scheduling

  Multiprocessing: Management of multiple processes within a multiprocessor

  Distributed processing: Management of multiple processes executing on multiple distributed systems; Clustering

- Concurrency
  - Encompasses a host of design issues, including communication among processes, sharing and competing for resources, synchronization of activities of multiple processes, and allocation of CPU time to processes
  - Concurrency arises with
    * Multiple applications – Processing time shared among a number of active applications
    * Structured applications – A single application effectively programmed as a set of concurrent modules
    * OS structure – OS implemented as a set of processes or threads
- `cobegin/coend`
  - Also known as `parbegin/parend`
  - Explicitly specify a set of program segments to be executed concurrently

```
cobegin
    p_1;
    p_2;
    ...
    p_n;
coend;
```

$$(a + b) \times (c + d) - (e/f)$$

```
cobegin
    t_1 = a + b;
    t_2 = c + d;
    t_3 = e / f;
coend
t_4 = t_1 * t_2;
t_5 = t_4 - t_3;
```

- `fork`, `join`, and `quit` Primitives
  - More general than `cobegin/coend`
  - `fork x`
    - Creates a new process `q` when executed by process `p`
    - Starts execution of process `q` at instruction labeled `x`
    - Process `p` executes at the instruction following the `fork`
  - `quit`
    - Terminates the process that executes this command
  - `join t, y`
    - Provides an indivisible instruction
    - Provides the equivalent of test-and-set instruction in a concurrent language

      ```
      if ( ! --t ) goto y;
      ```
  - Program segment with new primitives

```
         m = 3;
         fork p2;
         fork p3;
   p1 :  t1 = a + b; join m, p4; quit;
   p2 :  t2 = c + d; join m, p4; quit;
   p3 :  t3 = e / f; join m, p4; quit;
   p4 :  t4 = t1 × t2;
         t5 = t4 - t3;
```

- Modern parallel programming language (TBB)
  - Serial loop

    ```
    for ( int i = 0; i < 10000; i++ )
        a[i] = f(i) + g(i);
    ```
  - Parallel loop in Intel TBB (threading building blocks)

    ```
    tbb::parallel_for ( 0, 10000, [&](int i) { a[i] = f(i) + g(i); } );
    ```
  - `parallel_for` creates tasks that apply the loop body to each element in range
  - The `&` in the lambda expression indicates that variable `a` should be captured by reference

Process Control Subsystem in Unix

- Significant part of the Unix kernel (along with the file subsystem)
- Contains three modules
  - Interprocess communication
  - Scheduler
  - Memory management

Interprocess Communication

- Race conditions
  - A race condition occurs when two processes (or threads) access the same variable/resource without doing any synchronization
  - One process is doing a coordinated update of several variables
  - The second process observing one or more of those variables will see inconsistent results
  - Final outcome dependent on the precise timing of two processes
  - Example
    * One process is changing the balance in a bank account while another is simultaneously observing the account balance and the last activity date
    * Now, consider the scenario where the process changing the balance gets interrupted after updating the last activity date but before updating the balance
    * If the other process reads the data at this point, it does not get accurate information (either in the current or past time)
- OS concerns
  - Keeping track of different processes through PCBs
  - Allocating and deallocating various resources for active processes, including CPU time, memory, files, and I/O devices
  - Protecting data and physical resources of each process against unintended or deliberate interference by other processes
  - Functioning of a process and its I/O which proceed at different speeds, relative to the speed of other concurrent processes

Critical Section Problem

- Section of code that modifies some memory/file/table while assuming its exclusive control
- Mutually exclusive execution in time
- Template for each process that involves critical section

```
do
{
    ...                     /* Entry section;                 */
    critical_section();     /* Assumed to be present          */
    ...                     /* Exit section                   */
    remainder_section();    /* Assumed to be present          */
}
while ( 1 );
```

  You are to fill in the gaps specified by `...` for entry and exit sections in this template and test the resulting program for compliance with the protocol specified next

- Design of a protocol to be used by the processes to cooperate with following constraints
  - Mutual Exclusion – If process p_i is executing in its critical section, then no other processes can be executing in their critical sections.
  - Progress – If no process is executing in its critical section, the selection of a process that will be allowed to enter its critical section cannot be postponed indefinitely.

  - Bounded Waiting – There must exist 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.
- Assumptions
  - No assumption about the hardware instructions
  - No assumption about the number of processors supported
  - Basic machine language instructions executed atomically
- Disabling interrupts
  - Brute-force approach
  - Not proper to give users the power to disable interrupts
    * User may not enable interrupts after being done
    * Multiple CPU configuration
  - In current systems, interrupts must be disabled inside some critical kernel regions
    * Critical regions must be limited because kernel and interrupt handlers should be able to run most of the time to take care of any event
- Lock variables
  - Share a variable that is set when a process is in its critical section
- Strict alternation

```
shm int turn;    /* Shared memory variable accessible to both processes */

void process ( const int me ) /* me can be 0 or 1 */
{
    int other = 1 - me;
    do
    {
        while ( turn != me ) /* do nothing */ ;
        critical_section();
        turn = other;
        remainder_section();
    } while ( 1 );
}
```

  - Does not satisfy progress requirement
  - Does not keep sufficient information about the state of each process
- Use of a flag

```
shm int flag[2];          /* Shared memory variable; one for each process */

void process ( const int me ) /* me can be 0 or 1 */
{
    int other = 1 - me;
    do
    {
        flag[me] = 1;            /* true */
        while ( flag[other] );
        critical_section();
        flag[me] = 0;            /* false */
```

```
        remainder_section();
    } while ( 1 );
}
```

- Satisfies the mutual exclusion requirement
- Does not satisfy the progress requirement

Time T_0	p_0 sets flag[0] to true
Time T_1	p_1 sets flag[1] to true

  Processes p_0 and p_1 loop forever in their respective while statements
- Critically dependent on the exact timing of two processes
- Switch the order of instructions in entry section
  - No mutual exclusion

• Peterson's solution

- Combines the key ideas from the two earlier solutions

```
shm int flag[2];            /* Shared variables */
shm int turn;               /* Shared variable  */

void process ( const int me ) /* me can be 0 or 1  */
{
    int other = 1 - me;
    do
    {
        /* Entry section */
        flag[me] = true;        /* Raise my flag */
        turn = other;           /* Cede turn to other process */
        while ( flag[other] && turn == other ) ;

        critical_section();

        /* Exit section */
        flag[me] = false;

        remainder_section();

    } while ( 1 );
}
```

• Multiple Process Solution – Solution 4

- The array `flag` can take one of the three values `(idle, want-in, in-cs)`

```
enum state { idle, want_in, in_cs };
shm int turn;
shm state flag[n]; // Flag corresponding to each process in shared memory

process ( const int i )
{
    int   j;             // Local to each process

    do
    {
```

```
        do
        {
            flag[i] = want_in;     // Raise my flag
            j = turn;              // Set local variable
            while ( j != i )
                j = ( flag[j] != idle ) ? turn : ( j + 1 ) % n;

            // Declare intention to enter critical section

            flag[i] = in_cs;

            // Check that no one else is in critical section

            for ( j = 0; j < n; j++ )
                if ( ( j != i ) && ( flag[j] == in_cs ) )
                    break;

        } while ( j < n ) || ( turn != i && flag[turn] != idle );

        // Assign turn to self and enter critical section

        turn = i;
        critical_section();

        // Exit section

        j = (turn + 1) % n;
        while (flag[j] == idle)
           j = (j + 1) % n;

        // Assign turn to next waiting process; change own flag to idle

        turn = j;
        flag[i] = idle;

        remainder_section();
    } while ( 1 );
}
```

- p_i enters the critical section only if `flag[j]` $\neq$ `in-cs` for all `j` $\neq$ `i`.
- `turn` can be modified only upon entry to and exit from the critical section. The first contending process enters its critical section.
- Upon exit, the successor process is designated to be the one following the current process.
- Mutual Exclusion
  - p_i enters the critical section only if `flag[j]` $\neq$ `in_cs` for all `j` $\neq$ `i`.
  - Only p_i can set `flag[i] = in_cs`.
  - p_i inspects `flag[j]` only while `flag[i] = in_cs`.
- Progress
  - `turn` can be modified only upon entry to and exit from the critical section.
  - No process is executing or leaving its critical section $\Rightarrow$ `turn` remains constant.
  - First contending process in the cyclic ordering `(turn, turn+1, ..., n-1, 0, ..., turn-1)` enters its critical section.

- Bounded Wait
  - Upon exit from the critical section, a process must designate its unique successor the first contending process in the cyclic ordering `turn+1, ..., n-1, 0, ..., turn-1, turn`.
  - Any process waiting to enter its critical section will do so in at most `n-1` turns.

- Bakery Algorithm
  - Each process has a unique id
  - Process id is assigned in a completely ordered manner

```
shm bool choosing[n];      /* Shared Boolean array                     */
shm int  number[n];        /* Shared integer array to hold turn number */

void process_i ( const int i )     /* ith Process                          */
{
    do
        choosing[i] = true;
        number[i] = 1 + max(number[0], ..., number[n-1]);
        choosing[i] = false;
        for ( int j = 0; j < n; j++ )
        {
            while ( choosing[j] );    // Wait while someone else is choosing
            while ( ( number[j] ) && (number[j],j) < (number[i],i) );
        }

        critical_section();

        number[i] = 0;

        remainder_section();
    while ( 1 );
}
```

  - If p_i is in its critical section and p_k $(k \neq i)$ has already chosen its number[k] $\neq$ 0, then (number[i],i) $<$ (number[k],k).

Synchronization Hardware

- `test_and_set` instruction

```
int test_and_set (int& target )
{
    int tmp;
    tmp = target;
    target = 1;  /* True */
    return ( tmp );
}
```

- Implementing Mutual Exclusion with `test_and_set`

```
shm bool lock ( false );

do
   while ( test_and_set ( lock ) );
   critical_section();
```

```
    lock = false;
    remainder_section();
while ( 1 );
```

Semaphores

- Commonly used in many applications to communicate such as parking an airplane
- Producer-consumer Problem
  - Shared buffer between producer and consumer
  - Number of items kept in the variable `count`
  - Printer spooler
  - The `|` operator
  - Race conditions
- An integer variable that can only be accessed through two standard atomic operations – wait (P) and signal (V)

Operation	Semaphore	Dutch	Meaning
Wait	P	*proberen*	test
Signal	V	*verhogen*	increment

- The classical definitions for *wait* and *signal* are

```
wait ( S ):     while ( S <= 0 );
                S--;

signal ( S ):   S++;
```

- Mutual exclusion implementation with semaphores

```
do
    wait (mutex);
    critical_section();
    signal (mutex);
    remainder_section();
while ( 1 );
```

- Synchronization of processes with semaphores

p_1	S_1; `signal (synch);`
p_2	`wait (synch);` S_2;

- Implementing Semaphore Operations
  - Binary semaphores using `test_and_set`
    - Check out the instruction definition as previously given
  - Implementation with a *busy-wait*

```
class bin_semaphore
{
    private:
        bool       s;      /* Binary semaphore    */

    public:
        bin_semaphore()            // Default constructor
        : s ( false )
        {}

        void P()                   // Wait on semaphore
        {
            while ( test_and_set ( s ) );
        }

        void V ()                  // Signal the semaphore
        {
            s = false;
        }
};
```

– General semaphore

```
class semaphore
{
    private:
        bin_semaphore    mutex;
        bin_semaphore    delay;
        int              count;

    public:
        void semaphore ( const int num = 1 )     // Constructor
        : count ( num )
        {
            delay.P();
        }

        void P()
        {
            mutex.P();
            if ( --count < 0 )
            {
                mutex.V();
                delay.P();
            }
            mutex.V();
        }

        void V()
        {
            mutex.P();
            if ( ++count <= 0 )
                delay.V();
            else
                mutex.V();
```

```
        }
}
```

– Busy-wait Problem – Processes waste CPU cycles while waiting to enter their critical sections
  * Modify `wait` operation into the `block` operation. The process can block itself rather than busy-waiting.
  * Place the process into a wait queue associated with the critical section
  * Modify `signal` operation into the `wakeup` operation.
  * Change the state of the process from *wait* to *ready*.

– Block-Wakeup Protocol

```
// Semaphore with block wakeup protocol

class sem_int
{
    private:
        int                 value;      // Number of resources
        queue<pid_t>        l;          // List of processes

    public:
        void sem_int ( const int n = 1 )     // Constructor
        : value ( n )
        {
            l = queue<pid_t>( 0 );           // Empty queue
        }

        void P()
        {
            if ( --value < 0 )
            {
                pid_t p = getpid();
                l.enqueue ( p );   // Enqueue the invoking process
                block ( p );
            }
        }

        void V()
        {
            if ( ++value <= 0 )
            {
                process p = l.dequeue();
                wakeup ( p );
            }
        }
};
```

Producer-Consumer problem with semaphores

```
shm semaphore mutex;                     // To get exclusive access to buffers
shm semaphore empty ( n );               // Number of available buffers
shm semaphore full ( 0 );                // Initialized to 0

void producer()
{
    do
    {
```

```
        produce ( item );
        empty.P();        // empty is semaphore
        mutex.P();        // mutex is semaphore
        put ( item );
        mutex.V()
        full.V()
    } while ( 1 );
}

void consumer()
{
    do
    {
        full.P();
        mutex.P();
        remove ( item );
        mutex.V();
        empty.V();
        consume ( item );
    } while ( 1 );
}
```

Problem: What if order of `wait` is reversed in `producer`

Thundering herd

- All processes in a wait queue are woken up simultaneously in response to an event
- They race for a resource that can be accessed by only one of them; remaining processes are put back to sleep
- Avoid the problem by waking up only one process

Higher-Level Synchronization Methods

- P and V operations do not permit a segment of code to be designated explicitly as a critical section.
- Two parts of a semaphore operation; should be treated as distinct
  - Block-wakeup of processes
  - Counting of semaphore
- Possibility of a *deadlock* – Omission or unintentional execution of a V operation.
- Monitors
  - Implementation easiest to view as a class with private and public functions
  - Collection of data [resources] and private functions to manipulate this data
  - A monitor must guarantee the following:
    * Access to the resource is possible only via one of the monitor procedures
    * A process enters the monitor by invoking one of its public procedures
    * Procedures are mutually exclusive in time; only one process at a time can be active within the monitor
  - Additional mechanism for synchronization or communication – the `condition` construct

```
condition x;
```

    * `condition` variables are implemented as a named queue structure

- `condition` variables are accessed by only two operations – `wait` and `signal`
- `x.wait()` suspends the process that invokes this operation until another process invokes `x.signal()`
- `x.signal()` resumes exactly one suspended process; it has no effect if no process is suspended

– Selection of a process to execute within monitor after `signal`

- `x.signal()` executed by process `P` allowing the suspended process `Q` to resume execution
  1. `P` waits until `Q` leaves the monitor, or waits for another condition
  2. `Q` waits until `P` leaves the monitor, or waits for another condition

  Choice 1 advocated by Hoare

- The Dining Philosophers Problem – Solution by Monitors

```
enum state_type { thinking, hungry, eating };

class dining_philosophers
{
    private:
        state_type state[5];      // State of five philosophers
        condition  self[5];       // Condition object for synchronization

        void test ( int i )
        {
            if ( ( state[ ( i + 4 ) % 5 ] != eating )  &&
                 ( state[ i ] == hungry )            &&
                 ( state[ ( i + 1 ) % 5 ] != eating ) )
            {
                state[ i ] = eating;
                self[i].signal();
            }
        }

    public:
        void dining_philosophers()   // Constructor
        {
            for ( int i = 0; i < 5; state[i++] = thinking );
        }

        void pickup ( const int i )     // i corresponds to the philosopher
        {
            state[i] = hungry;
            test ( i );
            if ( state[i] != eating )
                self[i].wait();
        }

        void putdown ( const int i )    // i corresponds to the philosopher
        {
            state[i] = thinking;
            test ( ( i + 4 ) % 5 );
            test ( ( i + 1 ) % 5 );
        }
}
```

– Philosopher i must invoke the operations `pickup` and `putdown` on an instance `dp` of the `dining_philosophers` monitor

```
dining_philosophers dp;

dp.pickup(i);        // Philosopher i picks up the chopsticks
   ...
dp.eat(i);           // Philosopher i eats (for random amount of time)
   ...
dp.putdown(i);       // Philosopher i puts down the chopsticks
```

- No two neighbors eating simultaneously – no deadlocks
- Possible for a philosopher to starve to death

• Implementation of a Monitor

- Execution of procedures must be mutually exclusive
- A `wait` must block the current process on the corresponding `condition`
- If no process in running in the monitor and some process is waiting, it must be selected. If more than one waiting process, some criterion for selecting one must be deployed.
- Implementation using semaphores
  * Semaphore `mutex` corresponding to the monitor initialized to 1
    · Before entry, execute `wait(mutex)`
    · Upon exit, execute `signal(mutex)`
  * Semaphore `next` to suspend the processes unable to enter the monitor initialized to 0
  * Integer variable `next_count` to count the number of processes waiting to enter the monitor

```
mutex.wait();
    ...
void proc() { ... }    // Body of process
    ...
if ( next_count > 0 )
    next.signal();
else
    mutex.signal();
```

  * Semaphore `x_sem` for condition `x`, initialized to 0
  * Integer variable `x_count`

```
class condition
{
    int          num_waiting_procs;     // Processes waiting on this condition
    semaphore    sem;                   // To synchronize the processes
    static int   next_count;            // Processes waiting to enter monitor
    static semaphore next;
    static semaphore mutex;

    public:
        condition()          // Default constructor
        : num_waiting_procs ( 0 ), sem ( 0 )
        {}

        void wait()
        {
            num_waiting_procs++;    // # of processes waiting on this condition
            if ( next_count > 0 )   // Someone waiting inside monitor?
                next.signal();      // Yes, wake him up
            else
```

```
                mutex.signal();      // No, free mutex so others can enter
            sem.wait();              // Start waiting for condition
            num_waiting_procs--;     // Wait over, decrement variable
        }

        void signal()
        {
            if ( num_waiting_procs <= 0 )    // Nobody waiting?
                return;
            next_count++;            // # of ready processes inside monitor
            sem.signal();            // Send the signal
            next.wait();             // You wait; let signaled process run
            next_count--;            // One less process in monitor
        }
};
```

Message-Based Synchronization Schemes

- Process interaction involves two things: synchronization (mutual exclusion) and communication (information exchange)
- Communication between processes is achieved by:
  - Shared memory (semaphores, CCRs, monitors)
  - Message systems
    - Desirable to prevent sharing, possibly for security reasons or no shared memory availability due to different physical hardware
- Communication by Passing Messages
  - Processes communicate without any need for shared variables
  - Paradigm of choice for distributed systems, shared memory multiprocessors, and uniprocessors
  - Two basic communication primitives
    - `send` message
    - `receive` message

`send(P, message)`	Send a message to process P
`receive(Q, message)`	Receive a message from process Q

  - Messages passed through a *communication link*
- Producer/Consumer Problem

```
void producer ()
{
    while ( 1 )
    {
        produce ( data );
        send ( consumer, data );
    }
}
```

```
void consumer ()
{
    while ( 1 )
    {
        receive ( producer, data );
        consume ( data );
    }
}
```

- Issues to be resolved in message communication
  - *Synchronous v/s Asynchronous Communication*

    * Upon `send`, does the sending process continue (asynchronous or nonblocking communication), or does it wait for the message to be accepted by the receiving process (synchronous or blocking communication)?
    * What happens when a `receive` is issued and there is no message waiting (blocking or nonblocking)?
  – *Implicit v/s Explicit Naming*
    * Does the sender specify exactly one receiver (explicit naming) or does it transmit the message to all the other processes (implicit naming)?

`send (p, message)`	Send a `message` to process `p`
`send (A, message)`	Send a `message` to mailbox `A`

    * Does the receiver accept from a certain sender (explicit naming) or can it accept from any sender (implicit naming)?

`receive (p, message)`	Receive a `message` from process `p`
`receive (id, message)`	Receive a `message` from any process; `id` is the process id
`receive (A, message)`	Receive a `message` from mailbox `A`

Ports and Mailboxes

- Achieve synchronization of asynchronous process by embedding a busy-wait loop, with a non-blocking `receive` to simulate the effect of implicit naming
  – Inefficient solution
- Indirect communication avoids the inefficiency of busy-wait
  – Make the queues holding messages between senders and receivers visible to the processes, in the form of mailboxes
  – Messages are sent to and received from mailboxes
  – Most general communication facility between n senders and m receivers
  – Unique identification for each mailbox
  – A process may communicate with another process by a number of different mailboxes
  – Two processes may communicate only if they have a shared mailbox
- Properties of a communication link
  – A link is established between a pair of processes only if they have a shared mailbox
  – A link may be associated with more than two processes
  – Between each pair of communicating processes, there may be a number of different links, each corresponding to one mailbox
  – A link may be either unidirectional or bidirectional
- Ports
  – In a distributed environment, the `receive` referring to same mailbox may reside on different machines
  – Port is a limited form of mailbox associated with only one receiver
  – All messages originating with different processes but addressed to the same port are sent to one central place associated with the receiver

Remote Procedure Calls

- High-level concept for process communication, allowing functions to be called without using send/receive primitives
  – send/receive work like semaphores, taking attention away from the task at hand
  – RPCs allow the called function to be perceived as a service request

- Transfers control to another process, possibly on a different computer, while suspending the calling process
- Called procedure resides in separate address space and no global variables are shared
- Return statement executed by called function returns control to the caller
- Communication strictly by parameters

```
send (RP_guard, parameters);
receive (RP_guard, results);
```

- The remote procedure guard is implemented by

```
void RP_guard ( void )
{
    do
        receive (caller, parameters);
        ...
        send (caller, results);
    while ( 1 );
}
```

- Static versus dynamic creation of remote procedures

Signals and interprocess communication in Unix/Linux

- POSIX standard defines about 20 signals, two of which are user definable
- Process can react to signals in two ways
  1. Ignore the signal
  2. Asynchronously execute a signal handler
- If the process does not specify one of those two alternatives, kernel performs a default action based on signal number as follows:
  - Terminate the process
  - Dump core and terminate the process
    - Core includes the execution context and contents of the address space
  - Ignore the signal
  - Suspend the process
  - Resume the process if it was stopped
- `SIGKILL` and `SIGSTOP` signals cannot be handled directly by the process or ignored
- IPC resources
  - Shared memory, semaphores, and message queues
  - Acquired by a process using `shmget(2)`, `semget(2)`, and `msgget(2)`
  - Persistent: Must be explicitly deallocated by creator, current owner, or root
  - `msgsnd(2)` and `msgrcv(2)`
  - Shared memory
    - `shmget(2)` creates shared memory of required size
    - `shmat(2)` gets the starting address of new region within the process address space
    - `shmdt(2)` detaches the shared memory from process address space