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
Interprocess Communication

- 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
Interprocess Communication

- 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, \texttt{fork(2)} may be followed by an \texttt{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 \texttt{exec(2)} system call after \texttt{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

- \texttt{exit(2)} system call
  - Finish executing a process
  - Kernel releases resources owned by the process
  - Sends a \texttt{SIGCHLD} signal to parent

- \texttt{wait(2)} system call
  - Wait for child process to stop or terminate
  - Synchronize process execution with the exit of a previously forked process

- \texttt{signal(3)} library function
  - Control process response to extraordinary events
  - The complete family of \texttt{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 \texttt{stdin} or \texttt{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
    - \texttt{update} to synchronize the file system with its image in kernel memory
    - \texttt{cron} for general purpose task scheduling
    - \texttt{lpd} or \texttt{lpsched} as a line printer daemon to pick up files scheduled for printing and distributing them to the printers
    - \texttt{init} – the boss of it all
    - \texttt{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
  - \texttt{init} routinely issues \texttt{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

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

\[(a + b) \times (c + d) - (e/f)\]
Interprocess Communication

\[
\begin{align*}
\text{cobegin} & \\
& \quad t_1 = a + b; \\
& \quad t_2 = c + d; \\
& \quad t_3 = e / f; \\
\text{coend} & \\
& \quad t_4 = t_1 \times t_2; \\
& \quad t_5 = t_4 - t_3;
\end{align*}
\]

- 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
      \[
      \text{if} \ ( \! --t \ ) \ \text{goto} \ y;
      \]

- Program segment with new primitives
  \[
  \begin{align*}
  & m = 3; \\
  & \text{fork} \ p2; \\
  & \text{fork} \ p3; \\
  & p1 : t1 = a + b; \ \text{join} \ m, p4; \ \text{quit}; \\
  & p2 : t2 = c + d; \ \text{join} \ m, p4; \ \text{quit}; \\
  & p3 : t3 = e / f; \ \text{join} \ m, p4; \ \text{quit}; \\
  & p4 : t4 = t1 \times t2; \\
  & \quad t5 = t4 - t3;
  \end{align*}
  \]

- Modern parallel programming language (TBB)
  - Serial loop
    \[
    \text{for} \ ( \ \text{int} \ i = 0; \ i < 10000; \ i++ ) \\
    \quad a[i] = f(i) + g(i);
    \]
  - Parallel loop in Intel TBB (threading building blocks)
    \[
    \text{tbb::parallel_for} \ ( \ 0, \ 10000, \ [&](\text{int} \ i) \ { \ a[i] = f(i) + g(i); } ) ;
    \]
    - 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
  
```c
extern int turn;  /* Shared variable between 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
  
```c
extern int flag[2];  /* Shared 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 */
    } while ( 1 );
}
```
Satisfies the mutual exclusion requirement
- Does not satisfy the progress requirement

\[
\begin{align*}
\text{Time } T_0 & \quad p_0 \text{ sets flag}[0] \text{ to true} \\
\text{Time } T_1 & \quad p_1 \text{ sets flag}[1] \text{ to true}
\end{align*}
\]

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

```c
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)

```c
enum state { idle, want_in, in_cs }; 
extern int turn; 
extern 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 \( \text{flag}[j] \neq \text{in-cs} \) for all \( j \neq i \).
– \( \text{turn} \) 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 \( \text{flag}[j] \neq \text{in-cs} \) for all \( j \neq i \).
  * Only \( p_i \) can set \( \text{flag}[i] = \text{in-cs} \).
  * \( p_i \) inspect \( \text{flag}[j] \) only while \( \text{flag}[i] = \text{in-cs} \).
– Progress
  * \( \text{turn} \) can be modified only upon entry to and exit from the critical section.
  * No process is executing or leaving its critical section ⇒ \( \text{turn} \) remains constant.
  * First contending process in the cyclic ordering \( (\text{turn}, \text{turn+1}, \ldots, \text{n-1}, 0, \ldots, \text{turn-1}) \) 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

```c
extern bool choosing[n]; /* Shared Boolean array */
extern 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**

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

- **Implementing Mutual Exclusion with** test_and_set

```c
extern 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 \mid operator
  - Race conditions
- An integer variable that can only be accessed through two standard atomic operations – wait (P) and signal (V)

<table>
<thead>
<tr>
<th>Operation</th>
<th>Semaphore</th>
<th>Dutch</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wait</td>
<td>P</td>
<td>proberen</td>
<td>test</td>
</tr>
<tr>
<td>Signal</td>
<td>V</td>
<td>verhogen</td>
<td>increment</td>
</tr>
</tbody>
</table>

- 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

  \[
  \begin{array}{c}
  p_1 \quad S_1; \\
  \quad \text{signal (synch)}; \\
  p_2 \quad \text{wait (synch)}; \\
  \quad S_2; \\
  \end{array}
  \]

- 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:
  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**

  ```cpp
  // 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
  
  extern semaphore mutex; // To get exclusive access to buffers
  extern semaphore empty ( n ); // Number of available buffers
  extern semaphore full ( 0 ); // Initialized to 0
  
  void producer()
  {
    do
      {
        // Produce
        // Lock mutex
        // empty
        // produce
        // unlock mutex
        // full
        // Produce
        // Lock mutex
        // empty
        // produce
        // unlock mutex
      }
  }
  ```
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 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

```cpp
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)?

\[
\text{send (p, message)} \quad \text{Send a message to process p} \\
\text{send (A, message)} \quad \text{Send a message to mailbox A}
\]

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

\[
\text{receive (p, message)} \quad \text{Receive a message from process p} \\
\text{receive (id, message)} \quad \text{Receive a message from any process; id is the process id} \\
\text{receive (A, message)} \quad \text{Receive a message from mailbox A}
\]

**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
  
  \[
  \text{send (RP\_guard, parameters);} \\
  \text{receive (RP\_guard, results);} \\
  \]

• The remote procedure guard is implemented by

  \[
  \text{void RP\_guard ( void )} \\
  \{
    \text{do} \\
    \quad \text{receive (caller, parameters);} \\
    \quad \ldots \\
    \quad \text{send (caller, results);} \\
    \quad \text{while ( 1 );} \\
  \}
  \]

• 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 \text{shmget(2)}, \text{semget(2)}, and \text{msgget(2)}
  – Persistent: Must be explicitly deallocated by creator, current owner, or root
  – \text{msgsnd(2)} and \text{msgrcv(2)}
  
  – Shared memory
    
    * \text{shmget(2)} creates shared memory of required size
    * \text{shmat(2)} gets the starting address of new region within the process address space
    * \text{shmdt(2)} detaches the shared memory from process address space