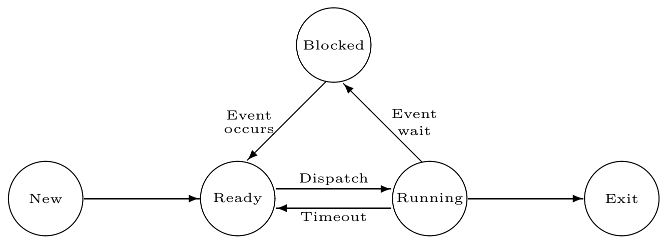
"Only a brain-damaged operating system would support task switching and not make the simple next step of supporting multitasking."

– Calvin Keegan

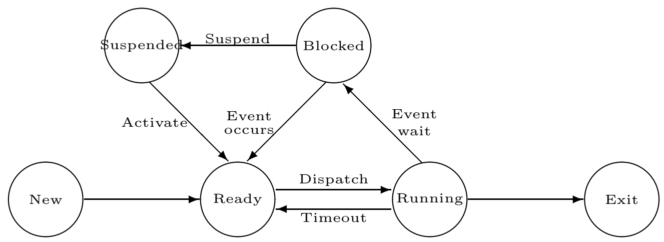
Processes

- Abstraction of a running program
- Unit of work in the system
- Pseudoparallelism
- A process is *traced* by listing the sequence of instructions that execute for that process
- The process model
  - Sequential Process/Task
    - A program in execution
    - Program code
    - Current activity
    - Process stack
      - subroutine 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 MS-DOS, parent suspends itself and lets the child execute
- Process states

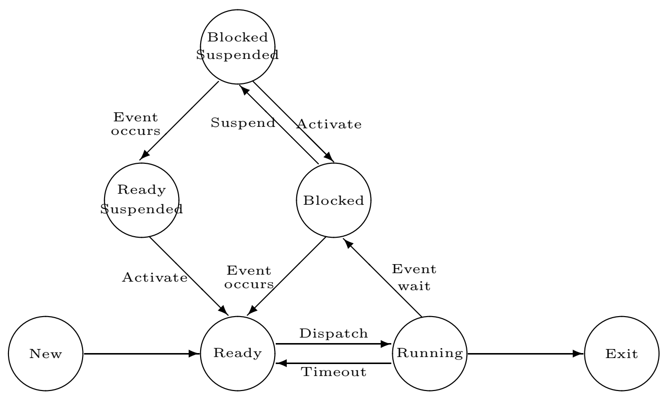
  - Running
  - Ready (Not running, waiting for the CPU)
  - Blocked / Wait on an event (other than CPU) (Not running)
  - Two other states complete the five-state model – New and Exit
    * A process being created can be said to be in state New; it will be in state Ready after it has been created
    * 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 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
  - Static or dynamic process creation
  - 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
  - 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
  - `wait(2)` system call
    - Wait for child process to stop or terminate
    - Synchronize process execution with the `exit` of a previously `fork`ed process
  - `brk(2)` system call
    - Change the amount of space allocated for the calling process's data segment
    - Control the size of memory allocated to a process
  - `signal(3)` library function
    - Control process response to extraordinary events
    - The complete family of `signal` functions (see man page) provides for simplified signal management for application processes
  - Daemons
    - 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
    - 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

- 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
- `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;
```

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)

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
- Lock variables
  - Share a variable that is set when a process is in its critical section
- Strict alternation

```
extern int turn;    /* Shared variable between both processes */

do
{
    while ( turn != i ) /* do nothing */ ;
    critical_section();
    turn = j;
    remainder_section();
} while ( 1 );
```

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

- Use of a flag

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

do
{
    flag[i] = 1;             /* true */
    while ( flag[j] );
    critical_section();
    flag[i] = 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

```
/* Code for process 0; similar code exists for process 1 */

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

void process_0()
{
    do
        /* Entry section */
        flag[0] = true;         /* Raise my flag */
        turn = 1;               /* Cede turn to other process */
        while ( flag[1] && turn == 1 ) ;

        critical_section();

        /* Exit section */
        flag[0] = 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 };
extern int turn;
extern state flag[n];   // Flag corresponding to each process (in shared memory)

// Code for process 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) do
       j = (j + 1) % n;

    // Assign turn to the next waiting process and 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

```
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

```
int test_and_set (int& target )
{
    int tmp;
    tmp = target;
```

```
    target = 1;  /* True */
    return ( tmp );
}
```

- Implementing Mutual Exclusion with `test_and_set`

```
extern bool lock ( false );

do
   while ( test_and_set ( lock ) );
   critical_section();
   lock = false;
   remainder_section();
while ( 1 );
```

Semaphores

- 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

```
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 ( 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`

Event Counters

- Solve the producer-consumer problem without requiring mutual exclusion
- Special kind of variable with three operations
    1. `E.read()`: Return the current value of `E`
    2. `E.advance()`: Atomically increment `E` by 1
    3. `E.await(v)`: Wait until `E` has a value of `v` or more
- Event counters always start at 0 and always increase

```
class event_counter
{
    int     ec;    // Event counter

    public:
        event_counter ()            // Default constructor
        : ec ( 0 )
        {}
        int read()                  const       { return ( ec ); }
        void advance()                          { ec++; }
        void await ( const int v ) const       { while ( ec < v ); }
};
```

```
extern event_counter    in, out;         // Shared event counters

void producer()
{
    int sequence ( 0 );                  // Local to producer
    do
    {
        produce ( item );
        sequence++;
        out.await ( sequence - num_buffers );
        put ( item );
        in.advance();
    }
    while ( 1 );
}

void consumer()
{
    int sequence ( 0 );                  // Local to consumer
    do
    {
        sequence++;
        in.await ( sequence );
        remove ( item );
        out.advance();
        consume ( item );
    }
    while ( 1 );
}
```

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
  - Implemented 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.
    - 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

```
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 P() { ... }    // Body of P()
    ...
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 waiitng for condition
            num_waiting_procs--;    // Wait over, decrement variable
        }

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

- Conditional Critical Regions (CCRs)
  - Designed by Hoare and Brinch-Hansen to overcome the deficiencies of semaphores
  - Explicitly designate a portion of code to be critical section
  - Specify the variables (resource) to be protected by the critical section

    `resource r :: v_1, v_2, ..., v_n`

  - Specify the conditions under which the critical section may be entered to access the elements that form the resource

    `region r when B do S`

    * `B` is a condition to guard entry into critical section `S`
    * At any time, only one process is permitted to enter the code segment associated with resource `r`
  - The statement `region r when B do S` is implemented by

```
semaphore mutex ( 1 ), delay ( 0 );
int       delay_cnt ( 0 );

mutex.P();
del_cnt++;
while ( !B )
{
    mutex.V();
    delay.P();
    mutex.P();
}
del_cnt--;
S;             // Critical section code
for ( int i ( 0 ); i < del_cnt; i++ )
    delay.V();
mutex.V();
```

Message-Based Synchronization Schemes

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

```
void consumer ( void )
{
    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
- `rendezvous` mechanism in Ada