Sistemas de Operação / Fundamentos de Sistemas Operativos

Interprocess communication

Artur Pereira <artur@ua.pt>

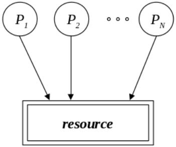
DETI / Universidade de Aveiro

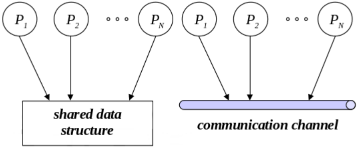
Contents

1. Concepts
2. Access primitives
3. Software solutions
4. Hardware solutions
5. Semaphores
6. Monitors
7. Message passing
8. Unix IPC primitives
9. Bibliography

Concepts
Independent and collaborative processes

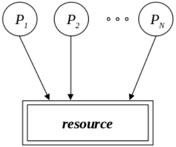
- In a multiprogrammed environment, two or more processes can be:
  - independent – if they, from their creation to their termination, never explicitly interact
    - actually. there is an implicit interaction, as they compete for system resources
    - ex: jobs in a batch system; processes from different users
  - cooperative – if they share information or explicitly communicate
    - the sharing requires a common address space
    - communication can be done through a common address space or a communication channel connecting them

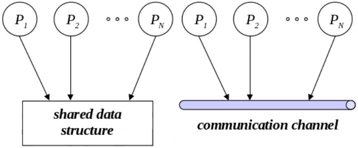




Concepts

Independent and collaborative processes (2)



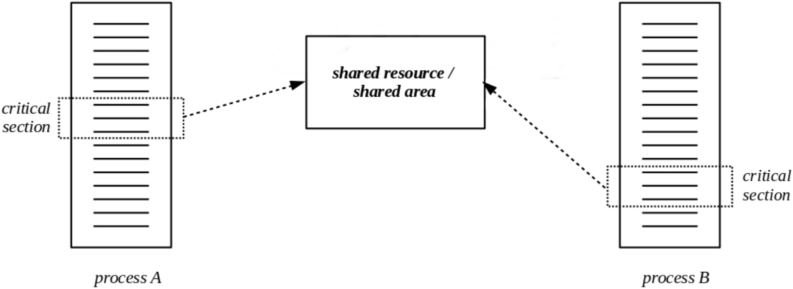


- Independent processs competing for a resource
- It is the responsibility of the OS to ensure the assignment of resources to processes is done in a controlled way, such that no information lost occurs
- In general, this imposes that only one process can use the resource at a time – mutual exclusive access

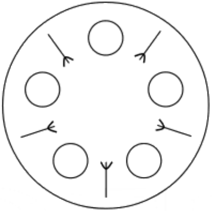
- Cooperative processes sharing information or communicating
- It is the responsibility of the processes to ensure that access to the shared area is done in a controlled way, such that no information lost occurs
- In general, this imposes that only one process can access the shared area at a time – mutual exclusive access
- The communication channel is typically a system resource, so processes compete for it

Concepts
Critical section

- Having access to a resource or to a shared area actually means executing the code that does the access
- This section of code, if not properly protected, can result in race conditions
  - which can result in lost of information
  - It is called critical section
- Critical sections should execute in mutual exclusion

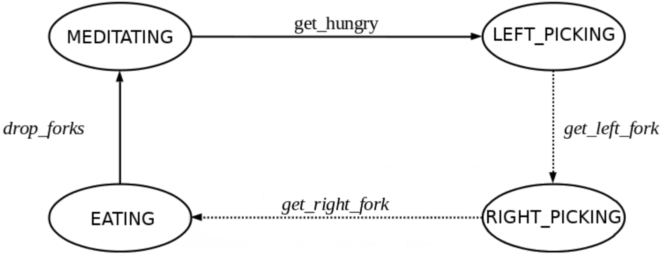


Philosopher dinner
Problem statement



- 5 philosophers are seated around a table, with food in from of them
  - To eat, every philosopher needs two forks, the ones at her/his left and right sides
  - Every philosopher alternates periods in which she/he medidates with periods in which she/he eats
- Modeling every philosopher as a different process or thread and the forks as resources, design a solution for the problem

Philosopher dinner
A solution – state diagram



- This is a possible solution for the dining-philosopher problem
    - when a philosopher gets hungry, he/she first gets the left fork and then holds it while waits for the right one
- Let’s look at an implementations of this solution!

Philosopher dinner

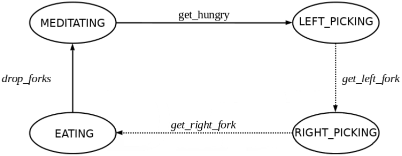
A solution – code

```
enum PHILO_STATE { MEDITATING, LEFT_PICKING, RIGHT_PICKING, EATING };

typedef struct TablePlace
{
        int state;
} TablePlace;

typedef struct Table
{
        int nplaces;
        TablePlace place[0];
} Table;

int set_table(unsigned int n);
int get_hungry(unsigned int f);
int get_left_fork(unsigned int f);
int get_right_fork(unsigned int f);
int drop_forks(unsigned int f);
```

- Let's execute the code

Philosopher dinner

A solution – a race condition



- This solution may work some times, but in general suffers from race conditions
- Let's look at a code snippet:
  - get_right_fork:

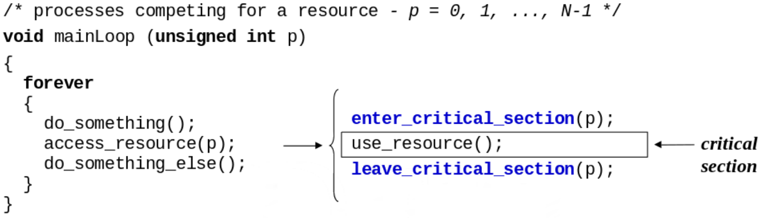
```
while (table->place[right(f)].state == EATING or
       table->place[right(f)].state == RIGHT_PICKING);
```

Concepts
Deadlock and starvation

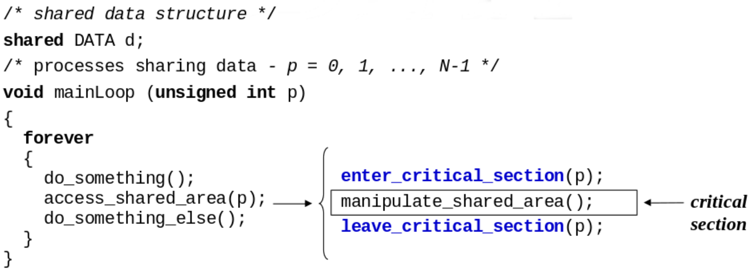
- Mutual exclusion in the access to a resource or shared area can result in
  - deadlock – when two or more processes are waiting forever to access to their respective critical section, waiting for events that can be demonstrated will never happen
    - operations are blocked
  - starvation – when one or more processes compete for access to a critical section and, due to a conjunction of circumstances in which new processes that exceed them continually arise, access is successively deferred
    - operations are continuously postponed

Access primitives

Access to a resource or to a shared area

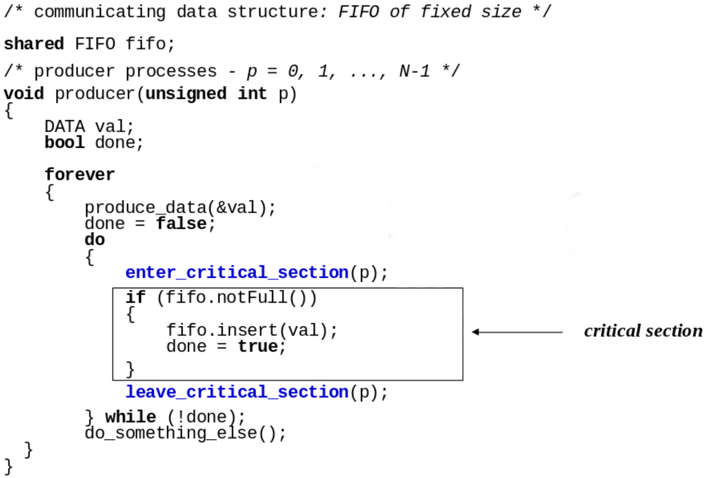


```
/* processes competing for a resource - p = 0, 1, ..., N-1 */
void mainLoop (unsigned int p)
{
  forever
  {
    do_something();                    enter_critical_section(p);
    access_resource(p);        →     { use_resource();                ← critical
    do_something_else();               leave_critical_section(p);       section
  }
}
```



```
/* shared data structure */
shared DATA d;
/* processes sharing data - p = 0, 1, ..., N-1 */
void mainLoop (unsigned int p)
{
  forever
  {
    do_something();                    enter_critical_section(p);
    access_shared_area(p);     →     { manipulate_shared_area();      ← critical
    do_something_else();               leave_critical_section(p);       section
  }
}
```

Access primitives
Producer-consumer example - producer

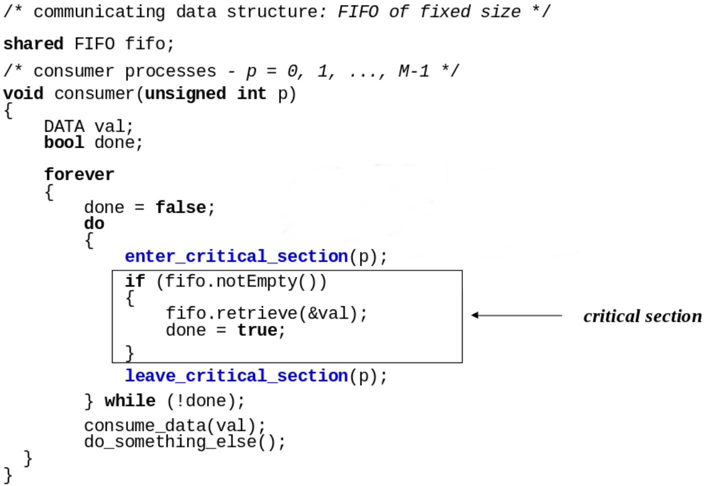


```
/* communicating data structure: FIFO of fixed size */

shared FIFO fifo;

/* producer processes - p = 0, 1, ..., N-1 */
void producer(unsigned int p)
{
    DATA val;
    bool done;

    forever
    {
        produce_data(&val);
        done = false;
        do
        {
            enter_critical_section(p);
            if (fifo.notFull())
            {
                fifo.insert(val);
                done = true;
            }
            leave_critical_section(p);
        } while (!done);
        do_something_else();
  }
}
```

critical section

Access primitives

Producer-consumer example - consumer



```
/* communicating data structure: FIFO of fixed size */

shared FIFO fifo;

/* consumer processes - p = 0, 1, ..., M-1 */
void consumer(unsigned int p)
{
    DATA val;
    bool done;

    forever
    {
        done = false;
        do
        {
            enter_critical_section(p);
            if (fifo.notEmpty())
            {
                fifo.retrieve(&val);
                done = true;
            }
            leave_critical_section(p);
        } while (!done);
        consume_data(val);
        do_something_else();
    }
}
```

critical section

Access primitives
Requirements

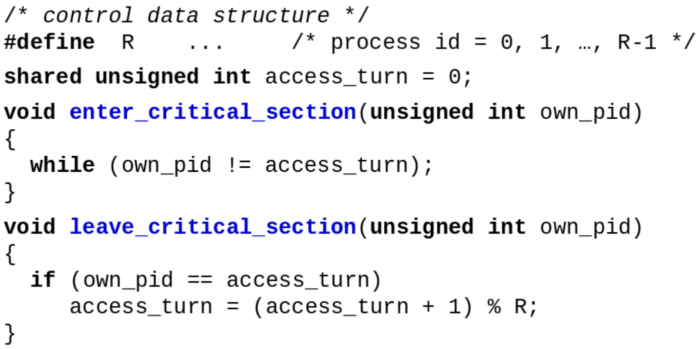
- Requirements that should be observed in accessing a critical section:
  - Effective mutual exclusion – access to the critical sections associated with the same resource, or shared area, can only be allowed to one process at a time, among all processes that compete for access
  - Independence on the number of intervening processes or on their relative speed of execution
  - a process outside its critical section cannot prevent another process from entering its own critical section
  - No starvation – a process requiring access to its critical section should not have to wait indefinitely
  - Length of stay inside a critical section should be necessarily finite

Access primitives
Types of solutions

- In general, a memory location is used to control access to the critical section
  - it works as a binary flag
- Two types of solutions: software solutions and hardware solutions
- software solutions – solutions that are based on the typical instructions used to access memory location
  - read and write are done by different instructions
  - interruption can occur between read and write
- hardware solutions – solutions that are based on special instructions to access the memory location
  - these instructions allow to read and then write a memory location in an atomic way

Software solutions

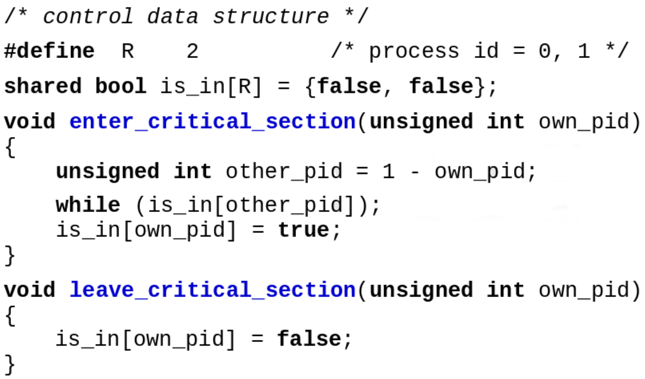
Constructing a solution - strict alternation



```
/* control data structure */
#define  R    ...     /* process id = 0, 1, …, R-1 */
shared unsigned int access_turn = 0;
void enter_critical_section(unsigned int own_pid)
{
  while (own_pid != access_turn);
}
void leave_critical_section(unsigned int own_pid)
{
  if (own_pid == access_turn)
     access_turn = (access_turn + 1) % R;
}
```

- Not a valid solution
  - Dependence on the relative speed of execution of the intervening processes
    - The process with less accesses imposes its rhythm to the others
  - A process outside the critical section can prevent another from entering there
    - If it is not its turn, a process has to wait, until its predecessor enters and give it access on leaving

Software solutions
Constructing a solution - 1st step

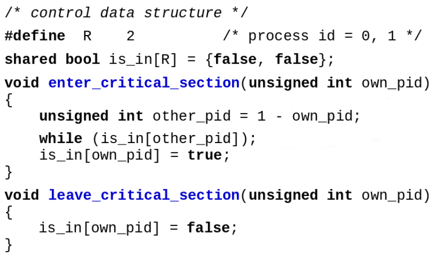


```
/* control data structure */
#define  R    2          /* process id = 0, 1 */
shared bool is_in[R] = {false, false};
void enter_critical_section(unsigned int own_pid)
{
    unsigned int other_pid = 1 - own_pid;
    while (is_in[other_pid]);
    is_in[own_pid] = true;
}
void leave_critical_section(unsigned int own_pid)
{
    is_in[own_pid] = false;
}
```

- Not a valid solution
  - Mutual exclusion is not guaranteed

Software solutions

Constructing a solution - 1st step



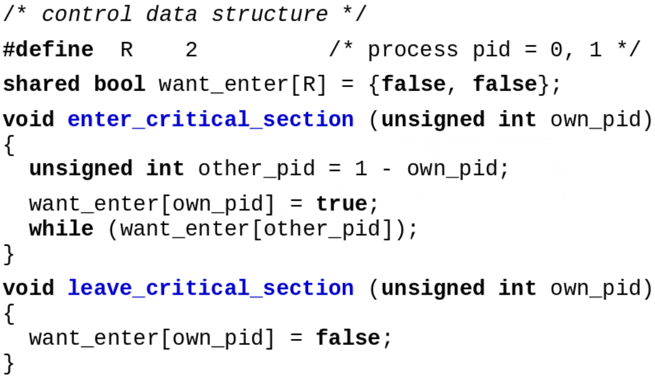
```
/* control data structure */
#define  R    2          /* process id = 0, 1 */
shared bool is_in[R] = {false, false};
void enter_critical_section(unsigned int own_pid)
{
    unsigned int other_pid = 1 - own_pid;
    while (is_in[other_pid]);
    is_in[own_pid] = true;
}
void leave_critical_section(unsigned int own_pid)
{
    is_in[own_pid] = false;
}
```

- Assume the following sequence of execution:
  - P_0 enters `enter_critical_section` and tests `is_in[1]` as being `false`
  - P_1 enters `enter_critical_section` and tests `is_in[0]` as being `false`
  - P_1 changes `is_in[1]` to `true` and enters its critical section
  - P_0 changes `is_in[0]` to `true` and enters its critical section
- Thus, both processes enter their critical sections

- It seems that the failure is a result of testing first the other's control variable and then change its own variable

Software solutions

Constructing a solution - 2nd step

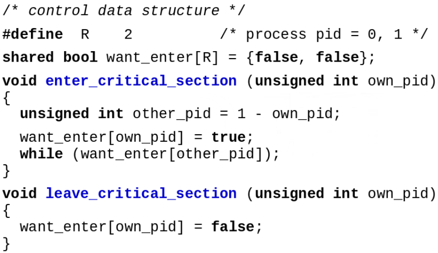


```
/* control data structure */
#define  R    2          /* process pid = 0, 1 */
shared bool want_enter[R] = {false, false};
void enter_critical_section (unsigned int own_pid)
{
  unsigned int other_pid = 1 - own_pid;
  want_enter[own_pid] = true;
  while (want_enter[other_pid]);
}
void leave_critical_section (unsigned int own_pid)
{
  want_enter[own_pid] = false;
}
```

- Not a valid solution
  - Mutual exclusion is guaranteed, but deadlock can occur

Software solutions

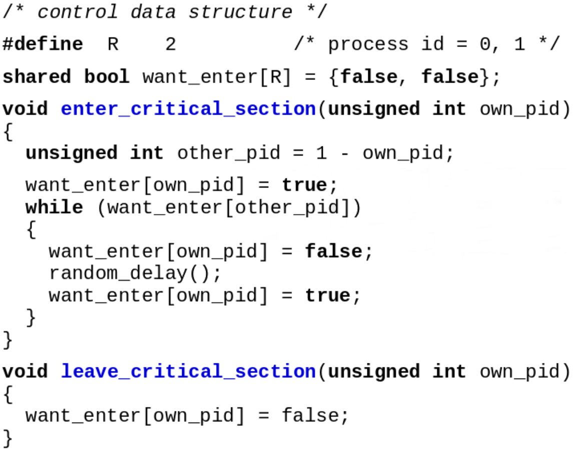
Constructing a solution - 2nd step



```
/* control data structure */
#define  R    2          /* process pid = 0, 1 */
shared bool want_enter[R] = {false, false};
void enter_critical_section (unsigned int own_pid)
{
  unsigned int other_pid = 1 - own_pid;
  want_enter[own_pid] = true;
  while (want_enter[other_pid]);
}
void leave_critical_section (unsigned int own_pid)
{
  want_enter[own_pid] = false;
}
```

- Assume that:
  - P_0 enters `enter_critical_section` and sets `want_enter[0]` to `true`
  - P_1 enters `enter_critical_section` and sets `want_enter[1]` to `true`
  - P_1 tests `want_enter[0]` and, because it is `true`, keeps waiting to enter its critical section
  - P_0 tests `want_enter[1]` and, because it is `true`, keeps waiting to enter its critical section
- Thus, both processes enter deadlock
- To solve the deadlock at least one of the processes have to go back

Software solutions
Constructing a solution - 3rd step

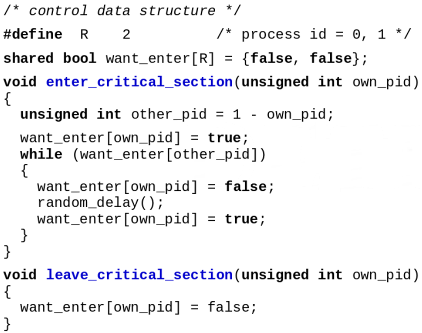


```
/* control data structure */
#define  R    2           /* process id = 0, 1 */
shared bool want_enter[R] = {false, false};
void enter_critical_section(unsigned int own_pid)
{
  unsigned int other_pid = 1 - own_pid;
  want_enter[own_pid] = true;
  while (want_enter[other_pid])
  {
    want_enter[own_pid] = false;
    random_delay();
    want_enter[own_pid] = true;
  }
}
void leave_critical_section(unsigned int own_pid)
{
  want_enter[own_pid] = false;
}
```

- An almost valid solution
  - The Ethernet protocol uses a similar approach to control access to the communication medium

Software solutions

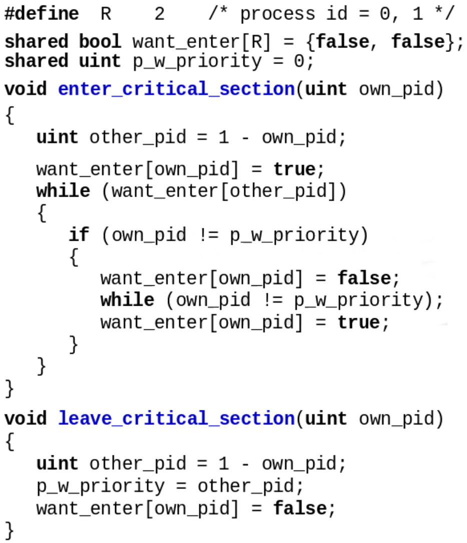
Constructing a solution - 3rd step



```
/* control data structure */
#define  R    2          /* process id = 0, 1 */
shared bool want_enter[R] = {false, false};
void enter_critical_section(unsigned int own_pid)
{
  unsigned int other_pid = 1 - own_pid;
  want_enter[own_pid] = true;
  while (want_enter[other_pid])
  {
    want_enter[own_pid] = false;
    random_delay();
    want_enter[own_pid] = true;
  }
}
void leave_critical_section(unsigned int own_pid)
{
  want_enter[own_pid] = false;
}
```

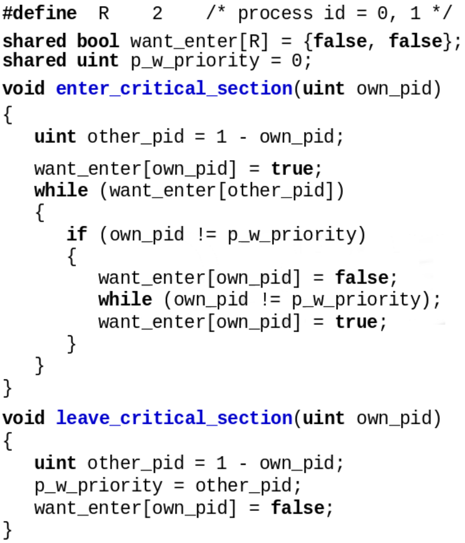
- An almost valid solution
  - The Ethernet protocol uses a similar approach to control access to the communication medium
- But, still not completely valid
  - Even if unlikely, deadlock and starvation can still be present
- The solution needs to be deterministic, not random

Software solutions
Dekker algorithm (1965)



```
#define  R    2    /* process id = 0, 1 */

shared bool want_enter[R] = {false, false};
shared uint p_w_priority = 0;

void enter_critical_section(uint own_pid)
{
   uint other_pid = 1 - own_pid;

   want_enter[own_pid] = true;
   while (want_enter[other_pid])
   {
      if (own_pid != p_w_priority)
      {
         want_enter[own_pid] = false;
         while (own_pid != p_w_priority);
         want_enter[own_pid] = true;
      }
   }
}

void leave_critical_section(uint own_pid)
{
   uint other_pid = 1 - own_pid;
   p_w_priority = other_pid;
   want_enter[own_pid] = false;
}
```

Software solutions
Dekker algorithm (1965)

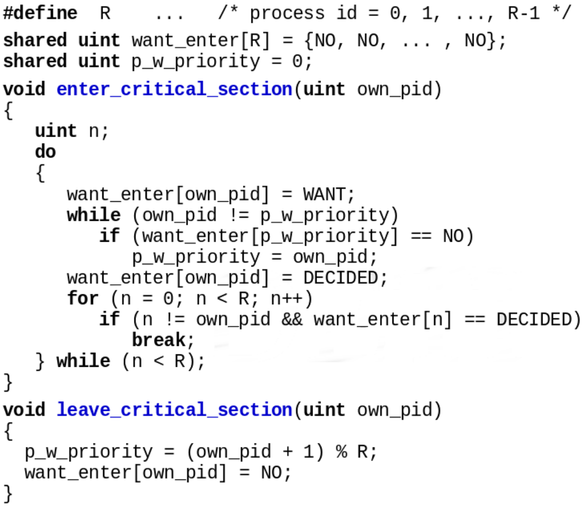


```
#define  R    2    /* process id = 0, 1 */
shared bool want_enter[R] = {false, false};
shared uint p_w_priority = 0;
void enter_critical_section(uint own_pid)
{
   uint other_pid = 1 - own_pid;
   want_enter[own_pid] = true;
   while (want_enter[other_pid])
   {
      if (own_pid != p_w_priority)
      {
         want_enter[own_pid] = false;
         while (own_pid != p_w_priority);
         want_enter[own_pid] = true;
      }
   }
}
void leave_critical_section(uint own_pid)
{
   uint other_pid = 1 - own_pid;
   p_w_priority = other_pid;
   want_enter[own_pid] = false;
}
```

- The algorithm uses an alternation mechanism (on the priority) to solve the conflict
- Mutual exclusion in the access to the critical section is guaranteed
- Deadlock and starvation are not present
- No assumptions are done in the relative speed of the intervening processes
- However, it can not be generalized to more than 2 processes, satisfying all the requirements

Software solutions

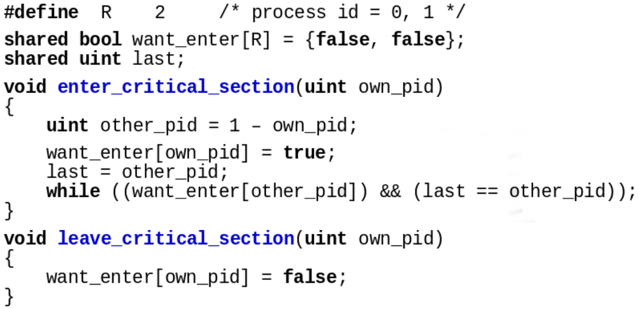
Dijkstra algorithm (1966)



```
#define  R    ...   /* process id = 0, 1, ..., R-1 */
shared uint want_enter[R] = {NO, NO, ... , NO};
shared uint p_w_priority = 0;
void enter_critical_section(uint own_pid)
{
   uint n;
   do
   {
      want_enter[own_pid] = WANT;
      while (own_pid != p_w_priority)
         if (want_enter[p_w_priority] == NO)
            p_w_priority = own_pid;
      want_enter[own_pid] = DECIDED;
      for (n = 0; n < R; n++)
         if (n != own_pid && want_enter[n] == DECIDED)
            break;
   } while (n < R);
}
void leave_critical_section(uint own_pid)
{
  p_w_priority = (own_pid + 1) % R;
  want_enter[own_pid] = NO;
}
```

- Works, but can suffer from starvation

Software solutions
Peterson algorithm (1981)

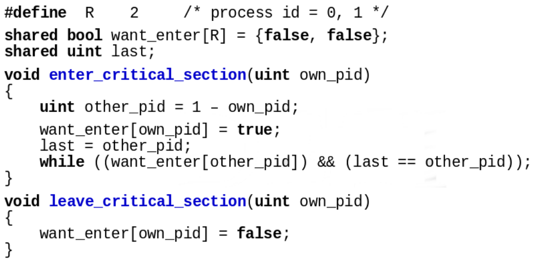


```
#define  R    2     /* process id = 0, 1 */
shared bool want_enter[R] = {false, false};
shared uint last;
void enter_critical_section(uint own_pid)
{
    uint other_pid = 1 - own_pid;
    want_enter[own_pid] = true;
    last = other_pid;
    while ((want_enter[other_pid]) && (last == other_pid));
}
void leave_critical_section(uint own_pid)
{
    want_enter[own_pid] = false;
}
```

- The Peterson algorithm uses the order of arrival to solve conflicts
  - Each process has to write the other's ID in a shared variable (last)
  - The subsequent reading allows to determine which was the last one

Software solutions

Peterson algorithm (1981)

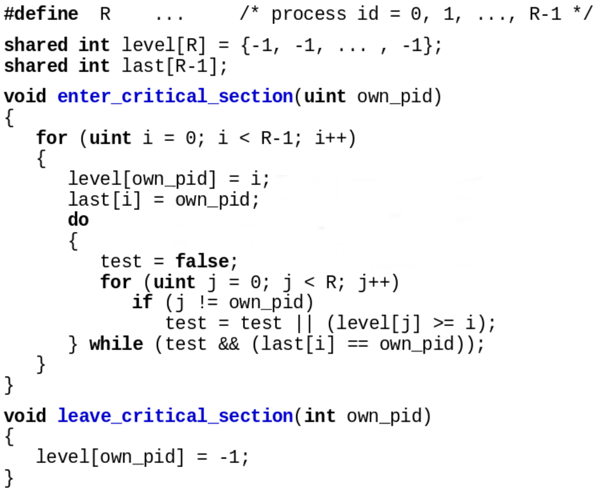


```
#define  R    2     /* process id = 0, 1 */
shared bool want_enter[R] = {false, false};
shared uint last;
void enter_critical_section(uint own_pid)
{
    uint other_pid = 1 – own_pid;
    want_enter[own_pid] = true;
    last = other_pid;
    while ((want_enter[other_pid]) && (last == other_pid));
}
void leave_critical_section(uint own_pid)
{
    want_enter[own_pid] = false;
}
```

- The Peterson algorithm uses the order of arrival to solve conflicts
  - Each process has to write the other’s ID in a shared variable (last)
  - The subsequent reading allows to determine which was the last one
- It is a valid solution
  - Guarantees mutual exclusion
  - Avoids deadlock and starvation
  - Makes no assumption about the relative speed of intervening processes

Software solutions

Generalized Peterson algorithm (1981)



```
#define  R    ...     /* process id = 0, 1, ..., R-1 */

shared int level[R] = {-1, -1, ... , -1};
shared int last[R-1];

void enter_critical_section(uint own_pid)
{
   for (uint i = 0; i < R-1; i++)
   {
      level[own_pid] = i;
      last[i] = own_pid;
      do
      {
         test = false;
         for (uint j = 0; j < R; j++)
            if (j != own_pid)
               test = test || (level[j] >= i);
      } while (test && (last[i] == own_pid));
   }
}

void leave_critical_section(int own_pid)
{
   level[own_pid] = -1;
}
```

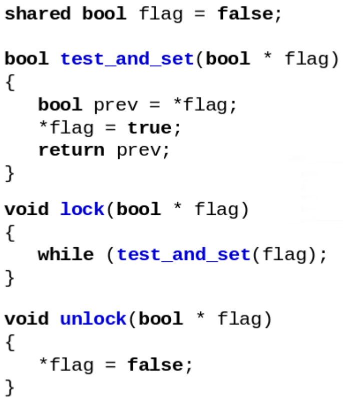
- Can be generalized to more than two processes
  - The general solution is similar to a waiting queue

Hardware solutions
disabling interrupts

- *Uniprocessor computational system*
  - The switching of processes, in a multiprogrammed environment, is always caused by an external device:
    - real time clock (RTC) – cause the time-out transition in preemptive systems
    - device controller – can cause the preempt transitions in case of waking up of a higher priority process
    - In any case, interruptions of the processor
  - Thus, access in mutual exclusion can be implemented disabling interrupts
  - Only valid in kernel
    - Malicious or buggy code can completely block the system
- *Multiprocessor computational system*
  - Disabling interrupts in one processor has no effect

Hardware solutions

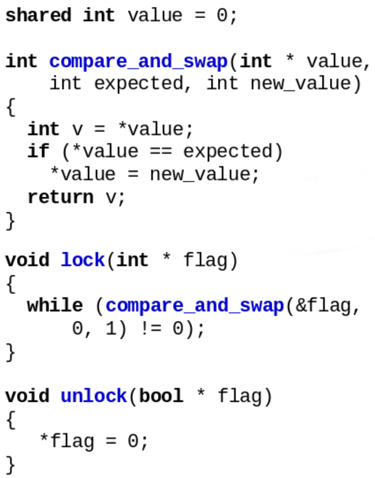
special instructions – TAS



```
shared bool flag = false;

bool test_and_set(bool * flag)
{
   bool prev = *flag;
   *flag = true;
   return prev;
}

void lock(bool * flag)
{
   while (test_and_set(flag));
}

void unlock(bool * flag)
{
   *flag = false;
}
```

- The `test_and_set` function, if implemented atomically (without interruptions), can be used to construct the lock (enter critical section) primitive
- In the instruction set of some of the current processors, there is an atomic instruction implementing this behavior
- Surprisingly, it is often called TAS (test and set)

Hardware solutions
special instructions – CAS



```
shared int value = 0;

int compare_and_swap(int * value,
    int expected, int new_value)
{
  int v = *value;
  if (*value == expected)
    *value = new_value;
  return v;
}

void lock(int * flag)
{
  while (compare_and_swap(&flag,
      0, 1) != 0);
}

void unlock(bool * flag)
{
   *flag = 0;
}
```

- The `compare_and_swap` function, if implemented atomically (without interruptions), can be used to construct the lock (enter critical section) primitive
- In the instruction set of some of the current processors, there is an atomic instruction implementing that behavior
- In some instruction sets, there is a `compare_and_set` variant this returns a bool

Hardware solutions

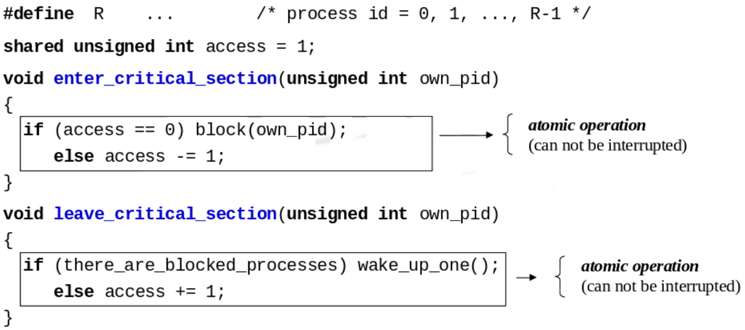
Busy waiting

- The previous solutions suffer from *busy waiting*
  - The lock primitive is in the active state (using the CPU) while waiting
  - It is often referred to as a spinlock, as the process spins around the variable while waiting for access
- In uniprocessor systems, busy waiting is unwanted, as there is
  - loss of efficiency – the time quantum of a process is used for nothing
  - risk of deadlock – if a higher priority process calls lock while a lower priority process is inside its critical section, none of them can proceed
- In multiprocessor systems with shared memory, busy waiting can be less critical
  - switching processes cost time, that can be higher than the time spent by the other process inside its critical section

Hardware solutions

Block and wake up

- In general, at least in uniprocessor systems, there is the requirement of blocking a process while it is waiting for entering its critical section



```
#define  R    ...         /* process id = 0, 1, ..., R-1 */
shared unsigned int access = 1;
void enter_critical_section(unsigned int own_pid)
{
 if (access == 0) block(own_pid);
    else access -= 1;
}
void leave_critical_section(unsigned int own_pid)
{
 if (there_are_blocked_processes) wake_up_one();
    else access += 1;
}
```

atomic operation
(can not be interrupted)

atomic operation
(can not be interrupted)

- Atomic operations are still required

Semaphores
Definition

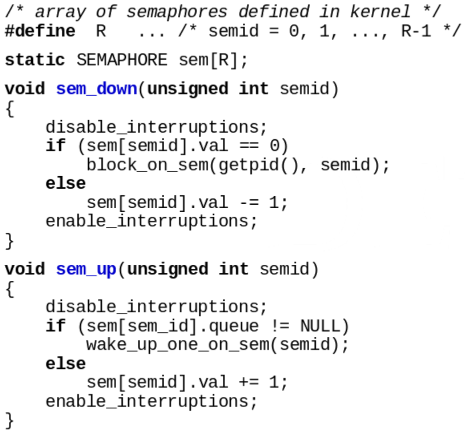
- A semaphore is a synchronization mechanism, defined by a data type plus two atomic operations, down and up
- Data type:

```
typedef struct
{
   unsigned int val;      /* can not be negative */
   PROCESS *queue;        /* queue of waiting blocked processes */
} SEMAPHORE;
```

- Operations:
  - down
    - block process if `val` is zero
    - decrement `val` otherwise
  - up
    - if `queue` is not empty, wake up one waiting process (accordingly to a given policy)
    - increment `val` otherwise
- Note that `val` can only be manipulated through these operations
  - It is not possible to check the value of `val`

Semaphores

An implementation of semaphores

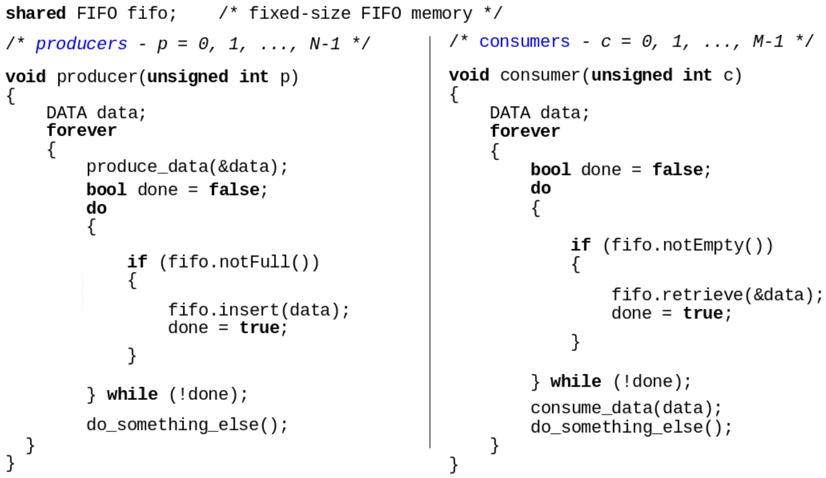


```
/* array of semaphores defined in kernel */
#define  R   ... /* semid = 0, 1, ..., R-1 */

static SEMAPHORE sem[R];

void sem_down(unsigned int semid)
{
    disable_interruptions;
    if (sem[semid].val == 0)
        block_on_sem(getpid(), semid);
    else
        sem[semid].val -= 1;
    enable_interruptions;
}

void sem_up(unsigned int semid)
{
    disable_interruptions;
    if (sem[sem_id].queue != NULL)
        wake_up_one_on_sem(semid);
    else
        sem[semid].val += 1;
    enable_interruptions;
}
```

- This implementation is typical of uniprocessor systems. Why?
- Semaphores can be binary or not binary
- How to implement mutual exclusion using semaphores?
  - Using a binary semaphore

Semaphores

Bounded-buffer problem – solving using semaphores



```
shared FIFO fifo;    /* fixed-size FIFO memory */
```

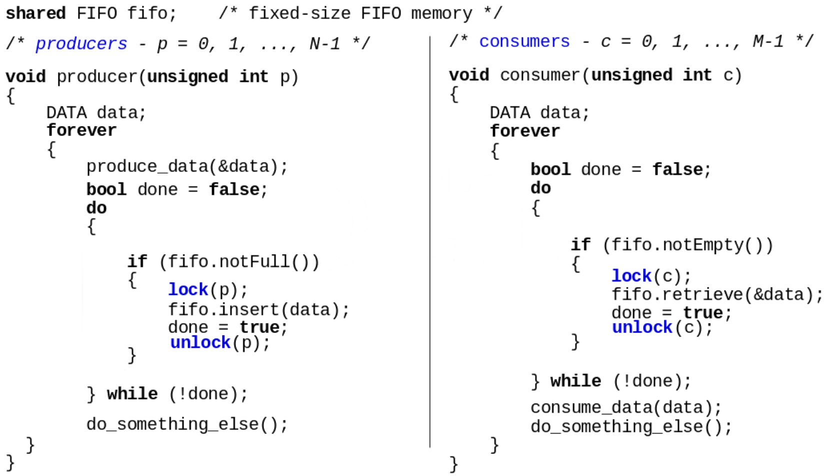
```
/* producers - p = 0, 1, ..., N-1 */

void producer(unsigned int p)
{
    DATA data;
    forever
    {
        produce_data(&data);
        bool done = false;
        do
        {

            if (fifo.notFull())
            {

                fifo.insert(data);
                done = true;

            }

        } while (!done);

        do_something_else();
  }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */

void consumer(unsigned int c)
{
    DATA data;
    forever
    {
        bool done = false;
        do
        {

            if (fifo.notEmpty())
            {

                fifo.retrieve(&data);
                done = true;

            }

        } while (!done);

        consume_data(data);
        do_something_else();
    }
}
```

- This solution can suffer race conditions

Semaphores

Bounded-buffer problem – solving using semaphores



```
shared FIFO fifo;    /* fixed-size FIFO memory */
```

```
/* producers - p = 0, 1, ..., N-1 */

void producer(unsigned int p)
{
    DATA data;
    forever
    {
        produce_data(&data);
        bool done = false;
        do
        {

            if (fifo.notFull())
            {
                lock(p);
                fifo.insert(data);
                done = true;
                unlock(p);
            }

        } while (!done);

        do_something_else();
    }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */

void consumer(unsigned int c)
{
    DATA data;
    forever
    {
        bool done = false;
        do
        {

            if (fifo.notEmpty())
            {
                lock(c);
                fifo.retrieve(&data);
                done = true;
                unlock(c);
            }

        } while (!done);
        consume_data(data);
        do_something_else();
    }
}
```

- Mutual exclusion is guaranteed, but suffers from busy waiting

Semaphores

Bounded-buffer problem – solving using semaphores

```
shared FIFO fifo;    /* fixed-size FIFO memory */
```

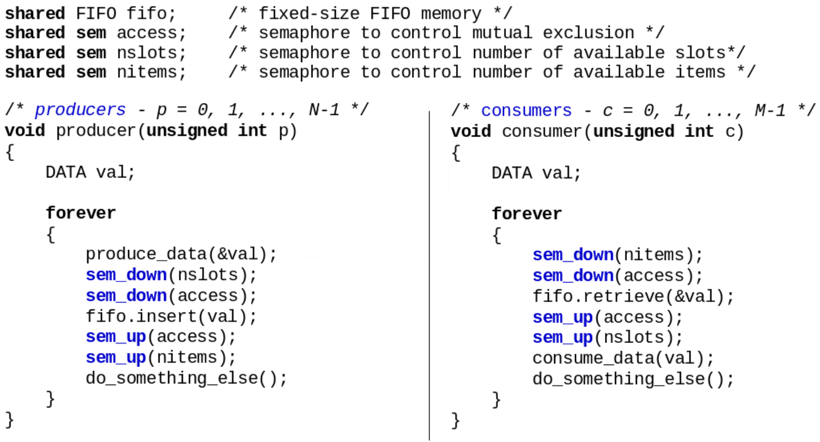
```
/* producers - p = 0, 1, ..., N-1 */

void producer(unsigned int p)
{
    DATA data;
    forever
    {
        produce_data(&data);
        bool done = false;
        do
        {

            if (fifo.notFull())
            {

                fifo.insert(data);
                done = true;

            }

        } while (!done);
        do_something_else();
    }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */

void consumer(unsigned int c)
{
    DATA data;
    forever
    {
        bool done = false;
        do
        {

            if (fifo.notEmpty())
            {

                fifo.retrieve(&data);
                done = true;

            }

        } while (!done);
        consume_data(data);
        do_something_else();
    }
}
```

- How to implement using semaphores?
  - guaranteeing mutual exclusion and absence of busy waiting

Semaphores

Bounded-buffer problem – solving using semaphores



```
shared FIFO fifo;     /* fixed-size FIFO memory */
shared sem access;    /* semaphore to control mutual exclusion */
shared sem nslots;    /* semaphore to control number of available slots*/
shared sem nitems;    /* semaphore to control number of available items */
```

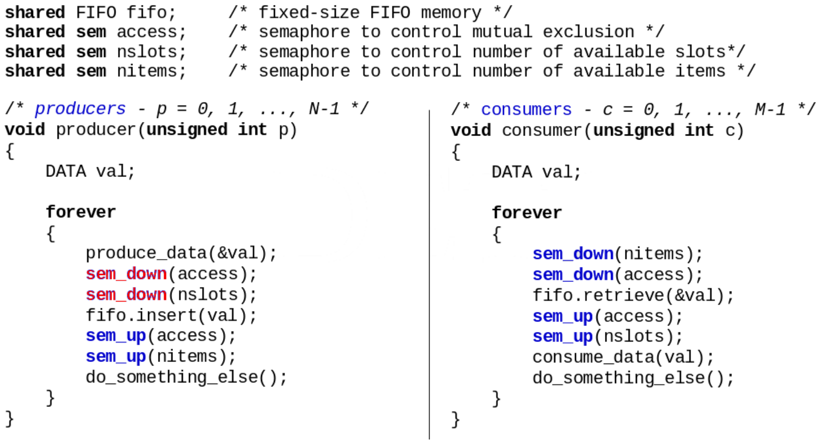
```
/* producers - p = 0, 1, ..., N-1 */
void producer(unsigned int p)
{
    DATA val;

    forever
    {
        produce_data(&val);
        sem_down(nslots);
        sem_down(access);
        fifo.insert(val);
        sem_up(access);
        sem_up(nitems);
        do_something_else();
    }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */
void consumer(unsigned int c)
{
    DATA val;

    forever
    {
        sem_down(nitems);
        sem_down(access);
        fifo.retrieve(&val);
        sem_up(access);
        sem_up(nslots);
        consume_data(val);
        do_something_else();
    }
}
```

- `fifo.notEmpty()` and `fifo.notFull()` are no longer necessary. Why?
- What are the initial values of the semaphores?

Semaphores

Bounded-buffer problem – wrong solution



```
shared FIFO fifo;     /* fixed-size FIFO memory */
shared sem access;    /* semaphore to control mutual exclusion */
shared sem nslots;    /* semaphore to control number of available slots*/
shared sem nitems;    /* semaphore to control number of available items */
```

```
/* producers - p = 0, 1, ..., N-1 */
void producer(unsigned int p)
{
    DATA val;

    forever
    {
        produce_data(&val);
        sem_down(access);
        sem_down(nslots);
        fifo.insert(val);
        sem_up(access);
        sem_up(nitems);
        do_something_else();
    }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */
void consumer(unsigned int c)
{
    DATA val;

    forever
    {
        sem_down(nitems);
        sem_down(access);
        fifo.retrieve(&val);
        sem_up(access);
        sem_up(nslots);
        consume_data(val);
        do_something_else();
    }
}
```

- It can be easy to make a mistake
- What is wrong with this solution? It can cause deadlock

Semaphores

Analysis of semaphores

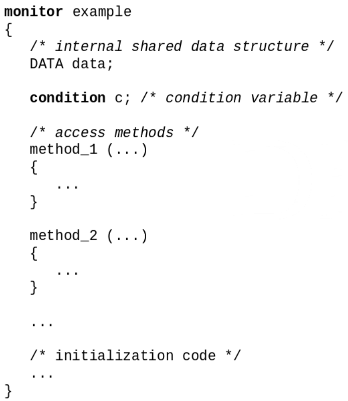
- Concurrent solutions based on semaphores have advantages and disadvantages
- Advantages:
  - support at the operating system level– operations on semaphores are implemented by the kernel and made available to programmers as system calls
  - general– they are low level contructions and so they are versatile, being able to be used in any type of solution
- Disadvantages:
  - specialized knowledge– the programmer must be aware of concurrent programming principles, as race conditions or deadlock can be easily introduced
    - See the previous example, as an illustration of this

Monitors
Introduction

- A problem with semaphores is that they are used both to implement mutual exclusion and to synchronize processes
- Being low level primitives, they are applied in a bottom-up perpective
  - if required conditions are not satisfied, processes are blocked before they enter their critical sections
  - this approach is prone to errors, mainly in complex situations, as synchronization points can be scattered throughout the program
- A higher level approach should followed a top-down perpective
  - processes must first enter their critical sections and then block if continuation conditions are not satisfied
- A solution is to introduce a (concurrent) construction at the programming language level that deals with mutual exclusion and synchronization separately

- A monitor is a synchronization mechanism, independently proposed by Hoare and Brinch Hansen, supported by a (concurrent) programming language
  - It is composed of an internal data structure, inicialization code and a number of accessing primitives

Monitors
Definition

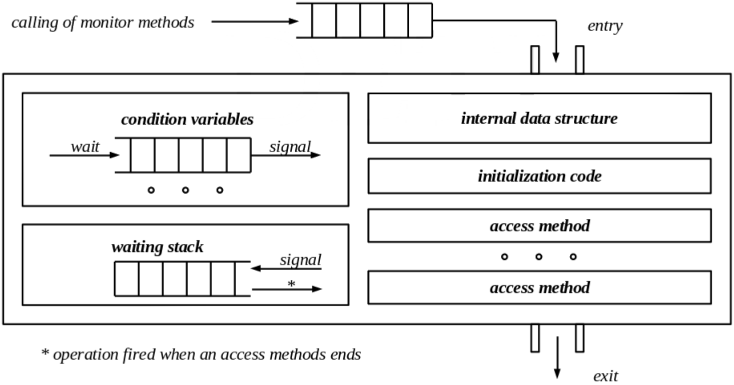


```
monitor example
{
   /* internal shared data structure */
   DATA data;

   condition c; /* condition variable */

   /* access methods */
   method_1 (...)
   {
      ...
   }

   method_2 (...)
   {
      ...
   }

   ...

   /* initialization code */
   ...
}
```

- An application is seen as a set of threads that compete to access the shared data structure
- This shared data can only be accessed through the access methods
- Every method is executed in mutual exclusion
- If a thread calls an access method while another thread is inside another access method, its execution is blocked until the other leaves
- Synchronization between threads is possible through condition variables
- Two operation on them are possible:
  - wait – the thread is blocked and put outside the monitor
  - signal – if there are threads blocked, one is waked up. *Which one?*

Monitors
Hoare monitor

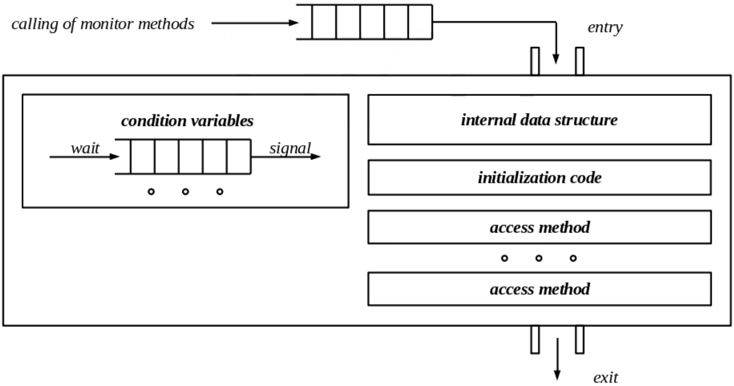
- What to do when signal occurs?
- Hoare monitor – the thread calling signal is put out of the monitor, so the just waked up thread can proceed
  - quite general, but its implementation requires a stack where the blocked thread is put



* operation fired when an access methods ends

Monitors
Brinch Hansen monitor

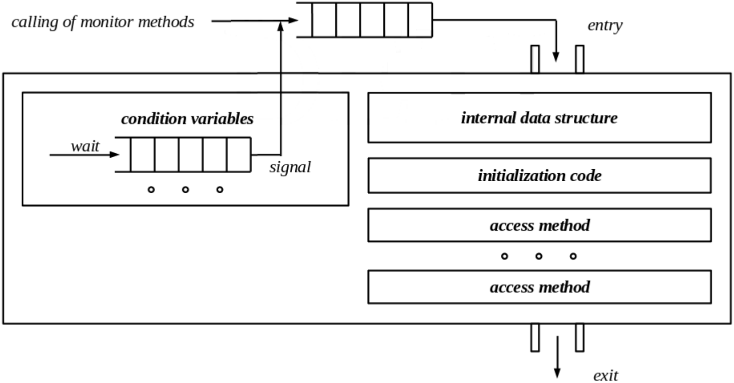
- What to do when signal occurs?
- Brinch Hansen monitor – the thread calling signal immediately leaves the monitor (signal is the last instruction of the monitor method)
  - easy to implement, but quite restrictive (only one signal allowed in a method)



Monitors

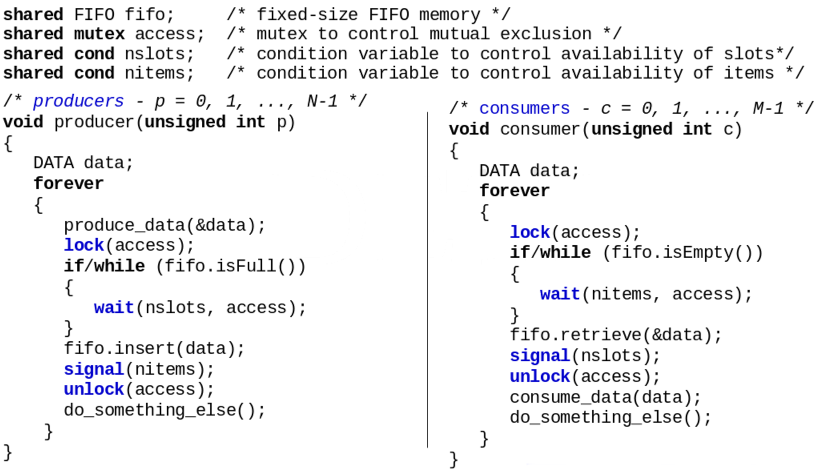
Lampson / Redell monitor

- What to do when signal occurs?
- Lampson / Redell monitor – the thread calling signal continues its execution and the just waked up thread is kept outside the monitor, competing for access
    - easy to implement, but can cause starvation



Monitors

Bounded-buffer problem – solving using monitors



```
shared FIFO fifo;      /* fixed-size FIFO memory */
shared mutex access;   /* mutex to control mutual exclusion */
shared cond nslots;    /* condition variable to control availability of slots*/
shared cond nitems;    /* condition variable to control availability of items */
```

```
/* producers - p = 0, 1, ..., N-1 */
void producer(unsigned int p)
{
   DATA data;
   forever
   {
      produce_data(&data);
      lock(access);
      if/while (fifo.isFull())
      {
         wait(nslots, access);
      }
      fifo.insert(data);
      signal(nitems);
      unlock(access);
      do_something_else();
    }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */
void consumer(unsigned int c)
{
   DATA data;
   forever
   {
      lock(access);
      if/while (fifo.isEmpty())
      {
         wait(nitems, access);
      }
      fifo.retrieve(&data);
      signal(nslots);
      unlock(access);
      consume_data(data);
      do_something_else();
   }
}
```

- What is the initial state of the mutex?

Message-passing
Introduction

- Processes can communicate exchanging messages
  - A general communication mechanism, not requiring explicit shared memory, that includes both communication and synchronization
  - Valid for uniprocessor and multiprocessor systems
- Two operations are required:
  - send and receive
- A communication link is required
  - That can be categorized in different ways:
    - Direct or indirect communication
    - Synchronous or asynchronous communication
    - Type of buffering

Message-passing
Direct and indirect communication

- Symmetric direct communication
  - A process that wants to communicate must explicitly name the receiver or sender
    - `send(P, msg)` – send message `msg` to process `P`
    - `receive(P, msg)` – receive message `msg` from process `P`
  - A communication link in this scheme has the following properties:
    - it is established automatically between a pair of communicating processes
    - it is associated with exactly two processes
    - between a pair of communicating processes there exist exactly one link

- Asymetric direct communication
  - Only the sender must explicitly name the receiver
    - `send(P, msg)` – send message `msg` to process `P`
    - `receive(id, msg)` – receive message `msg` from any process

Message-passing

Direct and indirect communication

- Indirect communication
  - The messages are sent to and received from mailboxes, or ports
    - `send(M, msg)` – send message `msg` to mailbox `M`
    - `receive(M, msg)` – receive message `msg` from mailbox `M`
  - A communication link in this scheme has the following properties:
    - it is only established if the pair of communicating processes has a shared mailbox
    - it may be associated with more than two processes
    - between a pair of processes there may exist more than one link (a mailbox per each)
  - The problem of two or more processes trying to receive a message from the same mailbox
    - Is it allowed?
    - If allowed, which one will succeed?

Message-passing

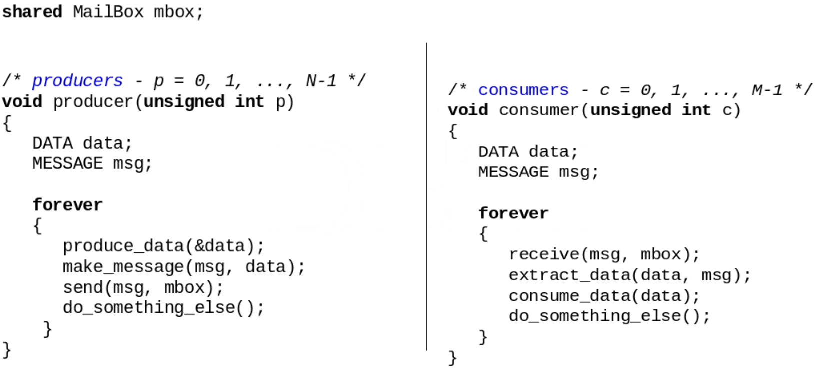
Synchronization

- From a synchronization point of view, there are different design options for implementing send and receive
  - Blocking send– the sending process blocks until the message is received by the receiving process or by the mailbox
  - Nonblocking send– the sending process sends the message and resumes operation
  - Blocking receive– the receiver blocks until a message is available
  - Nonblocking receive– the receiver retrieves either a valid message or the indication that no one exits
- Different combinations of send and receive are possible

Message-passing
Buffering

- There are different design options for implementing the link supporting the communication
  - Zero capacity – there is no queue
    - the sender must block until the recipient receives the message
  - Bounded capacity – the queue has finite length
    - if the queue is full, the sender must block until space is available
  - Unbounded capacity – the queue has (potentially) infinite length

Message-passing
Bounded-buffer problem – solving using messages



```
shared MailBox mbox;
```

```
/* producers - p = 0, 1, ..., N-1 */
void producer(unsigned int p)
{
   DATA data;
   MESSAGE msg;

   forever
   {
      produce_data(&data);
      make_message(msg, data);
      send(msg, mbox);
      do_something_else();
    }
}
```

```
/* consumers - c = 0, 1, ..., M-1 */
void consumer(unsigned int c)
{
   DATA data;
   MESSAGE msg;

   forever
   {
      receive(msg, mbox);
      extract_data(data, msg);
      consume_data(data);
      do_something_else();
   }
}
```

Unix IPC primitives
POSIX support for monitors

- Standard POSIX, IEEE 1003.1c, defines a programming interface (API) for the creation and synchronization of threads
  - In unix, this interface is implemented by the pthread library
- It allows for the implementation of monitors in C/C++
  - Using mutexes and condition variables
  - Note that they are of the Lampson / Redell type
- Some of the available functions:
  - `pthread_create` – creates a new thread; similar to `fork`
  - `pthread_exit` – equivalent to `exit`
  - `pthread_join` – equivalent a `waitpid`
  - `pthread_self` – equivalent a `getpid()`
  - `pthread_mutex_*` – manipulation of mutexes
  - `pthread_cond_*` – manipulation of condition variables
  - `pthread_once` – inicialization

Unix IPC primitives
Semaphores

- System V semaphores
  - creation: `semget`
  - down and up: `semop`
  - other operations: `semctl`
- POSIX semaphores
  - down and up
    - `sem_wait`, `sem_trywait`, `sem_timedwait`, `sem_post`
  - Two types: named and unnamed semaphores
  - Named semaphores
    - `sem_open`, `sem_close`, `sem_unlink`
    - created in a virtual filesystem (e.g., /dev/sem)
  - unnamed semaphores – memory based
    - `sem_init`, `sem_destroy`
  - execute `man sem_overview` for an overview

Unix IPC primitives
Message-passing

- System V implementation
  - Defines a message queue where messages of diferent types (a positive integer) can be stored
  - The send operation blocks if space is not available
  - The receive operation has an argument to specify the type of message to receive: a given type, any type or a range of types
    - The oldest message of given type(s) is retrieved
    - Can be blocking or nonblocking
  - see system calls: `msgget`, `msgsnd`, `msgrcv`, and `msgctl`
- POSIX message queue
  - Defines a priority queue
  - The send operation blocks if space is not available
  - The receive operation removes the oldest message with the highest priority
    - Can be blocking or nonblocking
  - see functions: `mq_open`, `mq_send`, `mq_receive`, ···

Unix IPC primitives
Shared memory

- Address spaces of processes are independent
- But address spaces are virtual
- The same physical region can be mapped into two or more virtual regions
- This is managed as a resource by the operating system

- System V shared memory
  - creation – `shmget`
  - mapping and unmapping – `shmat`, `shmdt`
  - other operations – `shmctl`

- POSIX shared memory
  - creation - `shm_open`, `ftruncate`
  - mapping and unmapping - `mmap`, `munmap`
  - other operations - `close`, `shm_unlink`, `fchmod`, ···

Bibliography

- Operating Systems: Internals and Design Principles, W. Stallings, Prentice-Hall International Editions, 7th Ed, 2012
  - Chapter 5: Concurrency: mutual exclusion and synchronization (sections 5.1 to 5.5)
- Operating Systems Concepts, A. Silberschatz, P. Galvin and G. Gagne, John Wiley & Sons, 9th Ed, 2013
  - Chapter 3: Processes (section 3.4)
  - Chapter 4: Process synchronization (sections 5.1 to 5.8)
- Modern Operating Systems, A. Tanenbaum and H. Bos, Pearson Education Limited, 4th Ed, 2015
  - Chapter 2: Processes and Threads (section 2.3)